DETERMINATION OF BELOW-GROUND VEGETATION AND WATER USE MODEL PARAMETERS FOR A REVISED SOUTH AFRICAN HYDROLOGICAL BASELINE LAND COVER

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PREFACE

The research contained in this dissertation was completed by the candidate while based in the Discipline of Hydrology, Centre of Water Resources Research, University of KwaZulu-Natal, Pietermaritzburg, South Africa. The research was financially supported by the Water Research Commission (WRC) of South Africa.

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.

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DECLARATION 1 – PLAGIARISM

I, *Megan Ann McNamara*, declare that

(i) the research reported in this dissertation, except where otherwise indicated, is my original work;

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DECLARATION 2 – PUBLICATIONS

DETAILS OF CONTRIBUTION TO PUBLICATIONS that form part of/or include research presented in this dissertation (including publications submitted and published, giving details of the contributions of each author to the research and writing each publication):

Publication 1 – Chapter 2 of this dissertation

McNamara, M.A. and Toucher, M.L. 2017. Understanding the sensitivity of the ACRU Model to land use parameters. *Submitted to WaterSA*

The analysis for this publication was conducted by M.A. McNamara. The publication was written in its entirety by M.A. McNamara and all figures, tables and graphs were produced by the same unless otherwise referenced in the text of the paper. Editing and advice regarding interpretation was provided by M.L. Toucher.

Publication 2 – Chapter 3 of this dissertation

McNamara, M.A. and Toucher, M.L. 2017. Quantifying and parameterising the Root Systems of Natural Vegetation in South Africa for use in a hydrological model. *Submitted to WaterSA*

The analysis for this publication was conducted by M.A. McNamara. The publication was written in its entirety by M.A. McNamara and all figures, tables and graphs were produced by the same unless otherwise referenced in the text of the paper. Editing and advice regarding interpretation was provided by M.L Toucher.

ABSTRACT

The combination of both natural and anthropogenic activities have caused significant changes to the natural land cover which have impacted on the hydrological responses. The assessment of the magnitude of these land use change impacts on the hydrological response is important for sound water resource management, and is largely dependent on the baseline land cover used. The development of an updated natural vegetation map of South Africa by SANBI (2012), together with improved field based measurements of natural vegetation water use in recent studies, has led to the assessment of this map as a new hydrological baseline for South Africa. The proposed new baseline provides an opportunity to address the concerns raised about the current Acocks' (1988) baseline used in South Africa. This study has provided estimates of the below-ground related vegetation and water use ACRU parameters for the proposed new baseline. These below-ground parameters estimated include the seasonal variations of the distribution of active roots in topsoil and subsoil horizons (ROOTA and ROOTB), the effective rooting depth (EFRDEP). The new and refined set of below-ground land cover ACRU input parameters will contribute to an improved and reliable baseline against which to assess any changes. As it was impractical to produce field-based measurements for the large number of natural vegetation species, and as it was not possible to form new spatial observations of theses below-ground root structures, the refined parameterisation of the below-ground component in ACRU was based primarily on review of measured values from past literature. The ROOTA values were estimated based on the vertical root distributions for various vegetation growth forms from previous studies together with the A-horizon soil depths of the vegetation clusters that constitute the baseline land cover. The effective rooting depth (EFRDEP) values were estimated by applying a linear regression relationship, relating rooting depths to Mean Annual Precipitation (MAP) for each baseline cluster. The study also involved a sensitivity analysis of the land cover input parameters to the ACRU Agrohydrological Model to determine the parameters to which the model is most sensitive.

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LIST OF ABBREVIATIONS

ACRU = Agricultural Catchments Research Unit

CAY = Water use crop coefficient

COIAM = Coefficient of initial abstraction

COLONA = Percentage root colonization in the A-horizon

COLONB = Percentage root colonization in the B-horizon

CWRR = Centre for Water Resources Research

c = Dimensionless shape-parameter (shape of the non-linear curve)

DEPAHO = Depth of the soil A-horizon

DEPBHO = Depth of the soil B-horizon

DWS = Department of Water and Sanitation

D_{50} = Depth (cm) at which $r(D) = 50\%(R_{max})$

D_{max} = Maximum rooting depth

EFRDEP = Effective rooting depth

ET = Evapotranspiration

Et = Actual transpiration

FAO = Food and Agricultural Organisation

FC = Field Capacity

IAHS = International Association of Hydrological Sciences

LAI = Leaf Area Index

LDR = Logistic Dose Response Curve

MAP = Mean Annual Precipitation

m.a.s.l = meters above sea level

NRF = National Research Foundation

NWA = National Water Act

O_{Base} = Output simulated from the base run input

O = Output from a particular change in input parameter

$\Delta O\%$ = Percentage change in output

PAW = Plant Available Water

PCSUCO = Percentage surface cover by vegetation or mulch/litter

ROOTA = Fraction of effective root system in the A-horizon

ROOTB = Fraction of effective root system in the B-horizon

r(D) = Cumulative percentage of roots (%) above profile depth D (cm)

R_{max} = Total percentage of roots in the profile (%)

SAEON = South African Environmental Observation Network

SANBI = South African National Biodiversity Institute

SFRA = Streamflow Reduction Activity

UBFLOW = Simulated Baseflow

USFLOW = Simulated streamflow

VEGINT = Potential interception by vegetation

WP = Wilting Point

WRC = Water Research Commission

CHAPTER 1: INTRODUCTION

The hydrological response of a catchment is, in part, dependent on the land cover and is thus influenced by changes to the land cover (Falkenmark *et al.*, 1999; Schulze, 2000). Therefore, the sound management of water resources requires an understanding of land use change and the impacts thereof on the hydrological response.

1.1 Background

The partitioning of rainwater into the various components of the hydrological cycle is determined by the land cover (Costa *et al.*, 2003; Woyessa *et al.*, 2008). Therefore, any changes to the land cover alters the partitioning (Falkenmark *et al.*, 1999). Changing land cover is a phenomenon that is increasing in magnitude and significance, both globally and in South Africa (Gillson *et al.*, 2012). In South Africa, the natural landscape has been changed and modified extensively to meet the growing population’s demands for water, fuel, food and fibre (Warburton *et al.*, 2012). Further to this, climate change may cause changes in the geographic distribution of natural vegetation (Turner *et al.*, 1995; Wasson, 1996) and shifts in the climatically optimum regions for agricultural crops and commercial forestry (Wasson, 1996; Warburton and Schulze, 2008), resulting in further land cover changes. The hydrological response which is dependent on the land use is sensitive to and affected by these changes (Falkenmark *et al.*, 1999; Schulze, 2000), placing additional pressure on the country’s already stressed water resources (Warburton *et al.*, 2015).

The distinction between land cover and land use needs to be emphasised. For the purpose of this research, the term “land cover” refers to the biophysical state of the ground surface and immediate subsurface, with regards to general land cover types such as grassland, cropland, natural or planted forestry and human settlements (Turner *et al.*, 1993, 1995). These land cover types may be changed or exploited by either natural causes (e.g. long-term climate change or volcanic activities) or most commonly by anthropogenic activities, causing them to be converted or modified to a land use (Turner *et al.*, 1995; Lambin *et al.*, 2000). A piece of land has a single quantifiable cover type which can have multiple uses (Gillson *et al.*, 2012). Therefore land cover changes include transformation of natural vegetation to agricultural crops and forest plantations, and the modifications to natural vegetation through bush encroachment and overgrazing, soil erosion, invasion by alien plant species, and accelerating urbanisation.

In order to protect and manage our water resources, it is essential to accurately assess the magnitude of impacts associated with land use changes or potential changes at a range of scales. To determine the magnitude of an impact it is necessary to identify a baseline, from which all changes may be evaluated. A “baseline” is the identification of a starting point or a reference condition. It defines the established pre-impacted state, against which all disturbances may be evaluated (Borjeson, 2009). In terms of hydrological and land use change studies this starting point would be the baseline hydrology, which is that produced under a baseline climate, a baseline spatial scale and baseline vegetation (Schulze, 2007). Among these components, the baseline vegetation is the subject that receives the most attention in deliberations, and the choice thereof has significant influence on the assessed impacts on water resources.

1.2 Baseline Land Cover for Hydrological Studies

A baseline land cover is a reference condition or benchmark system state (Jewitt *et al.*, 2009), against which the changes in hydrological responses may be evaluated (Warburton *et al.*, 2012). To the water resource planner whose ultimate goal is to assess the availability of water (Bulcock and Jewitt, 2010), the comparative water use between transformed land cover and the baseline land cover would be a priority. In South Africa, baseline land cover information is needed for such assessments of potential land use change impacts, as well as the assessment of reference flows (Schulze, 2007). The need for a baseline land cover against which to evaluate land use change impacts became increasingly important with the implementation of the South African National Water Act (NWA, 1998), because reference flows are needed for both ecological reserve calculations and specific land use impact assessments, such as assessing Streamflow Reduction Activities (SFRA’s) of land uses, especially the impacts on low flows. (Warburton *et al.*, 2015).

The pre-impacted condition of vegetation is used to establish the baseline vegetation, against which all current and potential land use change impacts on the hydrological response may be compared and assessed (Everson *et al.*, 2011). The results generated from assessments and studies differ when a different baseline or reference land cover is used (Warburton *et al.*, 2015). Quantification of land use change and the impacts thereof on the hydrological response depends largely on the baseline or reference land cover, and the hydrological response under baseline conditions, which was used as the basis of comparison (Jewitt *et al.*, 2009; Warburton *et al.*, 2010; Everson *et al.* 2011). The appropriate selection and quantification of reference land cover to represent baseline conditions is thus imperative, and introduces an additional layer of complexity to hydrological impact assessments of land use changes (Warburton *et al.*, 2015). Although natural vegetation gives a good representation of the pre-impacted vegetation, the baseline land cover or reference/benchmark surface used in various studies and assessments is not always natural vegetation. There are many different potential baseline land covers, of which natural vegetation is one option, which may be used. The baseline vegetation could be considered as a specific point in history where the land cover of that time may be used as a baseline. Alternatively, it may be considered as the site-specific land cover which existed prior to any changes or modifications. In most cases, the baseline vegetation is established by default, based primarily on the availability of data (Borjeson, 2009). For instance, Choi and Deal (2008) and Bewket and Sterk (2005) determined land use change impacts by assessing two points in time, while Neihoff *et al.* (2002) determined land use change impacts by using the present land use as the basis of comparison. The Food and Agricultural Organisation (FAO, 2006) use a grass reference surface as the baseline vegetation, against which to compare the water use of other vegetation types. The "short grass surface" (FAO 56) or sometimes "alfalfa crop", used by the FAO as the reference/baseline, provides an estimation of the standard evapotranspiration, against which all estimates of potential evapotranspiration rates of various vegetation types are made (by means of crop coefficients). The FAO defines this reference surface as "A hypothetical reference crop with an assumed crop height of 0.12 m, a fixed surface resistance of 70 s m^{-1} and an albedo of 0.23", which is similar in appearance to a broad surface of actively growing green grass having an even height, shading the entire ground surface and having access to sufficient water. The FAO uses this reference crop to evaluate various land use practices and land use change impacts on evapotranspiration (ET), as well as in the determination and evaluation of water footprints of various crops.

The characteristics of natural ecosystems are essential for establishing the pre-impacted state of the landscape and thus, the most commonly supported and currently accepted baseline land cover for water resource assessments is that of "natural vegetation", i.e. determination of land use change impacts by Schulze (2003) and Costa *et al.* (2003) used natural land cover for the basis of comparison. Using natural vegetation to define the baseline land cover describes the characterization of the structure and function (including patterns of spatial and temporal variation) of the natural vegetation before any human impacts or influences and thus, of the potential vegetation (Garbulsky and Paruelo, 2004). The difference in the water use of a given crop compared to the natural vegetation it replaces provides a direct representation of the impact on streamflow caused by the change in land cover (Le Maitre *et al.*, 2007a; Le Maitre *et al.*, 2007b; Jewitt, 2006). The impacts on water resources resulting from changes to natural ecosystems may then be determined. Natural ecosystems are self-regulating as they have feedback mechanisms that help to maintain the components of the system in one or other of its equilibrium or stable states. The functioning of these natural ecosystems may be negatively influenced, specifically causing significant hydrological implications, following any land use change in which a dryland-cultivation activity, or where the introduced vegetation, uses more water than the natural vegetation or the vegetation it would replace (Everson *et al.*, 2011). In South Africa, the concept of “naturalised” flows is an indirect expression of the catchment’s hydrology under “baseline” conditions, against which the effects of all developments and changes that occur within the catchment may be evaluated (Schulze, 2004). The baseline vegetation under which the baseline hydrology of naturalised flows are produced is that of natural vegetation. For these reasons, the natural vegetation condition is the supported and accepted baseline, against which to quantify and understand potential land use change impacts on water resources specifically. The currently accepted standard or reference land cover, used by the Department of Water and Sanitation (DWS), against which land use change impacts are assessed, is the “natural vegetation” as classified in the Acocks’ (1988) Veld Types (Schulze, 2004; Jewitt *et al.*, 2009). Therefore, all SFRAs, as well as other water use assessments, are currently monitored according to their comparison against the Acocks’ (1988) Veld Types. These Acocks’ (1988) Veld Types were supported as the baseline because it was the only classification available at the time for which hydrological parameters had been derived.

The accuracy of the baseline vegetation mapping and data is important for increasing the accuracy of land use change assessments and monitoring activities, specifically at the subcatchment scale where small changes have great consequences (Warburton, 2015). The maps produced by Acocks (1988) were mapped at a country-wide scale with minimal detail at the local scale, with only 70 Veld Types described to represent the entire variability of natural vegetation across the country. Further to this, the parameter values were estimated on the basis of expert knowledge and methods that consider climate factors responsible for driving the vegetation water use cycle throughout the year (Schulze, 2003), as limited research had been undertaken for natural vegetation water use at the time (Jewitt *et al.*, 2009). These issues raise concerns about the use of these Acocks' (1988) Veld Types as the baseline land cover, against which all estimations of water use are currently assessed. The Water Research Commission (WRC) funded project "Methods and Guidelines for the Licensing of SFRAs with particular reference to low flows" by Jewitt *et al.* (2009), identified the use of the Acocks' (1988) Veld Types as the greatest source of uncertainty in evaluating SFRA water use.

Given that estimates of land use impacts on streamflow depend almost entirely on the water yield under baseline conditions, the establishment of a relatively accurate, appropriately detailed baseline land cover is imperative (Jewitt *et al.*, 2009; Warburton *et al*, 2015). The derivation and parameterisation of this baseline should thus be based on sound observations and on a repeatable methodology. The sound parameterisation of baseline land cover is crucial for improving hydrological model simulations (Schulze, 2007). Field based measurements of natural vegetation water use from recent studies (e.g. Gush and Dye, 2009; Everson *et al.*, 2011; Gush *et al.*, 2011; Bulcock, 2011), as well as a more detailed natural vegetation map developed by Mucina and Rutherford (2006) and updated by SANBI (2012), have provided an opportunity to address the raised concerns.

1.3 A Revised Hydrological Baseline Land Cover for Use in Hydrological Modelling in South Africa

This MSc study forms part of a larger WRC project (K5/2437) which aims to produce a refined and parameterised hydrological baseline land cover for South Africa, against which the hydrological impacts of various land use changes may be evaluated (Warburton *et al.*, 2015). The natural vegetation map for Southern Africa developed by Mucina and Rutherford (2006), and updated by the South African National Biodiversity Institute (SANBI, 2012), has been proposed as the new baseline vegetation to be used (Jewitt *et al.*, 2009; Warburton, 2012). The reasons for this include that it is more spatially explicit and detailed as it defines 450 vegetation units (including 36 azonal units, available from www.bgis.sanbi.org/vegmap/map.asp). It was produced using a robust methodology that makes use of aerial photographs, satellite imagery, spatial predictive modelling and large databases together with traditional field-based ground-truthing (www.bgis.sanbi.org).

Although there is a need for the spatially explicit detail of the SANBI (2012) vegetation map, it was recognized that many of the differences between the 450 vegetation units are defined by their floristic and ecological characteristics, and that their hydrological response may be similar. Thus, the initial stages of the larger project clustered the 450 vegetation units into 128 hydrological clusters based primarily on differences in the vegetation structure (e.g. biome and tree/grass cover), geology and associated soil profiles, topography (e.g. altitude and slope), climate (e.g. frost duration), with the final step being expert review. Once the vegetation clusters were defined, the next stages of the larger WRC project were to derive the vegetation and water use input parameters needed for hydrological modelling for each of the vegetation clusters. The hydrological model, in this case, was the ACRU Agrohydrological Model. The ACRU Agrohydrological Model was used in the recently developed Streamflow Reduction Activities (SFRA) Tool (Jewitt *et al.*, 2009). As the baseline vegetation will be used in estimating SFRA's and other land use impacts, the ACRU Model was selected as the hydrological model for which the vegetation parameters needed to be derived. The six most important ACRU land cover variables identified by Schulze (2007) to best represent the land cover attributes governing the vegetation water use processes include the water use crop coefficient (CAY), potential interception by vegetation (VEGINT), coefficient of initial abstraction (COIAM), percentage surface cover by vegetation or mulch/litter (PCSUCO), the fraction of effective root system in the topsoil horizon (ROOTA) and percent root colonization (COLON). The sensitivities of these land cover input parameters need to be better understood. The least studied parameters were identified as the root components, thus forming the focus of this study. This MSc project addresses the parameterisation of the baseline vegetation clusters for use in the ACRU Agrohydrological Model, particularly focusing on the below-ground parameters due to the limited research for below-ground vegetation parameters.

1.4 Research Aims and Objectives

As the ultimate aim of the larger WRC project (K5/2437) was to derive the vegetation and water use parameters to produce a refined and parameterised hydrological baseline, the relative effect of each of these parameters on the simulated hydrological response must be understood. Therefore, the first objective of this study was to assess the sensitivity of the land cover parameters in the ACRU Agrohydrological Model to gain a better understanding of the land cover parameters that have a greater influence on the output of the model and thus, the parameters to which the output is most sensitive (Chapter 2).

The larger WRC project (K5/2437) required all six ACRU vegetation and water use parameters, i.e. CAY, VEGINT, COIAM, PCSUCO, ROOTA and COLON, to be estimated regardless of the outcomes of the sensitivity analysis. Given this and the limited knowledge available for the below-ground parameters of natural vegetation in South Africa, in addition to the complexities associated with estimating these parameters due to the many factors that affect root water uptake, as well as the associated extensive time required for this, the estimation of these root parameters gained first priority in the larger WRC project and formed the focus for this study. The estimation of the remaining vegetation components were derived by other project team members.

Thus, the second objective of this study was to develop a methodology to estimate the below-ground root parameters for the clusters for input to the ACRU Model (Chapter 3). The methodology, although developed in terms of ACRU Model requirements, was designed to be repeatable and more broadly applicable. From this research, the final objective was to produce a root parameter database for natural vegetation across the entire country, from which to derive model input data for land use change assessments (Chapter 3).

Following the approach now accepted by the University of KwaZulu-Natal, this dissertation is structured such that findings of the research are written as a series of two research papers marked for publication in peer reviewed journals. A literature review relevant to the specific steps in the methodology being covered is provided in each research paper. As outlined in the University of KwaZulu-Natal's dissertation guidelines the referencing style for each of the research papers adhere to the journal for which the paper is intended.

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Lead into Chapter 2

Chapter 2 focuses on the first objective of this study which is to test the sensitivity of the ACRU Model output to the land cover input parameters. The land cover parameters for the Acocks' (1988) Natal Mistbelt Ngongoniveld will be used to represent a fictitious natural grassland catchment in South Africa. Changes to these parameters will be considered individually to determine the effect of each parameter on the simulated hydrological responses.

CHAPTER 2: UNDERSTANDING THE SENSITIVITY OF THE ACRU MODEL TO LAND USE PARAMETERS

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ABSTRACT

The effective management and protection of water resources requires an assessment of the magnitude of the impacts of land use changes on these water resources. To understand the interactions between land use and hydrological response a process-based hydrological model that is sensitive to land use information and changes thereof is required. The ACRU daily time step model is one such model developed and used in South Africa. To build confidence in the application of a hydrological model such as ACRU, its representation of real-world interactions between land cover properties and hydrological processes must be tested by undertaking a sensitivity analysis of the simulated output to model input. For this purpose, a sensitivity analysis of the ACRU land cover parameters was performed in order to identify the parameters that are most sensitive in terms of simulated streamflow and baseflow volumes. A fictitious natural grassland catchment in South Africa was used to assess the sensitivity of the ACRU Model under typical grassland conditions. Using the vegetation input parameters for the Acocks' Natal Mistbelt Ngongoniveld, the hydrological response under typical grassland conditions for a period of 45 years (1955 – 1999) was simulated. The output of which was used as the base run. Thereafter, the vegetation parameters were adjusted, while all other inputs remained constant, to assess the resulting changes in simulated flows. Those land cover parameters to which the simulated streamflow and baseflow were found to be most sensitive (i.e. the crop coefficient, fraction of roots in the A-horizon and percentage surface cover) can all, except the fraction of roots in the A-horizon, be estimated with sufficient accuracy by physical field-based measurements or by aerial observations. Whereas those parameters found to be least sensitive (i.e. the percentage root colonisation, coefficient of initial abstraction and vegetation interception) can be estimated based on review of existing observations and measurements from the literature. Whether or not a land cover parameter was found to be

sensitive and thus, important in representing vegetation water use in ACRU, the sound estimation of all land cover parameters is essential for improving the accuracy of ACRU Model simulations. Testing the sensitivity of land cover parameters in ACRU was a useful tool to identify the parameters that have minimal effect on streamflow and baseflow output, and those to which the output is highly sensitive. The sensitivity results will enable improved ACRU Model simulations for assessing hydrological impacts of land use changes.

2.1 Introduction

The growing population's need for water, fuel, food and fibre, combined with the increasing effects of climate change, have caused changes to the natural landscape of South Africa (Warburton *et al.*, 2010). These modifications in land cover cause changes to the hydrological response which is dependent on the land use (Falkenmark *et al.*, 1999). To promote effective planning and sustainable development of the landscape and thus to ensure the sound management, safe-guarding and, in some cases, rehabilitation of water resources, the magnitude of impacts on hydrological responses due to changes in land use must be evaluated (Memarian *et al.*, 2014). As the land use influences the hydrological processes in various ways (Bulcock and Jewitt, 2010), an understanding of the complex interactions between land use processes and the water balance components is required (Choi *et al.*, 2003).

With the vertical (e.g. evapotranspiration) and lateral (e.g. through soils, hillslopes, aquifers and rivers) movement of water within a catchment, land use impacts are cascaded downstream (Falkenmark, 2003). The extent of land use impacts may be dependent on certain thresholds, with each catchment having different stable states from the next. Additionally, within any given catchment there exists feedbacks and feedforwards between the various processes and components of that catchment (Warburton *et al.*, 2010). Assessing land use change impacts is therefore complex, costly and time consuming to determine empirically in the field. These difficulties are further exasperated in catchments where there is a lack of adequate data and calibrated hydrological models (Aduah *et al.*, 2017). Many catchments, particularly in African countries, are ungauged or poorly gauged and the existing climatic measurement network is often declining (Sivapalan *et al.*, 2003). Predictions in these ungauged basins and poorly monitored catchments are highly uncertain. Given these reasons, most studies that consider land use change impacts on hydrological responses make use of a process-based hydrological model to simulate these changes (Gash *et al.*, 1995; Turner *et al.*, 1995; Ewen and Parkin, 1996;

Lambin *et al.*, 2000; Bronstert *et al.*, 2002; Niehoff *et al.*, 2002; De Fries and Eshleman, 2004; Samaniego and Bárdossy, 2006; Choi and Deal, 2008; Jewitt *et al.*, 2009).

The increasing application of, and high demand for these process-based models in data scarce regions follows on the recommendations by the International Association of Hydrological Sciences' (IAHS) initiate on a decade of Predictions in Ungauged Basins (Parajka *et al.*, 2013) that regards such tools to be a key method for predictions in ungauged or poorly gauged catchments (Aduah *et al.*, 2017). The use of these process-based models to estimate much more valuable information from the limited data available (Li *et al.*, 2009) is becoming more important. In applying these models, an improved understanding of land use change has been developed through many studies over the past few decades, where researchers have successfully represented more complex processes of land use and impacts of its changes on water resources (Woyessa *et al.*, 2008). These models aid in the understanding of hydrological processes in a data scarce basin as they directly link model parameters to physically measureable catchment characteristics (Bastola *et al.*, 2008; Li *et al.*, 2009). The land cover characteristics of a catchment are thus empirically represented by these model parameters. This means that hydrological models are particularly sensitive to changes in land use (Warburton *et al.*, 2010), and are thus ideal tools to assess land use change impacts.

Therefore, the successful application of a hydrological model to simulate the hydrological response in land use change assessments relies on the accurate physically-based conceptualisation of the catchment properties, specifically of the land cover properties (Schulze and Smithers, 2004). With the growing demand for applications of hydrological models in land use change studies (Parajka *et al.*, 2013, Woyessa *et al.*, 2008, Aduah *et al.*, 2017), it is essential that the conceptualisation of land cover and hydrological components within the model is clearly understood. Furthermore, to build confidence in the application of such a hydrological model, its representation of real-world interactions between land cover properties and hydrological processes must be tested by undertaking a sensitivity analysis of the simulated output to model input (Bergström, 1991). In terms of hydrological modelling, sensitivity is a measure of the effect of changes in model input, or model structure, on model output (Schulze, 1995). The analysis of a models sensitivity is a useful tool for building confidence in its structure and for identifying inputs that have little effect on outputs. Sensitivity analyses of process-based hydrological models are beneficial when using such models in studies and assessments characterised by a limited availability of data (Parajka *et al.*, 2013). In facing the challenges related to data scarcity when trying to parameterise each input variable, model sensitivity information would help to understand which land cover input variables the model is most sensitive to, thus prioritising the parameterisation of those variables. Furthermore, understanding whether model output is more sensitive when the input parameter is reduced or increased provides a better understanding of the response of the parameter when adjusted during calibration, including the effects and implications of over- or under-estimating an input parameter on model output, or whether the parameter is insensitive to the extent that a generic default value will suffice.

The ACRU Agrohydrological Model is the only physically-based hydrological model developed in South Africa. The ACRU Model is commonly applied in assessing land use change impacts and in various water use assessments in South Africa. Given this, the ACRU Model will be assessed in this study to test the sensitivity of the land cover input parameters and thus identify the parameters that are most sensitive in terms of estimating the hydrological response. The objective being to identify ACRU land use parameters that may be used to appropriately represent the water use of different land covers, as well as the impact on the hydrological response due to changes in the land cover. Based on the recommendations by Angus (1989) and Schulze (1995) for future sensitivity analyses of ACRU to investigate a smaller, more meaningful set of parameters, this study investigates only six land cover input parameters, whilst observing only two output variables, streamflow and baseflow. These six land cover variables were chosen as they were identified by Schulze (2007) to be the most important land cover variables governing the water use processes of vegetation in the ACRU Model and are listed in terms of the ACRU Modelling requirements as the water use crop coefficient (CAY), potential interception by vegetation (VEGINT), coefficient of initial abstraction (COIAM), percentage surface cover by vegetation or mulch/litter (PCSUCO), the fraction of effective root system in the topsoil horizon (ROOTA) and percent root colonization (COLON). The sensitivity study held all model parameters constant, except the ACRU land cover parameters which were allowed to vary one at a time. In doing this, the changes in hydrological responses can be directly attributed to the changes in vegetation. Benke *et al.* (2008) showed that the variation in model output is dependent on the variation in input parameters and thus, maintaining a parameter at a constant value removes the effect of this parameter from the variation in model output. In this way, only the sensitivity of the land cover input variables will be tested, thus providing an improved understanding of the conceptualization of the land cover component in ACRU. Given this, and that the inputs beyond the vegetation are required to remain constant for the comparison in this project, the conceptualisation of the land cover component and water use processes in ACRU will be reviewed.

2.2 The ACRU Agrohydrological Model

The ACRU Agrohydrological Model is a daily time step physical-conceptual model (Schulze, 1995) that has been applied in South Africa and many other countries to simulate and investigate land use change impacts on hydrological processes (e.g. Kienzle and Schulze, 1995; Kienzle *et al.*, 1997; Schulze *et al.*, 1997; Jewitt *et al.*, 2004; Warburton *et al.*, 2010; Mugabe *et al.*, 2011). ACRU is conceptual in that it attempts to encapsulate real world-processes in an idealised way, describing significant processes and couplings as a system (Schulze, 1995). It is neither a parameter-fitting nor optimising model (Schulze *et al.*, 1994), because physical processes and characteristics of a catchment (e.g. the land cover attributes and processes) are estimated or measured in the field. The model can therefore simulate the hydrological response and changes thereof under various land covers and land use changes. When detailed land cover or climatological information is not available from the field, estimated parameters may be obtained from various sources, such as national databases. However, these data must be used with caution, as they are generally characterized by a relatively coarse scale. Given the physically-based conceptualisation of land cover characteristics in the ACRU Model and the fact that hydrological processes are influenced by land cover in various ways (Bulcock and Jewitt, 2010), the structure of the model demonstrates high sensitivity to changes in land cover, land use and land management (Schulze *et al.*, 1995; Warburton *et al.*, 2010).

2.2.1 Conceptualisation of the hydrological cycle and land cover in ACRU

The conceptualisation of the hydrological cycle in the ACRU Model is illustrated in Figure 2.1. Precipitation is the major input to the system (Figure 2.1). A percentage of this precipitation is initially abstracted as either stormflow or interception, and the remaining water is infiltrated into the topsoil (A horizon). Once field capacity is reached, water further percolates into the subsoil (B horizon) as saturated drainage. If the subsoil then becomes saturated, water continues to percolate further down the soil profile, into the intermediate zone and finally reaches the groundwater, contributing to runoff as baseflow. Unsaturated soil water distribution, both up and down the soil profile, may also occur. The total evaporation includes the evaporation of water from intercepted surfaces and from the soil, as well as transpiration by plants (Figure 2.1). The model provides the option to separate the calculation of the actual total evaporation into soil evaporation and plant transpiration, using various equations (Schulze, 1994), which are based on a vegetation cover factor.

There are two soil-based parameters required as input to the ACRU Model to define the soil water content of a given soil. These include the permanent wilting point, representing the lower range of plant available water (PAW) and the field capacity, representing the upper range of the PAW (Schulze *et al.*, 1994). The generation of runoff, which depends on the antecedent soil water status and the rainfall intensity, requires that the soil water deficit be satisfied. The antecedent soil water deficit is thus, simulated at a daily time-step in ACRU in order to assess the stormflow generated following each individual rainfall event. A defined percentage of generated stormflow reaches the catchment outlet on the same day as the rainfall event. (Schulze *et al.*, 1994).

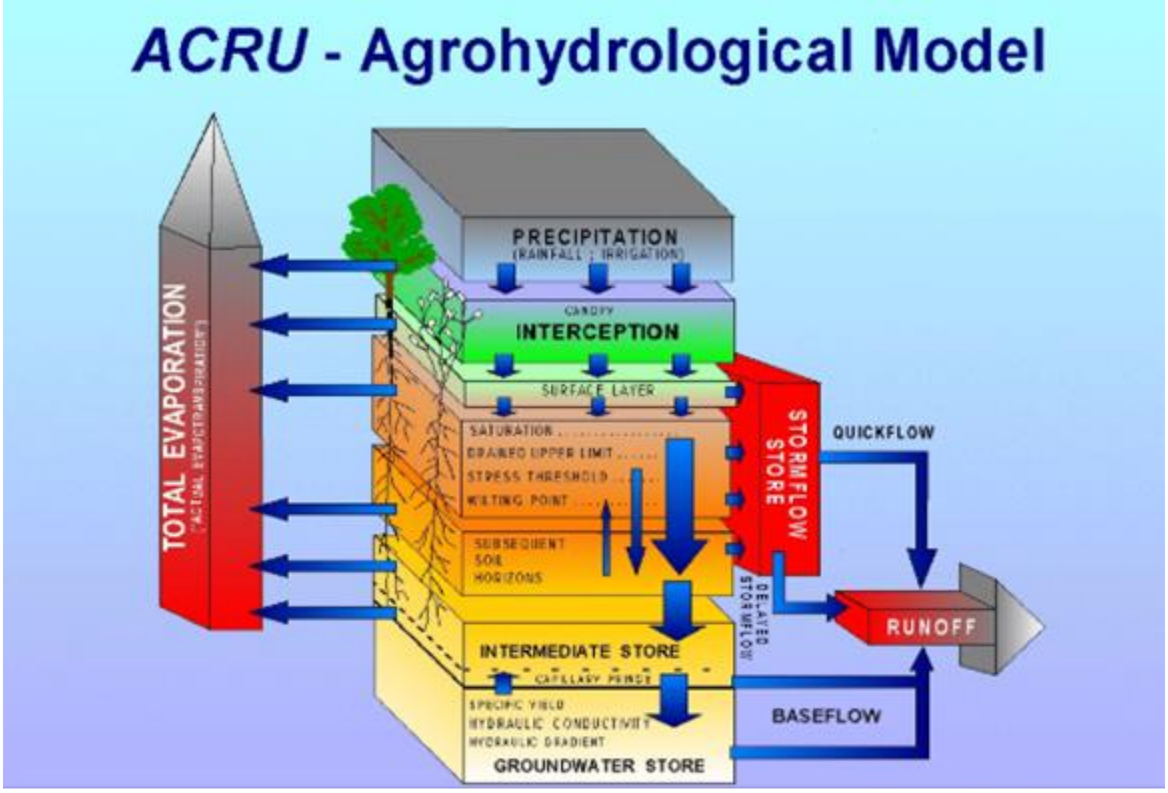

Figure 2.1: Structure of the hydrological cycle as conceptualised in the ACRU Model (Schulze *et al.*, 1994)

The land use determines the partitioning of rainfall and thus, determines the responses in surface runoff, interception, plant and soil water evaporation, infiltration and groundwater recharge (Woyessa *et al.*, 2008). Therefore, land cover is conceptualized in ACRU by using vegetation and water use input parameters that describe the land use processes and how the hydrological processes are governed by the vegetation. These land use processes can be grouped functionally into three major plant-related groups, according to the properties of the vegetation biomass and its characteristics above, below and on the ground surface (Schulze, 1995), as well as how these properties influence the uptake and distribution of rainwater.

The above-ground related land cover parameters reflect the land use processes governed by the above-ground plant attributes. The above-ground attributes define the land cover properties of the partitioning point at the canopy level (Jewitt, 2005; Schulze, 2007). It includes the plant biomass, which is determined by the vegetation type and by the season of year and is dependent on climatic related factors, such as water availability, heat units and frost duration. The above-ground biomass properties primarily determine the potential transpiration rates (i.e. the consumptive water use of the vegetation) and the canopy interception losses. Therefore, for purposes of the ACRU hydrological model, the above-ground biomass properties are usually expressed by these two processes, whereby the consumptive vegetation water use is expressed as a crop coefficient (CAY) and the canopy interception loss is either input as a monthly interception loss (mm.rainday^{-1}) by the vegetation (VEGINT) or calculated using the monthly input leaf area index (LAI). Another above-ground plant attribute is the above-ground plant structure, which has an important role to play in the erodibility of rainfall, in terms of the fall height of the raindrops and the relative terminal velocities (Schulze, 2007). The structure of the above-ground vegetation also determines the degree of shading of the soil surface by the vegetation. Another important above-ground related attribute is the physiological factors of the above-ground vegetation, which determine the level of available soil water at which plant water stress sets in (Schulze, 2007).

The ground-surface related land cover parameters reflect the land use process governed by plant attributes at the ground-surface. Ground-surface attributes define the land cover properties of the partitioning point at the soil-plant interface. It includes the infiltration properties of the soil, which in turn are controlling factors of the initial abstractions of rainfall before the generation of stormflow. The initial abstractions before stormflow commences, which consist mainly of interception, infiltration and depression storages, are represented in

ACRU through the coefficient of initial abstraction (COIAM). The infiltrability of the soil surface, together with the soil water content of the topsoil horizon, influence and determines the initial abstractions through the daily soil water budget. The coefficient of initial abstraction (COIAM) depends, to a large extent, on the rainfall intensities which can vary with season (Schulze, 1995). The ground-surface attributes also includes the presence and amount of litter and/or mulch, which has the potential to reduce and/or prevent soil erosion and soil water evaporation losses (Schulze, 2007). The presence and extent of surface cover is expressed in the ACRU Model as a percentage surface cover (PCSUCO). In the ACRU Model, the suppression of soil water evaporation losses by the surface cover (which includes mulch, litter, and stone/rock) is assumed to be a linear relationship. The relationship assumes that a maximum soil water evaporation, for example of 8 mm/day, is increasingly suppressed given greater surface cover, such that complete cover still allows for 20 % soil water evaporation.

The below-ground related land cover parameters reflect the land use processes governed by the plant and soil attributes below the ground-surface. Below-ground attributes define the land cover properties of the partitioning point below the ground surface. It includes three root-specific attributes that all contribute to determining the patterns of soil water uptake by the vegetation. Firstly, the soil depth to which the effective root system extends within the entire active soil profile (EFRDEP), secondly, the seasonal variation of the fraction of active roots in the different soil horizons (ROOTA and ROOTB) and, thirdly, the degree of root colonization within the soil horizons (COLONA and COLONB) (Schulze, 2004b). The below-ground attributes also include one non-root-specific vegetation attribute, which is the onset of plant stress. This is typically within ACRU considered to be the fraction of PAW of a soil horizon at which total evaporation is assumed to drop below maximum evaporation due to drying of the soil. With natural vegetation, this fraction is assumed to be 0.4 (Schulze, 1995).

In respect to the ACRU hydrological model, it is the water uptake function of roots that needs to be accounted for. This process of water uptake is affected by factors such as root growth, distribution, colonization, extension, the differences in the water potentials between plant and soil, the hydraulic conductivity of the soil and the availability of water in the soil. Thus, it is not a simple matter to attempt to model water uptake and, in ACRU assumptions, simplifications and generalisations have been made to simulate root water uptake. The monthly fraction of active root mass in the A-horizon (ROOTA) is required as an input, and using this fraction the B-horizon root mass (ROOTB) is computed within the model. It is these fractions of active root mass that determine the proportional soil water extraction that takes place from each horizon. The fraction of roots in each horizon has to account for the effect of genetic and environmental factors on transpiration, factors such as dormancy, senescence, regrowth, growth rates and impeding soil layers (Schulze, 1995). When the vegetation is not stressed, the fraction of roots largely determines the differential rates of drying of the two soil horizons. For instance, the contribution from each unstressed horizon to actual transpiration (Et) is computed by its fraction of root mass available for transpiration. Given that the ACRU model works on the premise that “roots search for water, and water does not search for roots”, a routine has been included in ACRU to allow for plant water uptake by the roots to occur from the soil horizon that is not stressed. This routine ensures that the contribution from an unstressed horizon to Et is enhanced to greater than computed by the fraction of root mass available for transpiration. This routine in ACRU for enhanced, “compensational” Et from the unstressed horizon is only employed when the vegetation is in a phase of active growth (i.e. greater than 5% of the active roots are in the unstressed horizon). It is important to note, that a ROOTA of 1 designates senescence or no active water uptake by roots, essentially meaning that no transpiration is occurring only soil water evaporation (Schulze, 1995).

According to previous research (Schulze, 2007), the most important above-, below- and on-the-ground land cover input variables, listed in terms of the ACRU Modelling requirements, include (a) the water use crop coefficient (CAY) and potential interception by vegetation (VEGINT), which are both above-ground related variables; (b) the coefficient of initial abstraction (COIAM) and percentage surface cover by vegetation or mulch/litter (PCSUCO), which are both on-the-ground related variables; and (c) the fraction of effective root system in the topsoil horizon (ROOTA) and percent root colonization (COLON) which are below-ground related variables. These land cover input variables for the ACRU Model have been parameterised by Schulze (2004a) and are widely used to assess the impacts of land use changes on hydrological responses. To improve model predictions of hydrological impacts of land use changes, the improved parameterization of such land cover variables needs to be relatively accurate. It would thus be beneficial to better understand which model input parameters have a greater effect on the model output and thus, the parameters to which the output is most sensitive to. To do this, a sensitivity analysis of the ACRU Model input parameters was undertaken. The list of six previously identified most important land cover input variables (Schulze, 2007) in terms of the ACRU Model was used to guide the selection of land cover variables to be investigated.

2.3 Methodology

The purpose of this study was to test the sensitivity of the ACRU Model to changes in land cover parameters. Natural grasslands are the most commonly transformed natural land covers in South Africa (Dye *et al.*, 2008). Given this, and that the grassland biome covers 27.9 % of South Africa (Mucina *et al.*, 2006), mostly within the higher rainfall regions where land use changes have the greatest impacts on the hydrological response (Dye *et al.*, 2008), the land cover conditions within a typical South African grassland catchment were simulated using a 15 km^2 fictitious catchment. As the catchment was fictitious, no external catchment factors from real-world scenarios were considered (e.g. dams, river flow routing, etc.). Land cover parameters typical of an undisturbed, natural grassland were used. The land cover parameters were then increased and decreased, one at a time, to assess the resulting changes in simulated streamflow and baseflow outputs. Thus, all changes in simulated streamflow were directly linked to changes in land cover parameters. The sensitivity of the parameters were assessed by comparing percentage changes in model outputs to percentage changes in land cover inputs. The variabilities in parameters sensitivities were defined by application of a ranking system.

2.3.1 ACRU Model configuration

Typical physical catchment properties of a grassland catchment in the summer rainfall region of South Africa were used as input to the ACRU Model. A good quality driver rainfall station with a rainfall pattern of wetter summer months and drier winter months typical of the region was selected. The selected station had a relatively high mean annual precipitation (MAP) to ensure that water limited conditions did not influence the land cover response. The daily rainfall record for the station was extracted from Lynch (2004) for the years 1955 - 1999. Daily minimum and maximum temperatures for the same location and period were extracted from Schulze and Maharaj (2004).

Beyond climate data, the ACRU Model requires soils information for both the A and B soil horizons which includes average soil horizon depths (DEPAHO and DEPBHO); porosity, field capacity (FC) and permanent wilting point (WP). Further to this, the response fractions of each horizon, representing the fraction of saturated soil water that is redistributed daily from the A horizon to the B horizon or from the B horizon to the intermediate zone, when the soil moisture status of the overlying soil exceeds the FC of that soil, are required. These soil input values were obtained from the gridded database that accompanies the South African Agrohydrology and Climatology Atlas (Schulze, 2007). The recommended, typical values for the streamflow response variables as suggested in Schulze (1995) were used. All soil and climate inputs were held constant throughout the sensitivity study, with each land cover parameter varied individually, ensuring that only the sensitivity of each of the vegetation inputs was assessed.

The Acocks' (1988) Veld Types are the currently accepted baseline land cover for South Africa. One of the most dominant natural grassland veld types recognised across South Africa is that of Natal Mist Belt Ngongoniveld, alternatively known as Acocks Veld Type number 45. The vegetation and water use parameters for the Acocks' (1988) Natal Mistbelt Ngongoniveld (Table 2.1) developed by Schulze (2004a) were used as input into the ACRU Model. The vegetation parameters that were input to the model to represent the Natal Mistbelt Ngongoniveld characteristics include the CAY, VEGINT, ROOTA, COIAM, COLON and the PCSUCO. Each of these six land cover parameters were then assessed in the sensitivity analysis described.

Table 2.1: Vegetation and water use parameters for Acocks' (1988) Natal Mistbelt Ngongoniveld (# 45) used as input to model base runs

	JAN	FEB	MAR	APR	MAY	JUN	JUL	AUG	SEPT	OCT	NOV	DEC
CAY	0.7	0.7	0.7	0.5	0.35	0.25	0.2	0.2	0.55	0.7	0.7	0.7
VEGINT	1.5	1.5	1.5	1.3	1.1	1.1	1.1	1.1	1.4	1.5	1.5	1.5
ROOTA	0.9	0.9	0.9	0.94	0.96	1	1	1	0.95	0.9	0.9	0.9
COIAM	0.15	0.15	0.2	0.3	0.3	0.3	0.3	0.3	0.3	0.3	0.2	0.15
COLON	60	60	60	60	60	60	60	60	60	60	60	60
PCSUCO	73.4	73.4	73.4	73.4	73.4	73.4	73.4	73.4	73.4	73.4	73.4	73.4

2.3.2 Procedure

A base run was completed using the Acocks' #45 (Natal Mistbelt Ngongoniveld) vegetation and water use parameters (Table 2.1). The output simulated from this base run (O_{Base}) was used as the reference output against which to assess the changes therefrom. Each of the six land cover parameters were then increased and decreased independently of one another in increments of 10 %, 20 %, 30 %, 40 % and 50 %, within their feasible limits. Except for the ROOTA and PSCUCO parameters which were only increased by up to 20 % and 40 %, respectively, due to the base run parameter values being close to the physical limits of these parameters, of 1 and 100 %, respectively. Therefore, the sensitivity analysis could not consider percentage increases resulting in values greater than 1 for ROOTA and greater than 100 % for PCSUCO. The base run vegetation and water use parameters, and the variations made to these are provided in Table A2.1 of the Appendix. The resulting new output (O), together with the base run output (O_{Base}), were used to estimate the percentage change in output ($\Delta O\%$) by applying the objective function (Equation 2.1).

The effect of varying the land cover parameters in ACRU was assessed by quantitatively observing the variation in the accumulated streamflow and baseflow output variables simulated over 45 years (1955 – 1999). The accumulated streamflow and baseflow output variables were selected as the objective functions to be assessed because the simulation of these two variables in ACRU is, to some extent, dependent on both the above-ground structure and function, and the below-ground size and distribution of the plant. This sensitivity study did not assess quick flow or stormflow as output components, as these variables are largely dependent on rainfall, and are far less dependent on the actual land cover and vegetative composition. Furthermore, the streamflow output is an integrator of the inputs to the model. To ensure consistency across this and previous sensitivity studies for ACRU (Schulze, 1995; Angus, 1989; Rowe, 2015), the same sensitivity analysis approach of assessing variations in objective functions was used in this study. The sensitivity of ACRU to a land cover variable was determined by the variation in the two objective functions, each of which were expressed as the percentage change in accumulated output due to the change in the input parameters, and were represented by:

$$\Delta O\% = \frac{O - O_{Base}}{O_{Base}} \times 100 \qquad (2.1)$$

Where: $\Delta O\%$ = percent change in output
O = output from a particular change in input parameter
O_{Base} = output from the base run input

The percentage changes in the accumulated streamflow and baseflow outputs over the period (1955 – 1999) were plotted against the percentage changes in the ACRU vegetation input parameters. Once the variability in the objective function had been estimated for each increase and decrease in the land cover variables, the objective functions could be compared to identify the ACRU vegetation input parameters to which simulated response is most sensitive.

Furthermore, the objective functions provided information about whether the model was more sensitive to increases or decreases in the vegetation parameters.

The sensitivities of the land cover parameters were categorised and compared by applying a ranking system. The effects of input parameters on model output were classified by Lane and Ferreira (1980) as either significant, moderate, or slight. They used only three broad categories to qualitatively account for the sensitivity of parameters. Angus (1989), Schulze (1995) and Rowe (2015) qualitatively measured the sensitivity of input parameters on model output by expressing the sensitivity of the parameters as either extremely, highly, moderately, or slightly sensitive or as insensitive. This more detailed five-class categorisation of parameter sensitivities provides a better description of the variation in objective functions due to changes in parameters. Furthermore, the five-class ranking system was suggested by Schulze (1995) to be applied in such studies for testing parameter sensitivity in ACRU. Given this, the results from this study were classified using the five-class ranking system, based on the output effect on total streamflow and baseflow. The classification describes the effect of reducing and increasing the input parameters from the starting/base values. For example, a parameter would be classified as highly sensitive if reducing the base parameter by 10 % resulted in a 10 – 20 % decrease in baseflow output.

The ranking system used to assess parameter sensitivities included the following five-classes of sensitivity:

- Extremely sensitive (E): the percentage change in output (e.g. streamflow) is more than twice that of the input parameter being tested, i.e. the change in streamflow is greater than 20% for a 10% change in input parameter.
- Highly sensitive (H): the percentage change in output (e.g. streamflow) is more than that of the input parameter being tested but less than twice, i.e. the change in streamflow is between 10% and 20% for a 10% change in input parameter.
- Moderately sensitive (M): the percentage change in output (e.g. streamflow) is less than that of the input parameter being tested, but by more than 50% of the input change, i.e. the change in streamflow is between 10 and 5 %, for a 10% change in input parameter.
- Slightly sensitive (S): the percentage change in output (e.g. streamflow) is between 10 – 50% of the change in the input parameter being tested, i.e. the change in streamflow is between 5 and 1 %, for a 10% change in input parameter.
- Insensitive (I): A less than 1% change in output to a 10% change in input.

Assessing one parameter at a time, for each incremented percentage change (i.e. 10, 20, 30, 40 and 50% increases and decreases) the resulting percentage change in output was given a sensitivity ranking (I, S, M, H or E). A single sensitivity ranking was derived for the sensitivity of outputs to the overall increase or overall decrease in the input parameter. This overall ranking was derived by selecting the most common (Mode) ranking that prevailed among the results from the five incremented increases. For example, where simulated baseflow output was moderately sensitive (M) to a 50 % increase in CAY, but highly sensitive (H) to a 10, 20, 30 and 40% increase in CAY, then the most common sensitivity ranking identified among all the percentage increases in CAY, in terms of baseflow output, was a ranking of highly sensitive (H). This establishment of a single ranking for an increase and for a decrease in each parameter was done to provide a single value that may then be compared against other parameter sensitivity rankings.

2.4 RESULTS

2.4.1 Crop Coefficient (CAY) sensitivity

The accumulated streamflow and baseflow output from the model was inversely related to the input values for the CAY. Thus, where the CAY monthly input parameters were increased the accumulated streamflow and baseflow output was reduced and conversely, where the CAY was reduced the accumulated streamflow and baseflow increased (Figure 2.2). The percentage increase in the accumulated baseflow with the percentage decrease in CAY was more significant than the percentage increase in the accumulated streamflow. The percentage increase in the accumulated streamflow was inversely proportional to the percentage decrease in CAY (e.g. when CAY was reduced by 30 %, the accumulated streamflow increased by 30 %). The percentage increase in CAY resulted in a percentage decrease in the accumulated streamflow and baseflow, but increasing the CAY input had a lower impact than reducing the CAY on the percentage change in the streamflow and baseflow output. The results from analysing the objective functions and applying the sensitivity ranking system show that streamflow is highly sensitive to decreases and moderately sensitive to increases in CAY. Baseflows were shown to be extremely sensitive to decreases in CAY, and highly sensitive to increases in CAY.

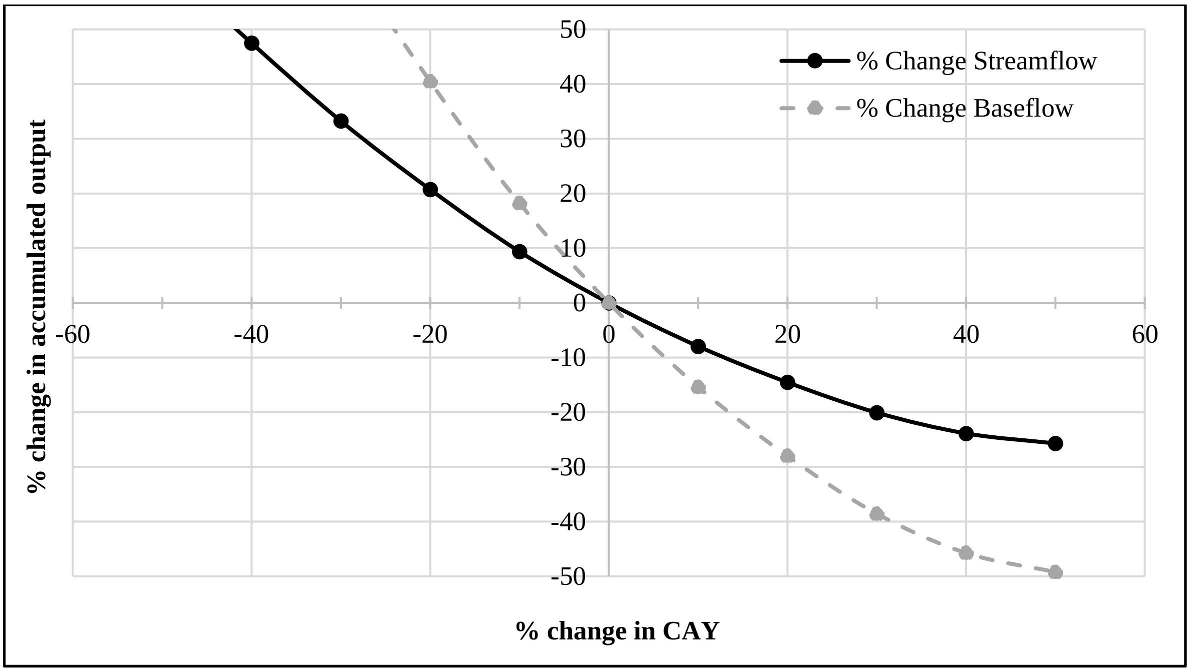

Figure 2.2: Percentage change in the accumulated streamflow and baseflow output (1955 – 1999) due to changes in the CAY monthly input parameters.

2.4.2 Fraction of Active Root Mass in A-Horizon (ROOTA) sensitivity

The monthly values for ROOTA are input to the ACRU Model, and this is used to compute the corresponding fraction of roots in the subsoil horizon (ROOTB). A routine has been included in ACRU to allow for soil water uptake by the roots to take place simultaneously from both horizons in proportion to the fraction of active roots in each soil horizon (Schulze *et al.*, 1995). If, however the ROOTA is set to 1, it designates that effectively only soil water evaporation is taking place from the topsoil horizon and no transpiration is occurring. As the initial input value for ROOTA was 0.9 or greater each month (Table 2.1), only a 10 and 20% increase could be considered. At 10%, the ROOTA value was 1 for six months and 0.99 in the other 6 months. At 20%, the ROOTA value was 1 for all months, implying that no transpiration was occurring only soil water evaporation. The lack of transpiration explains the increases shown in streamflow and the marked increases in baseflow for increases in ROOTA (Figure 2.3). Of more pertinence for this study are the effects of reducing the ROOTA values. A reduction in the ROOTA, and hence a relative increase in the fraction of roots in the B-horizon (ROOTB), input to the model resulted in a minor increase in the accumulated streamflow and baseflow output from the model.

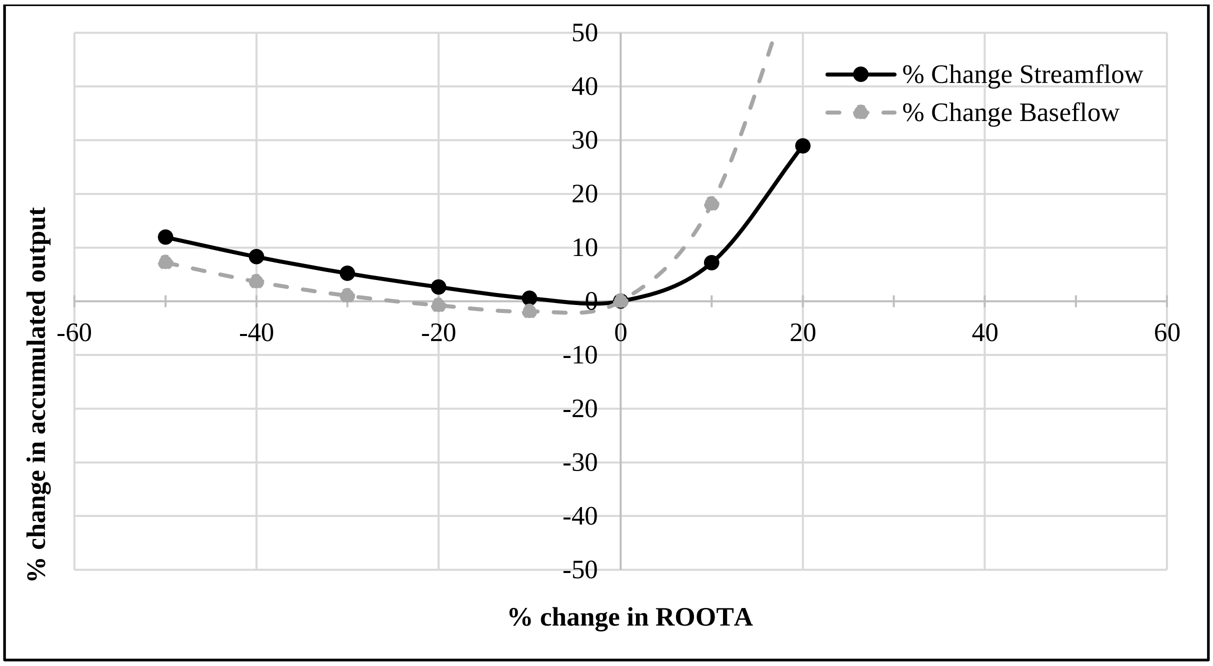

Figure 2.3: Percentage change in the accumulated streamflow and baseflow output (1955 – 1999) due to changes in the ROOTA monthly input parameters.

These increases in flows are again due to the changes in root distribution, with more roots in the B-horizon, the transpiration from the A-horizon is reduced. The reduction of ROOTA values by 50% from the baseline scenario resulted in a 12% increase in streamflow and 7% increase in baseflow (Figure 2.3). Thus, it can be concluded that the streamflow and baseflow responses are only slightly sensitive to decreases in the ROOTA values.

2.4.3 Canopy Interception Loss (VEGINT) sensitivity

The sensitivity of the accumulated streamflow and baseflow output to changes in the VEGINT monthly input parameters was similar across the two components and relatively low. A 50% decrease in VEGINT resulted in a 6% increase in flows, while a 50% increase in VEGINT resulted in a 6% decrease in flows (Figure 2.4). Thus, it can be concluded that the streamflow and baseflow responses are slightly sensitive to both increases and decreases in the VEGINT values. These changes are very close to threshold to be considered insensitive.

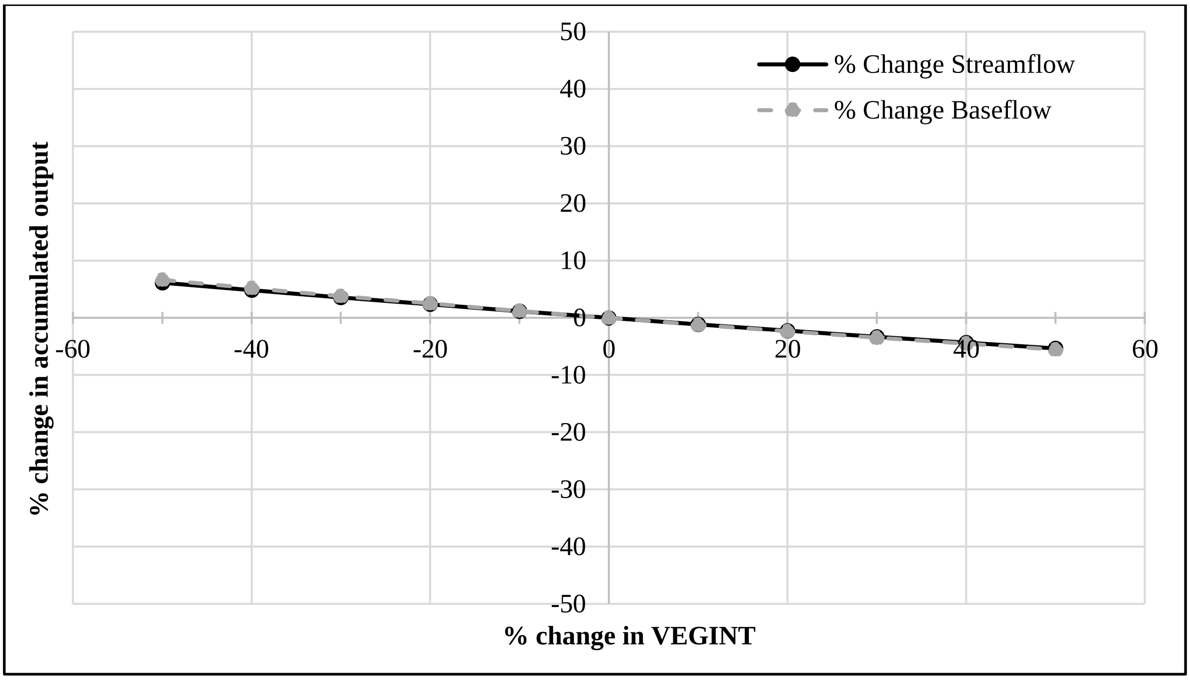

Figure 2.4: Percentage change in the accumulated streamflow and baseflow output (1955 – 1999) due to changes in the VEGINT monthly input parameters.

2.4.4 Coefficient of Initial Abstraction (COIAM) sensitivity

The accumulated streamflow output was insensitive to both increases and decreases in the COIAM input parameters (Figure 2.5), with only a 4% increase in streamflow associated with a 50% decrease in COIAM and a 1% decrease in streamflow with a 50% increase in COIAM. The accumulated baseflow output was reduced following a reduction in the COIAM input parameters and increased following an increase in the COIAM values (Figure 2.5). This is due to the increase in COIAM decreasing the stormflow component, and thus increasing the infiltration and baseflow component. The accumulated baseflow output was slightly sensitive to increases in the COIAM input and moderately sensitive to decreases in the COIAM.

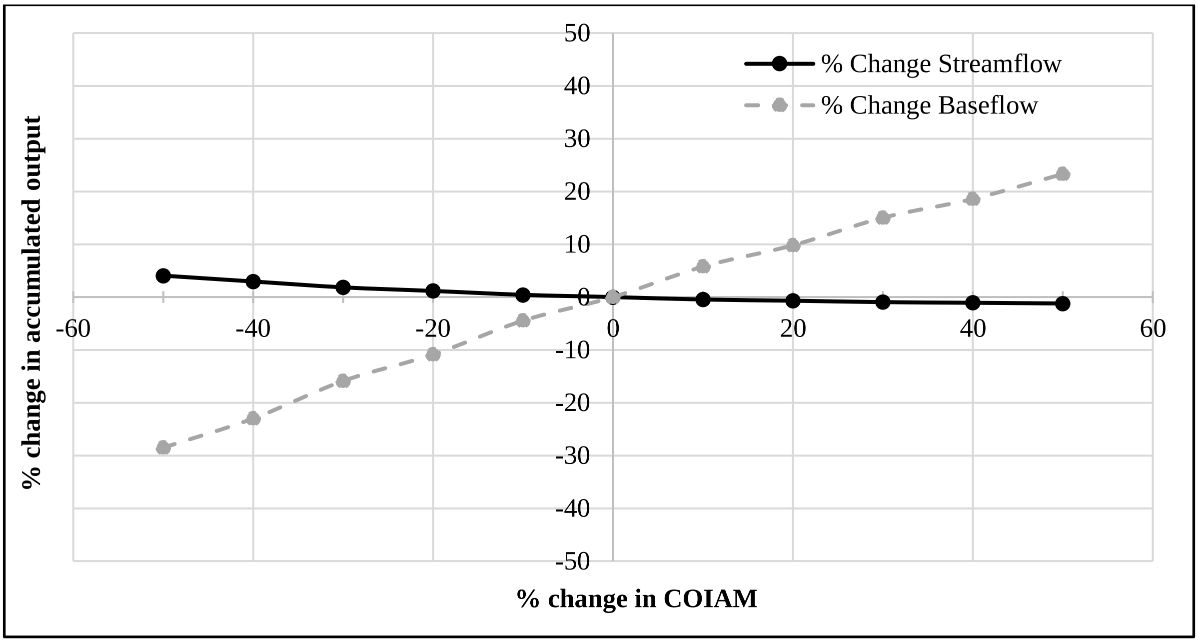

Figure 2.5: Percentage change in the accumulated streamflow and baseflow output (1955 – 1999) due to changes in the COIAM monthly input parameters.

2.4.5 Percentage Surface Cover (PCSUCO) sensitivity

There is a direct relationship between the percentage change in the accumulated streamflow and baseflow output and PCSUCO. A decrease in the PCSUCO input values resulted in a reduced accumulated streamflow and baseflow output, with the baseflow output being more sensitive than the streamflow output to changes in the PCSUCO input parameters. A 50% decrease in the PCSUCO input values to the model resulted in a 19 % decrease in accumulated streamflow and a 34 % decrease in baseflow output. An increase in the baseline scenario

PCSUCO input parameters resulted in a corresponding increase in the accumulated streamflow and baseflow output, however, this increase was variable with the changes in baseflow being greater than streamflow (Figure 2.6). As the initial input value for PCSUCO was 73.4% for each month (Table 2.1), only a 10, 20, 30 and 40% increase could be considered. At 40%, the PCSUCO value was 100% for all months, implying that the soil surface was completely covered by mulch, litter, and stone/rock. The PCSUCO variable in the ACRU Model is used to suppress the soil water evaporation losses in a linear relationship such that complete cover (i.e. PCSUCO = 100%) still allows for 20 % soil water evaporation.

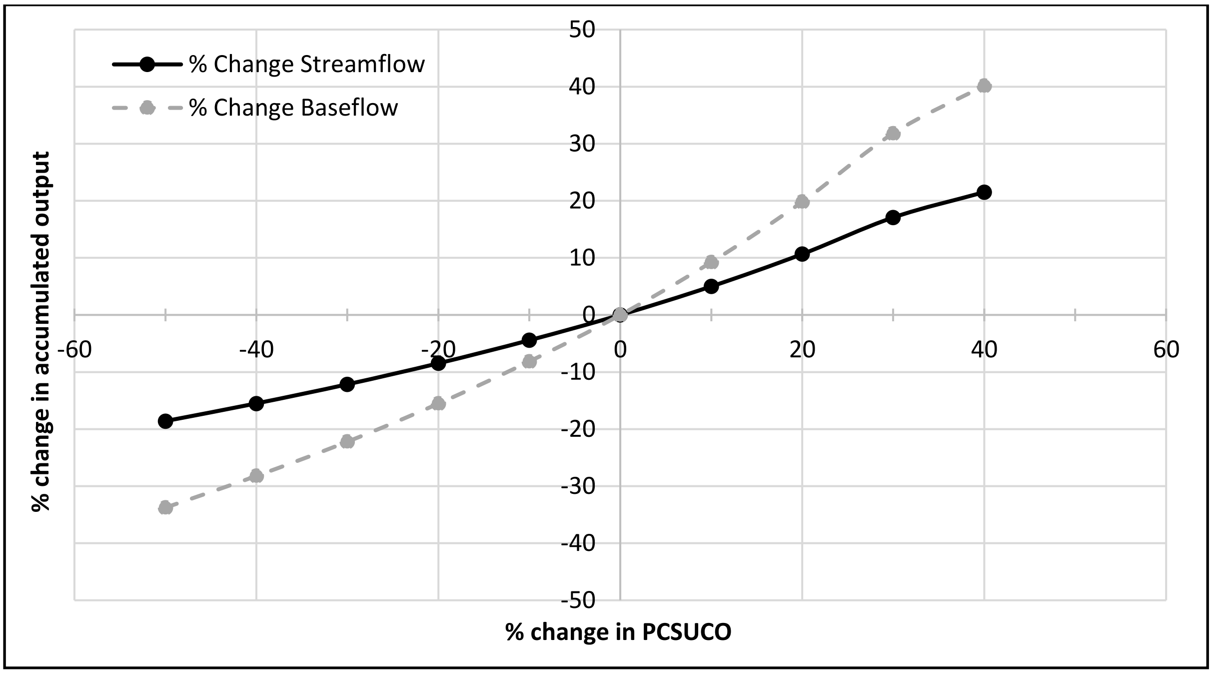

Figure 2.6: Percentage change in the accumulated streamflow and baseflow output (1955 – 1999) due to changes in the PCSUCO monthly input parameters.

The increases in streamflow and baseflow with increases in PCSUCO are due to reduced soil water evaporation, similarly the decreases in flows with decreased PCSUCO values are due to increased soil water evaporation. The resulting percentage increase in the baseflow output for each percentage increase increment in PCSUCO was directly proportional to the percentage change in PCSUCO input. The resulting percentage changes (both increases and decreases) in the streamflow output for each percentage increase and decrease increment in PCSUCO was equivalent to half the percentage change in PCSOCO input (i.e. %O(SFLW) = 0.5 x %I(PCSUCO)). Overall, the streamflow and baseflow was moderately sensitive to increases in

PCSUCO. While, the streamflow was slightly sensitive to decreases in PCSUCO and the baseflow was moderately sensitive.

2.4.6 Percentage Root Colonization in Subsoil Horizon (COLON) sensitivity

The percentage change in the accumulated streamflow and baseflow output, following changes in the percentage root colonization in the subsoil horizon (COLON), was relatively low (Figure 2.7). The accumulated baseflow output was slightly sensitive to both increases and decreases in the COLON input parameters. However, the results showed streamflow to be insensitive to both increases and decreases in COLON, as the percentage change in streamflow per 10% change in COLON was less than 1%.

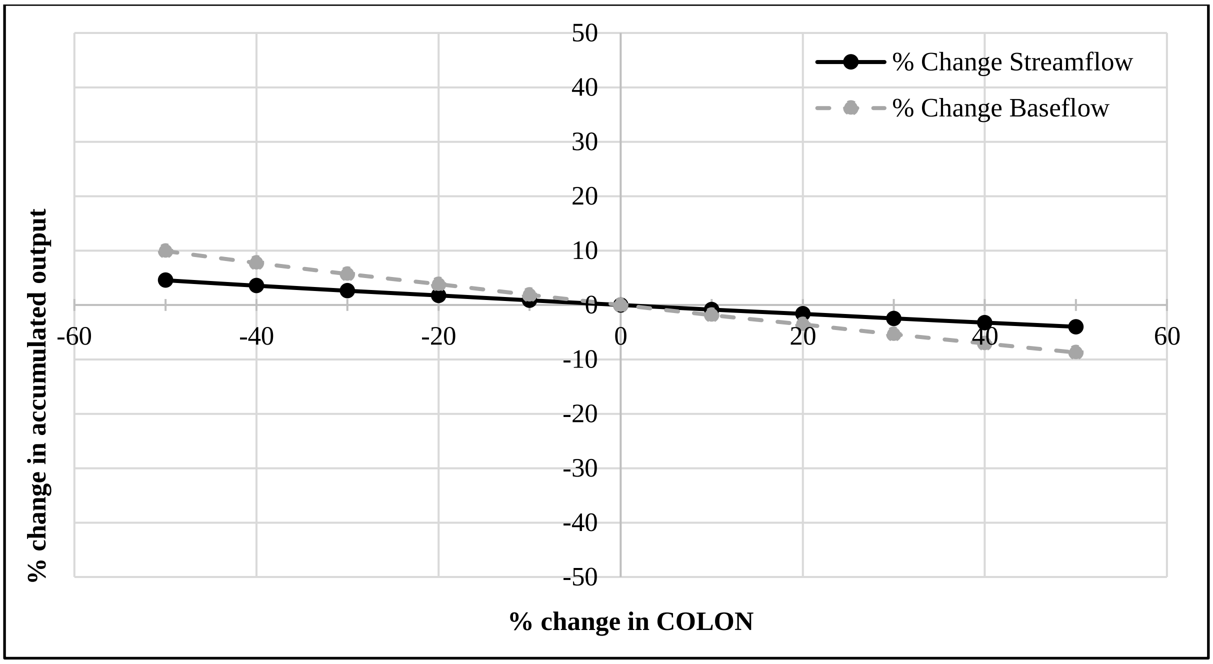

Figure 2.7: Percentage change in the accumulated streamflow and baseflow output (1955 – 1999) due to changes in the COLON monthly input parameters.

2.4.7 Ranking the sensitivity of land cover parameters

A summary of the classification of results is shown in Table 2.2, showing the Mode sensitivity rankings for the output changes resulting from an overall increase or decrease in each parameter and not for each incremented increase or decrease. The detailed classification of sensitivity rankings for the output change resulting from each incremented percentage change (i.e. 10, 20, 30, 40 and 50 % increases and decreases) may be found in Table A2.2 of the Appendix.

Table 2.2: Summarised classification of results from the sensitivity analysis of ACRU land cover parameters, based on the effect of varying input parameters on total streamflow and baseflow output volumes.

		Sensitivity when parameter is:	
Input Parameter	Output	**Decreased**	**Increased**
CAY	Streamflow	H	M
	Baseflow	E	H
ROOTA	Streamflow	S	M
	Baseflow	I	H
VEGINT	Streamflow	S	S
	Baseflow	S	S
COIAM	Streamflow	I	I
	Baseflow	M	S
PCSUCO	Streamflow	S	M
	Baseflow	M	M
COLON	Streamflow	I	I
	Baseflow	S	S

Where E : Extremely sensitive
H : Highly sensitive
M : Moderately sensitive
S : Slightly sensitive
I : Insensitive

2.5 Discussion

As the primary objective of this study was to assess the sensitivity of the ACRU Model simulated flows to variations in vegetation water use parameters, the configuration used was simple and all inputs besides the vegetation water use parameters were held constant. The most important land cover input variables identified by Schulze (2007) to best represent the conceptualisation of vegetation water use in the ACRU Model were identified as CAY, ROOTA, VEGINT, COIAM, PCSUCO and COLON. The sensitivity study undertaken allowed for indicative conclusions to be made regarding the sensitivity of streamflow and baseflow to the parameters for the six land cover input variables tested.

The conclusions regarding the sensitivity of the **streamflow** simulated by the ACRU Model to the vegetation water use monthly input parameters was:

- Highly sensitive to decreases in CAY and moderately sensitive to increases in CAY.
- Slightly sensitive to decreases in ROOTA.
- Slightly sensitive to both decreases and increases in VEGINT.
- Insensitive to both decreases and increases in COIAM.
- Slightly sensitive to decreases in PCSUCO and moderately sensitive to increases in PCSUCO.
- Insensitive to both increases and decreases in COLON.

The conclusions regarding the sensitivity of the **baseflow** simulated by the ACRU Model to the vegetation water use monthly input parameters was:

- Extremely sensitive to decreases in CAY, and highly sensitive to increases in CAY.
- Insensitive to decreases in ROOTA.
- Slightly sensitive to both decreases and increases in VEGINT.
- Moderately sensitive to decreases in COIAM and slightly sensitive to increases in COIAM.
- Moderately sensitive to both decreases and increases in PCSUCO.
- Slightly sensitive to both decreases and increases in COLON.

Overall, the CAY parameter was the most sensitive parameter in terms of simulated streamflow and particularly in terms of simulated baseflow. The ACRU Model output was moderately sensitive to changes in PCSUCO and the simulated baseflow was moderately sensitive to decreases in COIAM. The simulated streamflow and baseflow was insensitive or only slightly sensitive to the remaining land cover parameters assessed.

With the CAY, PCSUCO and COIAM parameters being identified as sensitive, an understanding of the conceptualisation of these sensitive parameters in the ACRU Model is imperative. The CAY parameter plays an important role in ACRU as it represents the physical attributes of the vegetation biomass that govern the vegetation water use, such as the vegetation height, albedo, canopy resistance and the associated evaporation from the soil. Within the

ACRU Model, the CAY parameter determines the potential transpiration rates and thus describes the consumptive water use by the vegetation. Total evaporation (ET) plays an important role in the hydrological cycle as one of the greatest drivers, and within the ACRU Agrohydrological Model, it is the primary process for returning water to the atmosphere. CAY and PCSUCO both have a role in controlling the ET component within the ACRU Model. The evaporation from the plant tissue (transpiration) and the soil surface (soil water evaporation) is usually treated as a lumped entity, and within ACRU is calculated using a meteorologically derived reference evaporation and crop coefficients (i.e. CAY) which define the water use of the vegetation. Therefore, the CAY accounts for differences between the reference surface and the vegetation surface, and within ACRU is used to compute the vegetation's potential evapotranspiration rate, relative to the evapotranspiration from a reference crop surface.

Given that the streamflow and baseflow outputs were found to be most sensitive to changes in the CAY input parameter, and even more particularly to decreases in CAY than increases, a reasonable amount of time and effort must therefore be spent on estimation, verification and selection of CAY parameters. To ensure sound representation of vegetation water use expressed by the CAY parameter in order to improve the accuracy of ACRU Model simulations, the estimation of the CAY parameters need to be based on actual observations and field-based measurements. Estimations of CAY parameters can be challenging. The accepted and recommended method by the FAO for estimating CAY is the Penman-Monteith method (Allen *et al.*, 1998), which requires an estimate of the vegetation ET. The ET may be in the form of actual ET data from in-situ methods where it is available, or alternatively spatially estimated (satellite derived) data of ET. Based on the results from this sensitivity study, it is important that hydrological studies use the "best estimate" of CAY. Considering the challenges encountered when estimating CAY, when in doubt, an overestimated CAY value is 'more conservative' than an underestimated one, as the outputs were more sensitive to the decreases in CAY than the increases.

The sensitivity of the PCSUCO input parameter in terms of streamflow and baseflow output was similar to, but slightly lower than, that of the CAY parameter. The PCSUCO parameter accounts for the presence and amount of litter, mulch and/or stone/rock. Plant litter plays an important role in protecting the soil surface and reducing the evaporation from the soil surface (Schulze, 2007) by covering the ground surface and having a high porosity which limits the capillary rise of water from the underlying soil profile (Sakaguchi and Zeng, 2009). The

PCSUCO parameter, reflects the state of the ground surface cover, describes the litter properties, and thus determines the degree of soil erosion, and plays an important role in controlling the evaporation of soil water. Increasing PCSUCO parameters suppresses the soil water evaporation losses in a linear relationship such that complete surface cover (100 %) still allows for 20 % soil water evaporation. As mentioned previously, a major determinant of the hydrological response in the ACRU Model is ET, which PCSUCO and CAY have an important role in controlling.

The PCSUCO values input to the model in this sensitivity study were those developed by Schulze (2004a) for the broad natural veld type, which is embedded in a decision support system database for land cover attributes in the ACRU Model. The rules developed by Schulze (2004a) to determine the PCSUCO values for the Acocks (1988) Veld Types were based on the assumption that the greater the above-ground biomass (indicated by CAY) the higher the litter cover (indicated by PCSUCO). Thus, the sensitivity of the PCSUCO parameter that is comparable with the sensitivity patterns of the CAY parameter is due to the value of PCSUCO being based on the value of CAY, where there is a direct relationship between CAY and PCSUCO. Therefore, where the ACRU Model is sensitive to changes in CAY it will also be sensitive, although to a lesser extent, to changes in PCSUCO. In order to improve the accuracy of ACRU Model simulations, the estimations of PCSUCO parameters should be based on actual physical measurements of the surface cover properties. However, the lack of information recorded for the ground-surface land cover properties of natural vegetation units in South Africa poses methodological challenges to such estimates.

The results from this study are comparable with Angus (1989) who showed total streamflow to be highly sensitive to decreases in CAY, slightly sensitive to decreases in ROOTA and slightly sensitive to decreases and increases in VEGINT. The results differed from the results from Angus (1989) who showed total streamflow to be highly sensitive to increases in CAY, moderately sensitive to decreases in COIAM, slightly sensitive to increases in ROOTA and increases in COIAM. However, the starting values for the input parameters for the baseline scenario in the study by Angus (1989) are not known and thus where a lower ROOTA starting value may have been used the percentage increases in ROOTA may have been more meaningful in identifying the sensitivity of streamflow to ROOTA changes. Whereas in the present study the starting ROOTA was relatively high and thus even increasing the starting values by 10 and 20 % increments led to ROOTA values approaching, or equal to, a value of

1. Therefore, the higher sensitivity of streamflow to the increased ROOTA parameters in the present study was influenced by the lack of transpiration associated with these very high starting ROOTA values approaching the maximum ROOTA of 1 and thus can't be used with complete confidence to explain the sensitivity of streamflow to increasing ROOTA inputs.

Analysing the effects of increasing the ROOTA parameter values on ACRU Model output has identified a possible shortcoming within the ACRU model. According the internal assumptions and rules within ACRU, setting the ROOTA input parameter to a value of 1, designates that effectively only soil water evaporation is taking place from the topsoil horizon and no transpiration is occurring. Although a value of 1 is generally assigned to ROOTA of vegetation during frost conditions and thus portraying aspects of senescence, implying minimum/negligible transpiration, this is not always the case for every vegetation type. Some plants, such as succulents and annuals (Schenk and Jackson, 2002a), and certain tree species in mangrove/swamp type conditions for instance (Clulow *et al.*, 2013), have shallow root systems extending only within the depth of the A-horizon, thus having 100 % of their root mass appearing in the topsoil horizon (i.e. a ROOTA of 1) throughout the year. For example, the results from Schenk and Jackson (2002a) indicated a median rooting depth for succulent stem species of 25 cm based on global root profiles from various studies. In accordance with the definition of the ROOTA parameter in ACRU, a ROOTA of 1 derived for these shallow rooted vegetation types simply implies 100 % of roots in the horizon and does not mean "no transpiration". Therefore, the assumption within ACRU for a ROOTA of 1 to designate that no transpiration is occurring is unrealistic in representing the water use of vegetation. Setting the ROOTA parameter to a value of 1 results in large increases in the simulated streamflow and more so in the simulated baseflow. This raised concern about the shortcoming in the conceptualisation of the roots in ACRU and its associated implications for vegetation water use estimations needs to be addressed in further research.

There are many challenges related to data scarcity when trying to parameterise each input variable, thus the knowledge gained through this study of identifying land cover input parameters that are most sensitive in the ACRU model assists in prioritising the parameters and understanding the uncertainties in the output results. In summary, changing the VEGINT or COLON parameters individually will have a relatively small, if not negligible, impact on the streamflow and baseflow output volumes simulated by the ACRU Model. Whereas, changing CAY, ROOTA, PCSUCO or COIAM will have a noticeable effect. As a result, the VEGINT and COLON parameters are not as dominant as CAY, ROOTA, PCSUCO and COIAM in simulating differences between the vegetation water use due to differences in vegetation properties of different land covers in the ACRU Model. Despite the sensitivity study results, all of the six land cover input parameters are required as input to the ACRU Model and thus, estimations of these parameters will need to be done when performing various land use change or climate change model simulations. Additionally, although some parameters may be insensitive or slightly sensitive when changed individually, when changed in combination with other parameters the impacts may be greater. For example, given that PCSUCO parameter estimations are based on the sigmoidal relationship between PCSUCO and CAY (Schulze, 2004), a relative and proportionate increase/decrease would be expected with an increase/decrease in CAY. Therefore, increasing or decreasing these two parameters, PCSUCO and CAY, simultaneously instead of individually, may result in a notable impact on ACRU model sensitivity.

The sensitivity study was for one fictitious location only, *viz* a typical natural grassland in South Africa, and the results produced can therefore not be applied in other regions to represent the response of output to input in ACRU. The recommendations given by Angus (1989), who also used only one location in the ACRU sensitivity study, suggested that future analyses be performed for several different climatic regimes. As the sole purpose of the present sensitivity study was to obtain a better understanding of the sensitivity of ACRU Model output to land cover input parameters for improving land use change studies, the use of one natural grassland scenario was deemed sufficient. However, further analysis of model output sensitivities to input parameters under various climatic and initial land use scenarios should be investigated in future studies.

A recommendation of the study is to investigate the sensitivity of the ACRU model to the land cover input parameters under various climatic conditions, by taking in to account several other climatic regions. Another recommendation for future research would be to further investigate the internal processes and assumptions within the ACRU model in terms of the root parameters and how the value of these parameters influence the conceptualisation of vegetation water use in the model. Although the CAY, PCSUCO and COIAM parameters were found to be the most sensitive land cover parameters in terms of the ACRU model, it is likely that other similar physically based hydrological models will demonstrate similar sensitivities.

2.6 Conclusion

The sensitivity study identified the land cover parameters that have a greater impact on the simulated hydrological response to improve understanding of the conceptualisation of vegetation and its water use in ACRU. The results from the sensitivity study may thus be used as a guideline in model predictions in ungauged basins, indicating that sensitive parameters must be estimated and quantified accurately. The results showed that the model output was found to be extremely sensitive to CAY inputs in terms of baseflow simulations and highly sensitive to CAY inputs in terms of streamflow simulations. This highlights the importance of accurate and representative CAY estimates for input to ACRU. The ACRU Model output was found to be moderately sensitive to the PCSUCO parameter, with the simulated baseflow also being moderately sensitive to the COIAM. All other land cover input parameters investigated were found to be only slightly sensitive. Although the simulated hydrological response was slightly sensitive to decreases in ROOTA, the high values (approaching maximum ROOTA of 1) assigned to the ROOTA variable for the base run, leaving minimal scope for increases, meant that the effect of increases in ROOTA could not be analysed sufficiently. Instead, the effect of the maximum ROOTA parameter (i.e. ROOTA of 1) indicated a possible shortcoming in the conceptualisation of roots in the ACRU Model. Despite the sensitivity study results, all of the six land cover input parameters are required as input to the ACRU Model and thus, accurate and representative estimations of these parameters will need to be done when undertaking land use change impact assessments and monitoring activities to ensure the sound management and protection of water resources.

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2.8 Appendix

Table A2.1: Initial ACRU land cover parameters and the incremented % changes to these.

Condition	VARIABLE	JAN	FEB	MAR	APR	MAY	JUN	JUL	AUG	SEP	OCT	NOV	DEC
Initial Values	CAY	0.7	0.7	0.7	0.5	0.35	0.25	0.2	0.2	0.55	0.7	0.7	0.7
	VEGINT	1.5	1.5	1.5	1.3	1.1	1.1	1.1	1.1	1.4	1.5	1.5	1.5
	ROOTA	0.9	0.9	0.9	0.94	0.96	1	1	1	0.95	0.9	0.9	0.9
	COIAM	0.15	0.15	0.2	0.3	0.3	0.3	0.3	0.3	0.3	0.3	0.2	0.15
	COLON	60	60	60	60	60	60	60	60	60	60	60	60
	PCSUCO	73.4	73.4	73.4	73.4	73.4	73.4	73.4	73.4	73.4	73.4	73.4	73.4
10% increase	CAY	0.77	0.77	0.77	0.55	0.39	0.28	0.22	0.22	0.61	0.77	0.77	0.77
	VEGINT	1.65	1.65	1.65	1.43	1.21	1.21	1.21	1.21	1.54	1.65	1.65	1.65
	ROOTA	0.99	0.99	0.99	1.00	1.00	1.00	1.00	1.00	1.00	0.99	0.99	0.99
	COIAM	0.17	0.17	0.22	0.33	0.33	0.33	0.33	0.33	0.33	0.33	0.22	0.17
	COLON	66.00	66.00	66.00	66.00	66.00	66.00	66.00	66.00	66.00	66.00	66.00	66.00
	PCSUCO	80.74	80.74	80.74	80.74	80.74	80.74	80.74	80.74	80.74	80.74	80.74	80.74
20% increase	CAY	0.84	0.84	0.84	0.60	0.42	0.30	0.24	0.24	0.66	0.84	0.84	0.84
	VEGINT	1.80	1.80	1.80	1.56	1.32	1.32	1.32	1.32	1.68	1.80	1.80	1.80
	ROOTA	1.00	1.00	1.00	1.00	1.00	1.00	1.00	1.00	1.00	1.00	1.00	1.00
	COIAM	0.18	0.18	0.24	0.36	0.36	0.36	0.36	0.36	0.36	0.36	0.24	0.18
	COLON	72.00	72.00	72.00	72.00	72.00	72.00	72.00	72.00	72.00	72.00	72.00	72.00
	PCSUCO	88.08	88.08	88.08	88.08	88.08	88.08	88.08	88.08	88.08	88.08	88.08	88.08
30% increase	CAY	0.91	0.91	0.91	0.65	0.46	0.33	0.26	0.26	0.72	0.91	0.91	0.91
	VEGINT	1.95	1.95	1.95	1.69	1.43	1.43	1.43	1.43	1.82	1.95	1.95	1.95
	ROOTA												
	COIAM	0.20	0.20	0.26	0.39	0.39	0.39	0.39	0.39	0.39	0.39	0.26	0.20
	COLON	78.00	78.00	78.00	78.00	78.00	78.00	78.00	78.00	78.00	78.00	78.00	78.00
	PCSUCO	95.42	95.42	95.42	95.42	95.42	95.42	95.42	95.42	95.42	95.42	95.42	95.42
40% increase	CAY	0.98	0.98	0.98	0.70	0.49	0.35	0.28	0.28	0.77	0.98	0.98	0.98
	VEGINT	2.10	2.10	2.10	1.82	1.54	1.54	1.54	1.54	1.96	2.10	2.10	2.10
	ROOTA												
	COIAM	0.21	0.21	0.28	0.42	0.42	0.42	0.42	0.42	0.42	0.42	0.28	0.21
	COLON	84.00	84.00	84.00	84.00	84.00	84.00	84.00	84.00	84.00	84.00	84.00	84.00
	PCSUCO	100.	100.	100.	100.	100.	100.	100.	100.	100.	100.	100.	100.
50% increase	CAY	1.05	1.05	1.05	0.75	0.53	0.38	0.30	0.30	0.83	1.05	1.05	1.05
	VEGINT	2.25	2.25	2.25	1.95	1.65	1.65	1.65	1.65	2.10	2.25	2.25	2.25
	ROOTA												
	COIAM	0.23	0.23	0.30	0.45	0.45	0.45	0.45	0.45	0.45	0.45	0.30	0.23
	COLON	90.00	90.00	90.00	90.00	90.00	90.00	90.00	90.00	90.00	90.00	90.00	90.00
	PCSUCO												
10% decrease	CAY	0.63	0.63	0.63	0.45	0.315	0.225	0.18	0.18	0.495	0.63	0.63	0.63
	VEGINT	1.35	1.35	1.35	1.17	0.99	0.99	0.99	0.99	1.26	1.35	1.35	1.35
	ROOTA	0.81	0.81	0.81	0.846	0.864	0.9	0.9	0.9	0.85	0.81	0.81	0.81
	COIAM	0.135	0.135	0.18	0.27	0.27	0.27	0.27	0.27	0.27	0.27	0.18	0.135
	COLON	54	54	54	54	54	54	54	54	54	54	54	54
	PCSUCO	66.06	66.06	66.06	66.06	66.06	66.06	66.06	66.06	66.06	66.06	66.06	66.06
20% decrease	CAY	0.56	0.56	0.56	0.4	0.28	0.2	0.16	0.16	0.44	0.56	0.56	0.56
	VEGINT	1.2	1.2	1.2	1.04	0.88	0.88	0.88	0.88	1.12	1.2	1.2	1.2
	ROOTA	0.72	0.72	0.72	0.752	0.768	0.8	0.8	0.8	0.76	0.72	0.72	0.72
	COIAM	0.12	0.12	0.16	0.24	0.24	0.24	0.24	0.24	0.24	0.24	0.16	0.12
	COLON	48	48	48	48	48	48	48	48	48	48	48	48
	PCSUCO	58.72	58.72	58.72	58.72	58.72	58.72	58.72	58.72	58.72	58.72	58.72	58.72
30% decrease	CAY	0.49	0.49	0.49	0.35	0.245	0.175	0.14	0.14	0.385	0.49	0.49	0.49
	VEGINT	1.05	1.05	1.05	0.91	0.77	0.77	0.77	0.77	0.98	1.05	1.05	1.05
	ROOTA	0.63	0.63	0.63	0.658	0.672	0.7	0.7	0.7	0.665	0.63	0.63	0.63
	COIAM	0.105	0.105	0.14	0.21	0.21	0.21	0.21	0.21	0.21	0.21	0.14	0.105
	COLON	42	42	42	42	42	42	42	42	42	42	42	42
	PCSUCO	51.38	51.38	51.38	51.38	51.38	51.38	51.38	51.38	51.38	51.38	51.38	51.38
40% decrease	CAY	0.42	0.42	0.42	0.3	0.21	0.15	0.12	0.12	0.33	0.42	0.42	0.42
	VEGINT	0.9	0.9	0.9	0.78	0.66	0.66	0.66	0.66	0.84	0.9	0.9	0.9
	ROOTA	0.54	0.54	0.54	0.564	0.576	0.6	0.6	0.6	0.57	0.54	0.54	0.54
	COIAM	0.09	0.09	0.12	0.18	0.18	0.18	0.18	0.18	0.18	0.18	0.12	0.09
	COLON	36	36	36	36	36	36	36	36	36	36	36	36
	PCSUCO	44.04	44.04	44.04	44.04	44.04	44.04	44.04	44.04	44.04	44.04	44.04	44.04
50% decrease	CAY	0.35	0.35	0.35	0.25	0.175	0.125	0.1	0.1	0.275	0.35	0.35	0.35
	VEGINT	0.75	0.75	0.75	0.65	0.55	0.55	0.55	0.55	0.7	0.75	0.75	0.75
	ROOTA	0.45	0.45	0.45	0.47	0.48	0.5	0.5	0.5	0.475	0.45	0.45	0.45
	COIAM	0.075	0.075	0.1	0.15	0.15	0.15	0.15	0.15	0.15	0.15	0.1	0.075
	COLON	30	30	30	30	30	30	30	30	30	30	30	30
	PCSUCO	36.7	36.7	36.7	36.7	36.7	36.7	36.7	36.7	36.7	36.7	36.7	36.7

Table A2.2: Sensitivity ranking for the effect on ACRU model output for each incremented increase and decrease in each land cover input parameter.

		Decrease Input					**Increase Input**				
	%change Input	-50	-40	-30	-20	-10	10	20	30	40	50
CAY	%change Output (USFLOW)	63	48	33	21	9	-8	-15	-20	-24	-26
	Sensitivity ranking	H	H	H	H	M	M	M	M	M	M
	%change Output (UBFLOW)	122	93	65	40	18	-15	-28	-39	-46	-49
	Sensitivity ranking	E	E	E	E	H	H	H	H	H	M
PCSUCO	%change Output (USFLOW)	-19	-16	-12	-8	-4	5	11	17	22	22
	Sensitivity ranking	S	S	S	S	S	S	M	M	M	S
	%change Output (UBFLOW)	-34	-28	-22	-16	-8	9	20	32	40	40
	Sensitivity ranking	M	M	M	M	M	M	M	H	H	M
COIAM	%change Output (USFLOW)	4	3	2	1	0	0	-1	-1	-1	-1
	Sensitivity ranking	I	I	I	I	I	I	I	I	I	I
	%change Output (UBFLOW)	-29	-23	-16	-11	-4	6	10	15	19	23
	Sensitivity ranking	M	M	M	M	S	M	S	M	S	S
VEGINT	%change Output (USFLOW)	6	5	4	2	1	-1	-2	-3	-4	-5
	Sensitivity ranking	S	S	S	S	S	S	S	S	S	S
	%change Output (UBFLOW)	7	5	4	3	1	-1	-2	-3	-5	-6
	Sensitivity ranking	S	S	S	S	S	S	S	S	S	S
ROOTA	%change Output (USFLOW)	12	8	5	3	1	7	29	29	29	29
	Sensitivity ranking	S	S	S	S	I	M	H	M	M	M
	%change Output (UBFLOW)	7	4	1	-1	-2	18	65	65	65	65
	Sensitivity ranking	S	I	I	I	S	H	E	E	H	H
COLON	%change Output (USFLOW)	5	4	3	2	1	-1	-2	-2	-3	-4
	Sensitivity ranking	I	I	I	I	I	I	I	I	I	I
	%change Output (UBFLOW)	10	8	6	4	2	-2	-4	-5	-7	-9
	Sensitivity ranking	S	S	S	S	S	S	S	S	S	S

Lead into Chapter 3

From Chapter 2, it was concluded that the most sensitive ACRU Model parameter in terms of simulated hydrological responses was CAY, with PCSUCO and COIAM being moderately sensitive and the remaining parameters (ROOTA, VEGINT and COLON) being only slightly sensitive. Despite the results from the sensitivity study, the sound estimation of all land cover parameters are required as input to ACRU for land use change assessments. Considering the disparity in research for the below-ground land cover parameters, as well as the influence of roots on the water uptake functions of plants, Chapter 3 focuses on the third objective to derive root-specific below-ground vegetation water use parameters for natural vegetation in South Africa. The two parameters include EFRDEP and ROOTA. Climatic and genetic factors are quantified in terms of their impact on these parameters.

CHAPTER 3: QUANTIFYING AND PARAMETERISING THE ROOT SYSTEMS OF NATURAL VEGETATION IN SOUTH AFRICA FOR USE IN A HYDROLOGICAL MODEL

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ABSTRACT

Contrary to the many studies that have investigated the above-ground plant structure and functions, little research has been undertaken on the below-ground components. Any changes to the land cover and hence to the root systems, result in changes to the hydrological response as the partitioning of rainwater is, in part, determined by the production and distribution of roots. With the role that roots play, it is important that they are appropriately represented in hydrological models, and parameterised accurately. Even less is understood and documented about the roots of natural vegetation than of agricultural crops and commercial forestry. This study estimated root-specific below-ground parameters for natural vegetation in South Africa for use as input to the ACRU Agrohydrological Model. The parameters estimated were the seasonal variations of the distribution of active roots in topsoil and subsoil horizons (ROOTA and ROOTB), and the effective rooting depth (EFRDEP). As it was impractical to produce field-based measurements and/or spatial observations of these below-ground root structures for the large number and diversity of natural vegetation species in South Africa, the estimations were based on root measurements from previous studies together with measured catchment properties (e.g. rainfall, soils and dominant species information). Estimates of ROOTA were based on using root profiles of various vegetation growth forms from previous studies in a non-linear regression model to obtain the cumulative roots above the depth of the A-horizon for the natural vegetation ecosystems. The EFRDEP values were estimated by applying a linear regression relationship that uses Mean Annual Precipitation (MAP) and growth form properties. This study produced a database of root parameters, using a sound and repeatable methodology based on observations and measurements, for use in a hydrological model.

3.1 Introduction

Approximately 15.7 % of South Africa's natural land cover has undergone some or other form of transformation, mainly by cultivation, mining, forestry, degradation of the natural cover or urban land use (Schoeman *et al.*, 2013). Given that land cover governs and influences the hydrological processes (Bulcock and Jewitt, 2010), these land cover changes have a great impact on the already stressed water resources in this water scarce country (Warburton *et al.*, 2010). The hydrological impacts of land use changes in South Africa have been relatively well researched. These studies have typically compared the water use between the new land use and the natural vegetation it replaces (Dye, 2001; Everson *et al.*, 2008; Gush, 2002; Gush and Dye, 2006, 2009), and most have been between seasonally dormant grasslands or fynbos and plantations of introduced tree species (Scott *et al.*, 2000; Dye and Versfeld, 2007). Natural vegetation in the form of the Acocks' (1988) Veld Types is the currently accepted baseline land cover, used by the Department of Water and Sanitation (DWS) in South Africa, against which land use impacts and particularly streamflow reduction activities (SFRAs) of commercial forestry are assessed (Schulze, 2004a; Jewitt *et al.*, 2009). To date, the assessment of SFRAs against the currently accepted natural vegetation of Acocks' (1988), have resulted in the implementation of restrictions on afforestation in South Africa, which despite the growing demand for timber products, have limited the expansion of the total national plantation area (Everson *et al.*, 2011).

There have been concerns raised about the use of the Acocks' (1988) Veld Types as the accepted natural vegetation in land use change assessments, which relate primarily to the country-wide scale resolution at which it was mapped and the expert-opinion-based "working rules" approach (Schulze, 2004a) used for estimation of the vegetation and water use parameters. However, up until recently, this was the only classification of natural land cover available for which hydrological parameters had been derived, and there had been limited research on natural vegetation water use to confirm these parameters. A revised natural vegetation map for South Africa developed by Mucina and Rutherford (2006) and updated by the South African National Biodiversity Institute (SANBI, 2012) has been proposed for a new hydrological baseline land cover (Jewitt *et al.*, 2009; Warburton, 2012) to address the raised concerns. The natural vegetation map of SANBI (2012) defines 450 vegetation units (www.bgis.sanbi.org/vegmap/map.asp; Figure 3.1) as opposed to 70 Veld Types in the currently used natural vegetation map by Acocks (1988).

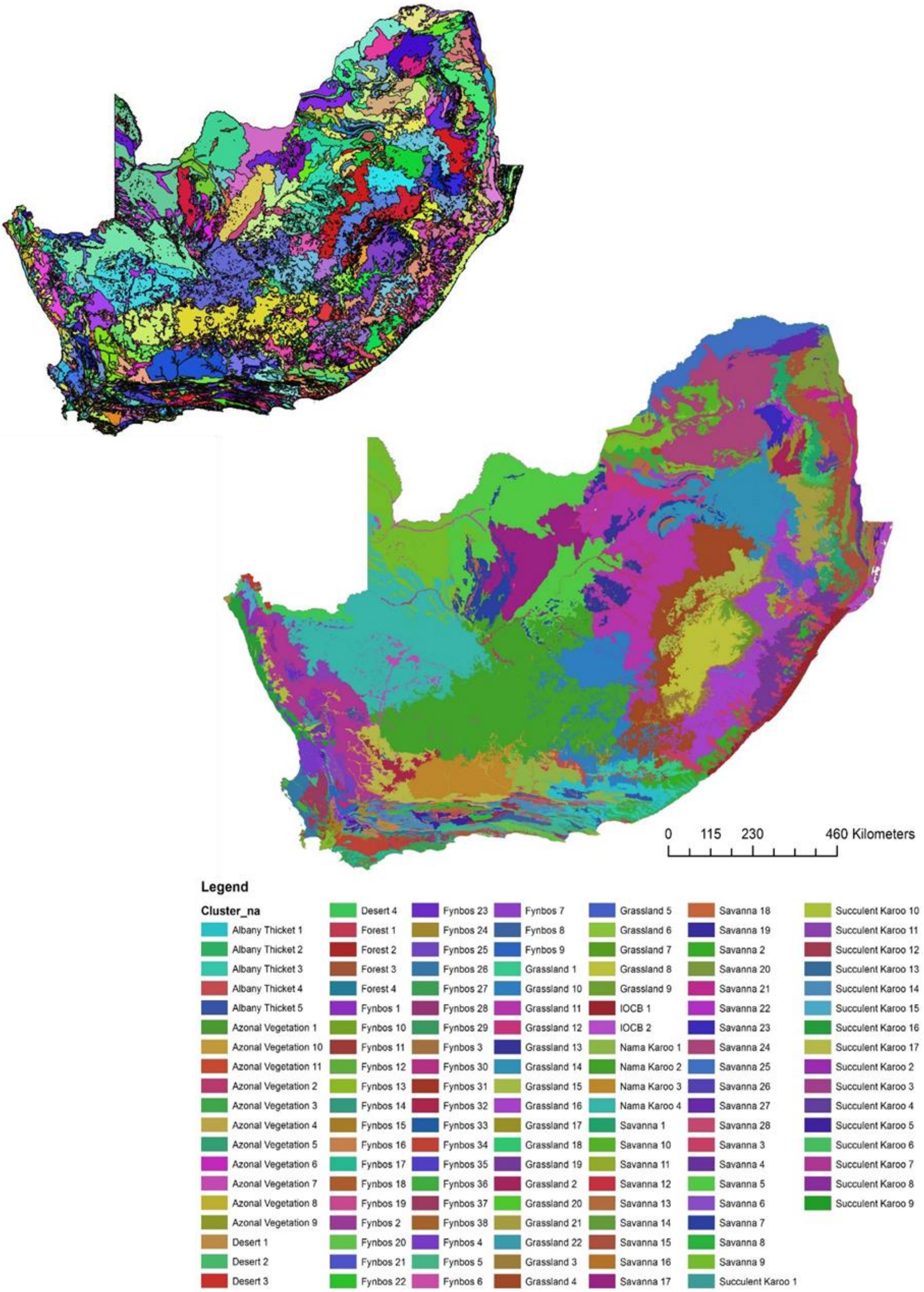

Figure 3.1: (a) The natural vegetation map produced by SANBI (2012) with 450 vegetation units; (b) 128 clustered SANBI vegetation units

Given that the majority of land use change assessments make use of hydrological models to simulate the transition from natural vegetation and to assess the impacts on the hydrological response (Warburton *et al.*, 2010; Turner *et al.*, 1995; Bronstert *et al.*, 2002; De Fries and Eshleman, 2004; Samaniego and Bárdossy, 2006; Choi and Deal, 2008), the revised natural vegetation of SANBI (2012) needs to be parameterised in order to represent natural vegetation in a hydrological model. The 450 vegetation units vary floristically and ecologically, however, there may be similarities in hydrological responses between several of these units. Further to this, estimating vegetation and water use model parameters for each of the individual 450 vegetation units is not feasible given the scale of the available data for parameterisation. Thus, the 450 SANBI (2012) vegetation units were grouped into 128 vegetation clusters (hereafter termed "clusters"; Figure 3.1) which have been assumed to behave, hydrologically, in a similar manner (Rouget *et al.*, 2017). To allow this to be used as a hydrological baseline land cover, vegetation and water use model input parameters need to be estimated for each of the 128 clusters. In trying to move beyond the application of "working rules" and expert opinions, these estimations should be based on physical data and observations. This has been made possible with water use measurements for natural vegetation produced in recent studies (Everson *et al.*, 2011; Gush, 2011; Bulcock, 2011).

The hydrological model for which parameters need to be estimated is the ACRU Agrohydrological model, because it is the model used in the SFRA Assessment Utility Tool (Jewitt *et al.*, 2009). The quantification of land cover attributes which govern the partitioning of water into the various components of the hydrological cycle (Costa *et al.*, 2003) is imperative to the accurate assessment of vegetation water use in hydrological models. Within ACRU the land cover is conceptualised by grouping land use processes according to those relating to above-, below- and on-the-ground surface. Vegetation and water use parameters that describe these land use processes are required as input to ACRU and are therefore required to be estimated for the 128 clusters of natural vegetation. The small and fragmented extent of natural vegetation remaining in the country creates challenges for using field-based measurements in the estimation of these vegetation and water use model parameters. Thus, the estimation will be based on existing measurements and observations of natural vegetation water use in South Africa from previous studies. Where necessary, the SANBI (2012) vegetation units that constitute the clusters will be used to inform the parameterisation.

The majority of plant-ecological studies in South Africa and globally have been limited to the above-ground component of various plant ecosystems (Snyman, 2005) thus, patterns of above-ground biomass and distribution are relatively well understood (Mokany *et al.*, 2006), while the below-ground component is poorly understood (Murphy and Moore, 2010; Raz-Yaseef *et al.*, 2013). In South Africa much of the limited literature on natural vegetation roots is available only through observational articles or reviews, with the focus being on grasslands and savannas. Our knowledge of African natural vegetation roots is mainly from studies undertaken in southern Africa (Snyman, 2005; Everson *et al.*, 2011), although some studies from other parts of Africa have also contributed to this knowledge (McNaughton *et al.*, 1995; Mordelet *et al.*, 1997). Given the general lack of knowledge on roots of African natural vegetation, much of the theory concerning roots of natural vegetation originates from North and South American based studies such as those by Kellman and Roulet (1990) and Liang *et al.* (1989). Although many of the principles learnt from international studies apply globally and provide a valuable foundation, the limited research on the roots of natural vegetation in South Africa (Everson *et al.*, 2011; Gush, 2011; Bulcock, 2011), has meant that root structures still remain the most unexplored component of natural vegetation.

The lack of root information is mainly due to the methodological challenges encountered when measuring fine roots (Nadelhoffer and Raich, 1992; Vogt *et al.*, 1996; Titlyanova *et al.*, 1999). Some of these difficulties in sampling include complexities in distinguishing between fine and large roots, as well as between live and dead roots; and the extensive depth that must be accessed to assess total root profiles. These methodological challenges, the time required to attain the resultant data and the high variability thereof, and the fact that little is understood about the important role of below-ground structures in total plant production, are of the most common reasons for this disparity in knowledge (Newbould, 1968; Singh and Coleman, 1973; Bohm, 1979; Singh *et al.*, 1984). Additionally, spatial estimations using spatially-based remote sensing measuring tools such as aerial photography and satellites are restricted due to the lack of visibility of these below-ground structures.

The few studies that have investigated root systems of natural vegetation, have mostly focused on estimating total root biomass production, its relation to above-ground biomass and its contribution to total net primary production (Newbould, 1968; Fogel, 1983; Vogt *et al.*, 1986b). Few studies have investigated the distribution of root biomass across soil horizons (McNaughton *et al.*, 1998), and even fewer have investigated the effective depth reached by these roots. Where information is available, it is specific to the climate, season, geographical location, soil water availability and specific plant species of the transformed research site at the time of the research and thus, introduces doubt as to the transferability of these results to other locations (Clulow *et al.*, 2013). Where this information for root production estimates is available from previous experiments the majority of these data have been derived using indirect methods, such as relating above-ground biomass, carbon mass in roots or even microzhorial root activities to estimate below-ground biomass (Mokany *et al.*, 2006; Vogt *et al.*, 1982, Vogt *et al.*, 1998 and Fogel *et al.*, 1983). Such data are vulnerable to uncertainties and possible biases (Singh *et al.*, 1984; Vogt *et al.*, 1986a) and should therefore be used tentatively. Thus, the magnitude to which climatic and site-specific factors affect the distribution and size of root systems (Nadelhoffer and Raich, 1992; van Wijk, 2011), and the full extent to which roots control the availability and uptake of water by plants remains unclear. Nevertheless, the below-ground component of vegetation has been shown to play an important role in governing vegetation water use processes (Canadell *et al.*, 1996; Raz-Yaseef *et al.*, 2013) and thus, should be better understood. This is especially true in semi-arid ecosystems, such as South Africa (Dye *et al.*, 2008), which are subject to greater, long-lasting consequences following small changes (Wiegand *et al.*, 2004).

Recognising that below-ground plant structures are the most unexplored component of vegetation highlighted the need to appropriately represent roots in a hydrological model. Therefore, this study aimed to develop a sound, repeatable methodology for estimating root-specific below-ground parameters for use in the ACRU Agrohydrological Model.

3.2 Conceptualisation of Root Water Uptake in the ACRU Model

The ACRU Agrohydrological Model is a daily, physical-conceptual model (Schulze, 1995) that is centred on a multi-soil-layer water budget which is sensitive to land use and changes thereof. As the below-ground vegetation related processes are of concern for this study, only the conceptualisation of these in ACRU will be discussed. The soil water uptake function of roots is conceptually the most important below-ground vegetation related process in the ACRU Model. The process of soil water uptake by vegetation is affected by factors such as root growth, distribution, colonisation, extension, the differences in the water potentials between plant and soil, the hydraulic conductivity of the soil and the availability of water in the soil. Thus, it is not a simple matter to attempt to model water uptake and, in ACRU assumptions, simplifications and generalisations have been made to simulate root water uptake (Schulze *et al.*, 1995).

Roots tend to grow as deep as is required to reach sufficient provisioning of resources, both water and nutrients (Schenk and Jackson, 2002a). This is especially true for fine roots, which are primarily responsible for taking up most of the soil water (ACRU FDSS Workshop No3, 1995), and also for obtaining nutrients and oxygen (De Kroon and Visser, 2003; Raz-Yaseef *et al.*, 2013). Coarse roots are responsible for supporting and anchoring the vegetation and supporting the fine root network (Fogel, 1983). Semi-arid ecosystems experience short, sporadic rainfall events which limit soil water infiltration to shallow depths (Sala *et al.*, 1982). Thus, as water is most readily available in the topsoil horizons, the fine roots in semi-arid ecosystems are found more commonly in the topsoil horizons (Raz-Yaseef *et al.*, 2013). In more arid ecosystems, sufficient resources are attained much deeper in the soil profile and thus, roots tend to move to deeper soil layers to find water (van Wijk, 2011).

Given that the roots track the availability of water and nutrients across the soil profile (Cheng and Bledsoe, 2001), the fraction of roots in each horizon through space and time reflects the transpiration of the vegetation which depends on the above-ground plant phenology and on the localised soil conditions such as soil temperature, moisture and nutrient availability (Das and Chaturvedi, 2008). Other factors affecting transpiration include dormancy, senescence, regrowth, growth rates and impeding soil layers. Therefore, changes in these genetic and environmental factors, and thus changes to the transpiration, result in corresponding changes in root distributions (Day *et al.*, 1996). Although plant roots will grow to depths sufficient for provision of resources, the growth of roots across the soil profile is constrained by the plant’s need to conserve energy during periods of stress (Schenk and Jackson, 2002a). For example, during the winter months in South Africa, when temperatures drop to near- or below freezing, the vegetation in grasslands begins to senesce and the roots become dormant, thus soil water extraction by the roots ceases (Schulze *et al.*, 1995).

The above is accounted for in ACRU, by (a) the Effective Rooting depth (EFRDEP), which defines the soil depth to which the effective root system extends within the entire active soil profile (Schulze, 2004b), and (b) the Fraction of Roots in the A- and B-horizons (ROOTA and ROOTB), which describes the seasonal variation of the fraction of the plant’s effective root system (i.e. active roots) in the critical topsoil horizon (i.e. the A horizon) and subsoil horizon (i.e. the B-horizon), respectively, relative to those in the entire active soil profile, with respect to a two-layer soil horizonation (Schulze, 2007). The EFRDEP parameter is a single input, but monthly ROOTA parameters are required as the distribution is assumed to vary throughout the year for most vegetation types. Soil water extraction by roots is considered to occur simultaneously from both soil horizons in proportion to the assumed active rooting mass distributions in each horizon. Seasonal variations in monthly ROOTA parameters are input to the model and used to internally compute the monthly ROOTB parameters. During periods of senescence when no active water uptake by roots is assumed, the ROOTA parameter in ACRU is set to 1 to designate that effectively no transpiration is occurring only soil water evaporation from the topsoil (Schulze, 1995). The internal processes in ACRU designate that when the vegetation is not under stress, the fraction of active roots in each horizon largely determine the differential transpiration from each horizon. Emphasizing the need for ROOTA and ROOTB parameters to consider the effects of genetic and environmental factors on transpiration. Some factors affecting transpiration and thus, variations in ROOTA and ROOTB include dormancy, senescence, regrowth, growth rates and impeding soil layers.

Variations in ROOTA and ROOTB generally reflects some broad consistent patterns (Raz-Yaseef *et al.*, 2013). In most environments, the largest proportion of roots (60 – 80% of root volume) occur within the upper 20 - 30 cm of the soil profile (Jackson *et al.*, 1996; Schenk and Jackson, 2002; Ruark *et al.*, 1982). Therefore, a decrease in root density is usually observed with an increase in vertical distance from the top soil horizons. The broad patterns in root distribution are usually specific to plants of similar growth forms, i.e. deeper rooting trees generally display higher percentage of roots deeper in the soil profile, while shallower rooting grasses display higher percentage of roots in the upper soil horizons. In general, the ROOTA parameter input to ACRU is usually between 0.6 – 1, implying that the ROOTB parameter generally stays between 0 – 0.4. However, this is not always the case as there are several environmental, climatic and genetic factors that play a role in determining root size and distribution. Given that the ROOTA and EFRDEP parameters determine the water uptake by plants, it is important that the estimation of these parameters consider the various factors affecting root growth.

Considering the various factors that influence water uptake functions of roots and hence determine the size and distribution of roots, it is important that the estimation of ROOTA and EFRDEP in this study quantifies the effect of these factors. These factors include MAP, frost, species composition and soil horizon depths. For the purpose of this study, we assume that the active roots within the soil profile are only those within the fine root category (root mass with diameters ≤ 2 mm) and thus, all estimates of EFRDEP and ROOTA in this study will be a reflection of the fine (active) roots only.

3.3 Methods

The root parameters, ROOTA and EFRDEP, in this study were estimated for clusters falling in the grassland, forest, savanna and desert biomes across South Africa. The methodology developed can then be applied to the remaining biomes. Savanna and grassland biomes cover 32.5 % and 27.9 % of South Africa, respectively (Mucina *et al.*, 2006). The grassland and forest biomes are characteristic of the higher rainfall regions, in which land use changes have the greatest impacts on catchment water yield (Dye *et al.*, 2008). Emphasis was given to these four natural vegetation biomes as they are the most commonly replaced or transformed natural ecosystems in land use change studies (Dye *et al.*, 2008). Each of the biomes had several clusters within it, i.e. 22 grassland clusters, 25 savanna clusters, 4 forest clusters and 4 desert clusters.

Given the reasons highlighted in Section 3.1, the methodology for estimating ROOTA and EFRDEP was based on using historical root measurements and observations from previous studies and linking these to the physical properties of the vegetation clusters. To achieve this, EFRDEP estimates were derived using regression parameters that describe the attributes of various plant growth forms from a collection of global root studies together with the Mean Annual Precipitation (MAP) for each cluster. ROOTA estimates were based on existing root distribution profiles from a limited number of previous field studies, together with the EFRDEP and the cluster A-horizon soil depth. Seasonal variations in ROOTA were based on the frost conditions in each cluster. Relationships between the known variables (i.e. MAP, soils, growth form properties and frost) and the unknown variables (i.e. EFRDEP and ROOTA) were used to derive sound ROOTA and EFRDEP estimates. Therefore, environmental, climatic and genetic factors were quantified in terms of their influence on ROOTA and EFRDEP.

3.3.1 EFRDEP estimations

Root mass and distribution are dependent, *inter alia*, on the plant's demand for water, as well as the availability of that water within the soil (Raz-Yaseef *et al.*, 2013). Therefore, the variability of rooting depths due to water availability can be explained by MAP (Holdo *et al.*, 2018). Schenk and Jackson (2002a) demonstrated that MAP could be used successfully in a linear regression equation (Equation 3.1) to derive rooting depths for all plant growth forms, except trees, in water limited ecosystems ($50 < MAP < 1000$). The other independent variables included in the linear regression equation were those assigned to broad growth form categories (Table 3.1), which were derived based on global root profiles from various studies. With many regions in South Africa being classed semi-arid (Dye *et al.*, 2008), the linear regression equation developed by Schenk and Jackson (Equation 3.1; 2002a) was selected to estimate EFRDEP for the clusters. The MAP of each cluster was determined from surfaces of gridded MAP for South Africa (Lynch, 2003).

Within each cluster, the EFRDEP for each individual growth form category was estimated independently using the linear equation:

$$\log 10\ D = a + b \log 10\ MAP \tag{3.1}$$

where D = rooting depth and where the values for the regression parameters of a and b are given for each growth form category (Table 3.1; Schenk and Jackson, 2002a)

Table 3.1: Regression parameters for the relationship between rooting depth (D) and Mean Annual Precipitation (MAP) for various growth form categories (Schenk and Jackson, 2002a).

Growth form	**a**	**b**
Annuals	-2.312	0.809
Perennial forbs	-1.603	0.629
Perennial grasses	-1.053	0.409
Semi-shrubs	-0.316	0.178
Shrubs	-0.053	0.158
Trees	1.000	-0.208

With the diversity of growth forms in clusters, the estimated EFRDEP for each cluster needed to reflect the various dominant growth forms within the cluster. To ensure this, the EFRDEP for each dominant plant growth form, except trees and succulents, were estimated using the various growth form regression parameters, together with the MAP value derived for the cluster. As the relationship between MAP and rooting depths could not be used for estimations of tree rooting depths, the EFRDEP for trees was set to a value of 300 cm based on the database of global root profiles developed by Schenk and Jackson (2002a). The effect of MAP on rooting depths of stem succulents has not been investigated thus the EFRDEP for stem succulents was also based on the database of global root profiles (Table 3.2) and set to 25 cm.

Table 3.2: Summary table of medians for maximum rooting depths (D), lateral root spreads (L), and L/D ratios for seven plant growth forms, based on various global root profiles (Schenk and Jackson, 2002a).

Growth Form	**Rooting Depth (Cm)**	**Lateral Spread (Cm)**	**L/D Ratio**
Trees	300	767	333
Shrubs	215	210	91
Semi-Shrubs	130	62	50
Perennial Grasses	107	30	34
Perennial Forbs	122	30	28
Annuals	37	12	30
Succulents	25	151	563

To determine the dominant growth forms in each cluster, the dominant species in each cluster were classified into the seven broad growth form categories defined by Schenk and Jackson (2002a, Table 3.2). Dominant species are defined by Mucina *et al.* (2006) as those important species in the vegetation units that demonstrate a high dominance in terms of their biomass in the local communities, a higher abundance, a high frequency of occurrence or their prominence in the landscape of the unit. All dominant species in the vegetation units that make up each cluster were grouped by Mucina *et al.* (2006) into growth form categories and sub-categories based on the behaviour and structure of the vegetation as observed in the field, using a system developed within the Ecological Flora of Southern Africa database. In some cases the same species were identified by Mucina *et al.* (2006) as different growth forms (i.e. tall shrubs and small trees), because some species are polymorphic across their range. For instance, the same species may have been growing as a tall shrub (i.e. multi-stemmed) in one vegetation unit but as a small tree (single-stemmed) in another unit. The classification of dominant species into the seven broad growth form categories was informed by the grouping of dominant species in the vegetation units into sub-categories and categories of growth forms provided in Mucina *et al.* (2006) and consistent rules.

The consistent rules applied were:

- To deal with polymorphic species, dominant species were categorised according to the growth form given for the species in the specific vegetation units that make up the given cluster.
- Schenk and Jackson (2002a) did not provide details about whether small tree root profiles were included in the broad “tree” group or in the broad “shrubs” group. Although both tall shrubs and small trees display woody thickening of tissues, small tree species were placed into the broad “tree” category based on their single-stemmed nature, and tall shrubs were placed into the broad “shrubs” category in terms of their multi-stemmed growth habit. Considering this, tree rooting depths may be somewhat overestimated in grasslands, and shrubs rooting depths slightly underestimated in forests. However, the magnitude of such systematic error is too small to influence the overall EFRDEP of the cluster and cancels each other out.
- Semi-shrubs were distinguished from shrubs in the clusters because Schenk and Jackson (2002a, 2002b), as well as other studies, treated these two separately as differences in the rooting depths of shrubs and semi-shrubs were identified in previous studies (Leishman and Westoby, 1992).
- Shrub species that rarely reach heights above 1 m (Schenk and Jackson, 2002a) and those that displayed little or no secondary woody thickening of tissues and hence more herbaceous growth (Mucina *et al.,* 2006), were classified as semi-shrubs. Therefore, soft shrub species (woody main stem and herbaceous branch tips) and succulent shrub species (succulent leaves and/or stems) were assigned to “semi-shrubs”. Geoxylic suffrutex species were also assigned to this semi-shrubs group, because according to the description of these species by Mucina *et al.* (2006), they have large underground woody rhizomes. Furthermore, Schenk and Jackson (2002a) also grouped suffrutescent forbs under semi-shrubs.
- Succulent tree species were categorised as succulent stems. According to Schenk and Jackson (2002a) the 25 cm median rooting depth derived for succulents was based on root profiles for stem succulents that characteristically had a succulent stem, and not those

succulents that only had succulent leaves or branches. Therefore, all stem-succulent shrubs and stem- and leaf-succulent shrubs (recognised only in desert clusters) were also assigned to the stem succulents group. Succulent shrubs, succulent herbs and leaf-succulent shrubs (recognised only in desert clusters) were not included in this group.

- Woody climber species were assigned to shrubs as they share the same woody properties as tall and low shrubs within this broader shrub group.
- Tree ferns were assigned to the broader tree group as they behave similarly to small tree species also within this group (Mucina *et al.*, 2006).
- The broad "Forbs" group includes all dominant species of herbs, geophytic herbs, megaherbs, herbaceous climbers and succulent herbs, none of which display woody thickening of tissues.
- Grasses included graminoid, climbing graminoid and mega-graminoid species.

The EFRDEP's derived for the individual growth form categories in each cluster were weighted against each other to obtain a single, growth-form weighted average EFRDEP estimate for each cluster. This weighting was according to the dominance of the various growth forms within the cluster, i.e. if there were more trees than any other plant forms then the EFRDEP of the trees were weighted the highest.

3.3.2 ROOTA estimations in growing seasons

Estimates of ROOTA require information about the vertical distribution of roots through the soil profile. Previous studies that assessed the vertical distribution of root mass across various soil depth intervals were interrogated as identified from global root databases (ISLSCP II DAAC root database - http://daac.ornl.gov/; Schenk and Jackson, 2003). ROOTA estimations reflect the fraction of active roots (i.e. fine roots ≤ 2 mm) present in the topsoil horizon relative to the total active roots in the soil profile. Thus, the criteria for selection of published root distribution estimates was African-based studies that assessed fine root mass distributions in at least four soil depth increments. Sixteen studies (hereafter termed "case studies") were identified. Where some studies assessed very fine roots (< 0.5 mm) and fine roots (0.5 – 2 mm) separately, these two mass estimates were combined to form one fine root mass distribution estimate.

The 16 selected case studies provided 41 estimates of fine root mass distribution (hereafter termed “root profiles”) for various plant growth forms from grassland, savanna, forest and thicket biomes in 12 geographical locations in South Africa and surrounding African countries (Table 3.3). For each root profile details about location, climate, altitude, temperature and frost were obtained from the case study papers. If none were provided these details were based on information from alternative databases and sources. The presence and dominance of plant growth forms, as well as features analysed (i.e. burnt grasslands, waterlogged conditions, grazed rangelands) were also recorded. The information was cross referenced against similar information for the clusters to determine which root profiles should be used to derive each cluster’s ROOTA estimation.

Table 3.3: Root profiles for various plant growth forms in African natural vegetation biomes from 16 case studies allocated to the dominant growth forms in each cluster.

Biome	Growth form	Location	n*	Source (Case study)
Grassland	Grasses	Bloemfontein, South Africa	3	Snyman, 2005; Snyman, 2009a; Snyman, 2009b
		Serengeti, Tanzania	3	McNaughton *et al.*, 1998
	Grasses and Forbs	Transkei, South Africa	2	Shackleton *et al.*, 1988
Savanna	Grasses	Cote d'Ivoire	2	Mordelet *et al.*, 1997; Le Roux *et al.*, 1995
		Nylsvley, South Africa	2	Scholes and Walker, 1993
		Kruger Park, South Africa	4	February and Higgins, 2010
	Grasses and forbs	Kenya	2	Belsky, 1994
	Grasses and Semi-shrubs	Tsitsikamma, South Africa	1	Milne and Haynes, 2004
	Grasses and Shrubs	Tsitsikamma, South Africa	2	Milne and Haynes, 2004
	Grasses, Trees, Forbs and Semi-shrubs	Ghana	1	Lawson *et al.*, 1970
	Grasses and Trees	Kenya	2	Belsky, 1994
		Nylsvley, South Africa	2	Knoop and Walker, 1985
		Northern Province, South Africa	1	Smit and Rethman, 1998
	Trees	Cote d'Ivoire	2	Mordelet *et al.*, 1997; Le Roux *et al.*, 1995
		Nylsvley, South Africa	2	Scholes and Walker, 1994
		Kruger Park, South Africa	4	February and Higgins, 2010
Forest	Trees	St. Lucia, South Africa	2	Clulow *et al.*, 2013
	Trees and Semi-shrubs	Tsitsikamma, South Africa	1	Milne and Haynes, 2004
Thicket	Grasses	Accra Plains, Ghana	1	Okali *et al.*, 1973
	Trees and Forbs	Accra Plains, Ghana	1	Okali *et al.*, 1973
	Trees and Shrubs	Accra Plains, Ghana	1	Okali *et al.*, 1973

*n: number of growth form root profiles sampled from various biomes in various locations

Most case studies provided separate root profiles for the different growth forms analysed. However, some case studies did not distinguish between the roots from different growth forms. These combined root profiles were allocated to clusters with the same growth form grouping and environmental factors, and unless distinctions between growth form compositions were provided in the case study paper or otherwise recognised, were used to derive the ROOTA for both growth forms in question. Considering the Tree: Grass ratio uncertainties in the combined tree-grass root profiles, the tree ROOTA parameters that were based on these combined tree-grass profiles may be somewhat overestimated and grass ROOTA parameters slightly underestimated. However, the magnitude of such methodical error was tested and is too small to influence the overall result, where the weighting of each growth form accounts for the over- and under-estimation by each.

At least one root profile representing the roots of each dominant growth form or a combination of growth forms (i.e. grasses and trees) within the clusters was allocated. Burning regimes were also taken into account when assigning case study root profiles to clusters. For example, root profiles from burnt natural grasslands were assigned to derive ROOTA for grassland clusters which had no tree species. For grassland clusters, the combined tree and grass root profiles sampled from savanna-type ecosystems were used for estimations of tree ROOTA only, as the bias caused by the deeper tree and grass roots typical of savanna conditions results in a ROOTA that is not representative of grass species in grassland ecosystems.

Root profiles differed in the root measurements sampled, where the majority of root profiles were published as absolute root mass per depth interval, others were presented as percentages of total root mass per depth, and a few were estimated in terms of the number of roots per depth. The variability of sampled root profile data was made consistent by computing the cumulative percentage of roots with increasing soil depth for each of the root profiles. In addition to the differences in root measurements, root profiles differed in the number and depth of intervals sampled. The root profiles were thus standardised in this study so that statistical analyses could weight each profile equally. To achieve this, root profiles were interpolated by fitting a non-linear smoothing function to each cumulative root profile. The non-linear model used was a logistic dose-response curve (LDR, equation 3.2), which was previously applied in Schenk and Jackson (2002b) for the interpolations and extrapolations of global root profiles.

$$r(D) = \frac{R_{max}}{[1 + \left(\frac{D}{D_{50}}\right)^{c}]} \qquad (3.2)$$

Where: r(D) : Cumulative percentage of roots (%) above profile depth D (cm)

R_{max} : Total percentage of roots in the profile (%)

D_{50} : Depth (cm) at which r(D) = 50%(R_{max})

C : Dimensionless shape-parameter (shape of the non-linear curve)

Beyond the differences in root measurements and intervals sampled, root profiles also differed in terms of the maximum depth sampled with few sampled to a depth at which no more roots were found. Therefore, most root profiles did not include the entire extent of the root systems, which meant that the distribution of roots presented in such case studies may have differed had the entire root system been sampled. Among the few root profiles that were sampled to a depth at which no further roots were found, the root profiles of similar growth forms still differed in the maximum rooting depths and thus in the distribution of roots across the soil profile, due to differences in conditions and water availability at the geographical location. Sampled root profiles reflect the MAP and use of available water by the roots in the specific catchment, from which the profiles were extracted. Therefore, the data from root profiles are subject to sampling biases which introduce doubt as to the transferability of these results to regions of the clusters where the actual maximum rooting depth may be deeper. The need to translate these root profiles to represent the availability of water in the clusters rather than that in the case study sites was recognised. Thus, the methodology of Schenk and Jackson (2002b) was applied in this study to deal with the uncertainties of maximum rooting depths.

The sampled root profiles were extrapolated to deeper maximum rooting depths to derive the unknown distribution of roots beyond the sampling depth and to determine how the sampled distribution of roots differs when the root profile extends deeper into the soil profile. Contrary to Schenk and Jackson (2002b), the extended depth for restrictions of extrapolations is known for this study. The extrapolations of sampled root profiles in this study were not restricted to abstract depths of either twice the sample depth or to 3 m, but rather were restricted to the EFRDEP for each growth form category in each cluster (as determined in Chapter 3.4.1), as these reflect the water availability in the clusters. There was often more than one root profile allocated to a group of plant growth forms within a cluster. Therefore the selected root profiles were each, independently, extrapolated to the restricted EFRDEP derived for the given growth form in the cluster. Considering the EFRDEP of growth forms varies with MAP, the extrapolation of root profiles to growth form EFRDEP accounts for variations in ROOTA due to the availability of water and the growth form specific use of available water.

The extrapolation of sampled profiles to EFRDEP estimates used the same non-linear LDR model (equation 3.2) that was used for interpolations. The LDR model was fitted to all profiles, constraining R_{max} to 100 % and restricting the maximum rooting depth (D_{max}) to the sampling depth for each profile. For the extrapolations, R_{max} was initially allowed to vary to obtain the best fit. To standardise the sampled root profiles to represent cluster conditions and thus to avoid excessive errors in extrapolations, the maximum depth (D_{max}) was set to the EFRDEP for the growth form that the root profile represented, and the cumulative amount of roots at D_{max} (i.e. at EFRDEP) was set to 100 %.

For the dominant growth forms in the clusters, the extrapolated root profiles could then be assessed to determine at any given depth what the cumulative percentage of roots would be above that depth. Given this, and that the purpose of this study was to derive the percentage of roots in the A-horizon (ROOTA), the depth of the A-horizon (DEPAHO) for each cluster was determined from surfaces of gridded soils information for SA (Schulze, 2007). The DEPAHO estimated for each cluster was used to determine, from the extrapolated root profiles for the growth forms present in that cluster, the cumulative percentage of roots above the depth of the A-horizon (i.e. ROOTA). Often more than one root profile was extrapolated for a single growth form category in a cluster and thus, the mean ROOTA for a growth form was determined from the ROOTA's derived from each extrapolated root profile for a given growth form. Thereafter the growth form specific ROOTA estimates were weighted to obtain the growth-form weighted average ROOTA for the cluster. The weighting of dominant growth forms in clusters was the same as those used for EFRDEP estimations. While the root profiles from case studies were sufficient for estimating monthly ROOTA inputs for the moisture growing season, the monthly ROOTA input parameters to the ACRU Model must consider the seasonal variations in ROOTA, reflecting changes in transpiration due to genetic and environmental factors.

3.3.3 Accounting for seasonal variations in ROOTA

The ROOTA estimated in Chapter 3.2.2 for months in the moisture growing season were used as the starting point for determining seasonal variations in the ROOTA monthly parameters for clusters in the grassland and savanna biomes where frost occurs. The forest and desert biomes do not experience frost conditions hence, monthly ROOTA inputs remained constant throughout the year for clusters in these biomes. The root profiles from case studies that provided seasonal variations in root distributions for regions outside of South Africa (e.g. the Savanna case study in Cote d'Ivoire; Mordelet *et al.*, 1997) could not be used to derive seasonal changes because the seasonality of rainfall differs. The seasonal changes in estimated ROOTA values were thus determined based on climatic factors specific to the clusters' location. Such climatic factors include low winter temperatures (i.e. when temperatures drop to near- or below freezing), frost and reduced availability of water. These factors reflect relative changes in the above-ground biomass of the vegetation in the clusters.

For determining the frost conditions that prevail within each cluster in the grassland and savanna biomes, the start and end dates of frost were determined from gridded surfaces of frost information for South Africa (Schulze, 2005). The start and end dates of frost were used to determine the duration of frost and hence, the duration of plant senescence (i.e. ROOTA = 1). Only frost conditions that exceeded a magnitude of two events were considered. Therefore, the following conditions were used to adjust the estimated growing season ROOTA parameters during the winter months for all grassland clusters and for those savanna clusters that senesce:

- If the first day of frost occurred at the start of the month (e.g. < 10 days into the month) and thus, experienced senescence throughout the entire month, the ROOTA for this month increased to 1 for grasslands and 0.85 for savannas as savanna vegetation is exposed to frost for much shorter durations, if at all, and thus the herbaceous roots senesce for a very short duration before recovering to normal growing season root distributions.
- If the first day of frost occurred in the middle of the month (e.g. 10 – 20 days in the month) and thus, plants were exposed to frost for only half the month and roots would only become completely dormant by the following month, the ROOTA for this month increased to 0.98 for grasslands and 0.83 for savannas. This input value to the model implies that there is still some transpiration occurring from the subsoil horizons as the roots have not yet moved completely into the A-horizon. The month following this month was increased to 1 for grasslands and 0.85 for savannas.
- If the first day of frost occurred near the end of the month (e.g. < 10 days to the end of the month/ > 20 days into the month) and thus, experienced only a few days of senescence, the ROOTA for this month was increased to 0.95 for grasslands and 0.80 for savannas. The month following this month was increased to 1 for grasslands and 0.85 for savannas.

- If the last day of frost occurred at the end of the month (e.g. < 10 days to the end of the month/ > 20 days into the month) and thus, continued to be in senescence for the entire month, the ROOTA for this month was the last monthly input that was increased to 1 for grasslands and 0.85 for savannas.
- If the last day of frost occurred in the middle of the month (e.g. 10 – 20 days in the month) and thus, roots remained dormant for the most part of the month slowly recovering to normal growing season root distributions closer to the end of the month the ROOTA for this month was increased to 0.98 for grasslands and 0.83 for savannas. The ROOTA of the month preceding this month was the last monthly input increased to 1 for grasslands and 0.85 for savannas.
- If the last day of frost occurred at the start of the month (e.g. < 10 days into the month) and thus experienced the lasting effects of senescence for a short period at the start of the month before recovering to normal growing season conditions, the ROOTA of this month was increased to 0.95 for grasslands and 0.80 for savannas. The ROOTA for the month preceding this month was the last monthly input increased to 1 for grasslands and 0.85 for savannas.

3.4 Results

The EFRDEP estimates are presented first, followed by the ROOTA estimates from extrapolated root profiles and lastly the seasonal variations in ROOTA estimates for the grassland and savanna clusters are presented.

3.4.1 Growth form weighted EFRDEP estimates for Clusters

The median EFRDEP estimates for all individual growth forms that were calculated using the linear regression equation (Equation 3.1) varied across the four biomes (Table 3.4) and clusters (Table 3.5 – 3.8), due to differences in MAP. The median EFRDEP estimates for all growth forms (Table 3.4) were deepest in the forest biome, which had the highest MAP (Table 3.7), and shallowest in the desert biome, which had the lowest MAP (Table 3.8). The median EFRDEP estimates across all biomes were deepest for shrubs and shallowest for annuals. The overall median EFRDEP estimates for all growth forms except annuals were most heavily influenced by the grassland and savanna biomes as these have the largest number of clusters

(Table 3.4). The desert biome was the only one that had the presence of annual forbs in its clusters and thus, the overall median EFRDEP estimates for annuals was directly attributed to the annuals in the desert biome.

Table 3.4: Medians for growth form-specific EFRDEP (cm) estimates.

	All biomes		**Grassland**		**Savanna**		**Forest**		**Desert**	
	n*	Median EFRDEP	n*	Median EFRDEP	n*	Median EFRDEP	n*	Median EFRDEP	n*	Median EFRDEP
Shrubs	51	246	20	247	24	242	4	262	3	174
Semi-shrubs	17	154	4	156	8	152	3	164	2	101
Forbs	33	150	19	155	9	131	4	187	1	37
Grasses	55	125	22	128	25	120	4	146	4	51
Annuals	1	16							1	16

*n: number of cluster EFRDEP estimates contributing to median EFRDEP for growth forms

The EFRDEP estimated for the dominant growth forms in each cluster, as well as the growth form weighted EFRDEP for each cluster, is demonstrated for four of the grassland clusters (Table 3.5) and for four of the savanna clusters (Table 3.6). The remaining growth form weighted EFRDEP estimates for the grassland and savanna clusters are given in the Appendix (Table A3.1). Given that there were only four forest and four desert clusters, the EFRDEP estimates for the dominant growth forms in each cluster in the forest and desert biomes, and for the clusters, are given in Tables 3.7 and 3.8, respectively.

EFRDEP estimates for grassland clusters

All EFRDEP estimates for the 22 grassland clusters were shallower than 200 cm (Table 3.5; Table A3.1 in the Appendix), with the majority deeper than 130 cm. The four grassland clusters selected as examples (Table 3.5) to represent the range of grassland EFRDEP estimates (Table A3.1 of the Appendix) include Gr_5 and Gr_6, which experience typical rainfall conditions for a grassland catchment (e.g. MAP = 600 – 800 mm) and Gr_7 and Gr_10, which experience extremes on either end of the MAP range of 1136 mm and 400 mm, respectively. In general, deeper EFRDEP estimates were observed for clusters in higher rainfall regions, e.g. Gr_7 with the highest MAP of 1136 mm had the deepest EFRDEP of 198 cm.

Table 3.5: EFRDEP estimates for dominant growth forms in grassland clusters and the subsequent growth form weighted EFRDEP for grassland clusters.

Cluster code	MAP (mm)	Dominant Growth Forms*	No. of Dominant Species (n)	Growth Form Weighting (%)	Growth form EFRDEP (cm)	Cluster EFRDEP (cm)
Gr_5	704	Forbs	1	7	154	**131**
		Grasses	14	93	129	
		Total	15	100		
Gr_6	609	Trees	3	17	300	**180**
		Shrubs	4	22	244	
		Forbs	1	6	141	
		Grasses	10	56	122	
		Total	18	100		
Gr_7	1136	Trees	1	3	300	**198**
		Shrubs	6	19	269	
		Forbs	9	29	208	
		Grasses	15	48	157	
		Total	31	100		
Gr_10	400	Shrubs	22	26	228	**134**
		Forbs	4	5	108	
		Grasses	58	68	103	
		Succulents	1	1	25	
		Total	85	100		

*Trees: tall trees and small trees; Shrubs: tall shrubs, low shrubs and woody climbers; Semi-shrubs: succulent shrubs; Forbs: herbs, geophytic herbs, herbaceous climber and succulent herbs; Grasses: graminoids; Succulents: succulent trees.

The EFRDEP of the two grassland clusters, Gr_5 and Gr_6, that shared similar rainfall properties, differed only due to differences in dominant growth form composition. Gr_6 has a deeper EFRDEP despite being slightly drier, due to the higher dominance of woody species (i.e. trees and shrubs) characteristic of deep roots whereas Gr_ 5 has only herbaceous species (i.e. forbs and grasses) characteristic of shallow roots. Similarly, the lowest rainfall grassland cluster, Gr_10, has a slightly deeper EFRDEP than Gr_ 5, despite being 304 mm drier, due to the dominance of deeper rooting shrubs, whereas Gr_5 has no shrubs and a dominance of shallow rooting grasses. Besides MAP, the dominance of deep rooting trees and shrubs has a significant impact on the EFRDEP, for example, the highest rainfall grassland cluster, Gr_7, has only a slightly deeper EFRDEP than Gr_6 despite being 527 mm wetter, due to the higher dominance of deep rooting trees and shrubs in Gr_6.

Gr_9 was the only grassland cluster to vary beyond this, with an EFRDEP of 52 cm due to the cluster's high altitude (e.g. of 3052 m.a.s.l) and associated low temperatures (Mucina *et al.*, 2006), high frost frequency and prolonged senescence for more than half the year (from March to December), including occasionally in summer (Mucina *et al.*, 2006). The EFRDEP for the dominant shrubs and grasses in Gr_9 were set to values of 60 cm (A-horizon depth + B-horizon depth) and 20 cm (equivalent to the A-horizon depth), respectively because the high MAP included in the linear regression equation and the high dominance of shrubs would have resulted in an unrealistic overestimation of EFRDEP. The weighting of these two growth form specific EFRDEP values resulted in the 52 cm for the cluster.

EFRDEP estimates for savanna clusters

In general, the savanna clusters are expected to have deeper EFRDEP estimates than the grassland clusters because of the higher dominance of deeper rooting woody species generally associated with savannas, as compared to the grasslands. The majority of EFRDEP estimates for the 25 savanna clusters were within the range of 200 - 245 cm. However, the few that were characterised by either: (a) a MAP < 500 mm; (b) dominance of succulent tree species with very shallow rooting depths; (c) dominance of grass species markedly greater than the tree species; or (d) a combination of two or more of these three conditions had EFRDEPs shallower than 200 cm. The four savanna clusters selected as examples (Table 3.6) to represent the major patterns observed among the range of savanna EFRDEP estimates (Table A3.1 of the Appendix) include two savanna clusters, Sa_1 and Sa_2, that experience typical rainfall conditions for savanna catchments (e.g. MAP = 500 – 600 mm) and two savanna clusters, Sa_5 and Sa_10, that experience extremes on either end of the MAP range of 870 mm and 183 mm, respectively. The wettest savanna cluster, Sa_5, does not have the deepest EFRDEP, due to the grass species (60%) being more dominant than the woody species (40%), resulting in a shallower EFRDEP (Table 3.6). The driest savanna cluster, Sa_10, has an equal dominance of woody species to herbaceous species (50% : 50%) thus, the shallow EFRDEP of this cluster is directly attributed to the low rainfall. Sa_2, despite a slightly higher rainfall (29 mm higher) than Sa_1, has a shallower EFRDEP, due to the dominance of shallow rooting succulents and grasses in Sa_2. Sa_1, despite having average rainfall conditions, has the deepest EFRDEP out of all the savanna clusters, which is linked directly to the higher dominance of deep rooted woody species (trees + shrubs = 76 %), the relatively low dominance of herbaceous grass species (24 %) and the absence of succulent species characterised by even shallower roots.

Table 3.6: EFRDEP estimates for dominant growth forms in savanna clusters and the subsequent growth form weighted EFRDEP for savanna clusters.

Cluster code	MAP (mm)	Dominant Growth Forms*	No. of Dominant Species (n)	Growth Form Weighting (%)	Growth form EFRDEP (cm)	Cluster EFRDEP (cm)
Sa_1	572	Trees	28	56	300	**245**
		Shrubs	10	20	241	
		Grasses	12	24	119	
		Total	50	100		
Sa_2	601	Trees	18	39	300	**210**
		Shrubs	8	17	243	
		Grasses	19	41	121	
		Succulents	1	2	25	
		Total	46	100		
Sa_5	870	Trees	7	35	300	**202**
		Shrubs	1	5	258	
		Grasses	12	60	141	
		Total	20	100		
Sa_10	183	Trees	5	21	300	**158**
		Shrubs	7	29	202	
		Forbs	1	4	66	
		Grasses	11	46	75	
		Total	24	100		

*Trees: tall trees and small trees; Shrubs: tall shrubs, low shrubs and woody climbers; Semi-shrubs: soft shrubs, geoxylic suffrutex shrubs, succulent shrubs and woody succulent climbers; Forbs: herbs, geophytic herbs, herbaceous climber, succulent herbs and megaherbs; Grasses: graminoids; Succulents: succulent trees.

EFRDEP estimates for forest clusters

The forest clusters have the highest weighting of tree species characteristic of deep roots, thus the deepest EFRDEP estimates. The relationship between MAP and EFRDEP is strong and positive in water limited ecosystems for all plant growth forms except trees and shrubs (Schenk and Jackson, 2002a), thus an EFRDEP of 3 m was assigned to all tree species. Given this, and that tree roots are heavily, and similarly weighted (60 – 66 %) in all four forest clusters, the constant tree EFRDEP of 3 m causes a smoothing effect thus, the growth form weighted EFRDEPs of the forest clusters do not differ extensively, ranging from 248 to 269 cm (Table 3.7).

Table 3.7: EFRDEP estimates for dominant growth forms in forest clusters and the subsequent growth form weighted EFRDEP for forest clusters.

Cluster code	**MAP (mm)**	**Dominant Growth Forms***	**No. of Dominant Species (n)**	**Growth Form Weighting (%)**	**Growth Form EFRDEP (cm)**	**Cluster EFRDEP (cm)**
Fo_1	942	Trees	49	64	300	**264**
		Shrubs	8	11	261	
		Semi-shrubs	3	4	163	
		Forbs	12	16	185	
		Grasses	4	5	146	
		Total	76	100		
Fo_2	965	Trees	61	66	300	**269**
		Shrubs	13	14	262	
		Semi-shrubs	3	3	164	
		Forbs	8	9	188	
		Grasses	7	8	147	
		Total	92	100		
Fo_3	1007	Trees	40	65	300	**268**
		Shrubs	7	11	264	
		Semi-shrubs	1	2	165	
		Forbs	11	18	193	
		Grasses	3	5	150	
		Total	62	100		
Fo_4	650	Trees	18	60	300	**248**
		Shrubs	4	13	246	
		Forbs	3	10	147	
		Grasses	5	17	125	
		Total	30	100		

*Trees: tall trees, small trees and tree ferns; Shrubs: tall shrubs, low shrubs and woody climbers; Semi-shrubs: soft shrubs; Forbs: herbs, geophytic herbs, herbaceous climber, succulent herbs and megaherbs; Grasses: graminoids and climbing graminoids.

The two forest clusters with the highest rainfall, Fo_2 and Fo_3, have the deepest EFRDEPs of 269 cm and 268 cm, respectively. Despite Fo_2 having a lower MAP than Fo_3, the EFRDEP is similar, due to the higher dominance of woody species and lower dominance of herbaceous forb species. Although Fo_4 receives 300 mm less rainfall per annum, the EFRDEP is still similar to that of the other three forest clusters, because of the similar heavy weighting of tree species with constant EFRDEPs of 3 m. None of the forest clusters had the presence of stem succulent species thus, the EFRDEP of these clusters were not influenced by shallow rooting succulents, as within other biomes.

EFRDEP estimates for desert clusters

All EFRDEP estimates for the four desert clusters are shallower than 91 cm driven by the low MAP across these clusters, with the shallowest EFRDEP of 55 cm estimated for De_2 (Table 3.8). The absence of deep rooting tree species and the relatively low dominance of deep rooting shrub species in all four desert clusters also contributes to the shallow EFRDEP estimates. Additionally, the high dominance of stem succulent species with shallow root systems, as well as the presence of annual forbs, in these desert clusters further account for the shallow growth form weighted EFRDEP estimates. De_1 has the deepest EFRDEP out of the four clusters due to the higher dominance of deeper rooting semi-shrub species (82 %) and the associated lower abundance of shallower rooting grasses and succulents (18 %). Despite the absence of semi-shrubs in De_4, the EFRDEP for this this cluster was similar to De_2 and De_3 due to the slightly higher MAP of De_4.

Table 3.8: EFRDEP estimates for dominant growth forms in desert clusters and the subsequent growth form weighted EFRDEP for desert clusters.

Cluster code	**MAP (mm)**	**Dominant Growth Forms**	**No. of Dominant Species (n)**	**Growth Form Weighting (%)**	**Growth Form EFRDEP (cm)**	**Cluster EFRDEP (cm)**
De_1	70	Semi-shrubs	9	82	103	**91**
		Grasses	1	9	50	
		Succulents	1	9	25	
		Total	11	100		
De_2	73	Shrubs	2	10	174	**55**
		Semi-shrubs	3	14	104	
		Forbs	1	5	37	
		Grasses	4	19	51	
		Succulents	9	43	25	
		Annuals	2	10	16	
		Total	21	100		
De_3	54	Shrubs	2	14	166	**65**
		Semi-shrubs	3	21	98	
		Grasses	3	21	45	
		Succulents	6	43	25	
		Total	14	100		
De_4	77	Shrubs	1	17	176	**59**
		Grasses	2	33	52	
		Succulents	3	50	25	
		Total	6	100		

*Shrubs: other shrubs; Semi-shrubs: leaf-succulent shrubs; Forbs: succulent herbs; Grasses: graminoids; Succulents: succulent trees, stem- and leaf-succulent shrubs, stem-succulent shrubs; Annuals: annual herbs.

3.4.2 Growth Form Weighted ROOTA Estimates for Clusters

The dominant growth forms in each cluster were allocated root profiles. Although the ideal would have been to have a root profile from the same location as the cluster, in most cases there was no case study available for the exact location of the cluster. Thus, such clusters were allocated root profiles based on similarities in location, MAP, altitude, burning regime and, most importantly, dominant species. For most of the growth forms in the clusters, more than one root profile was allocated. Given that the ROOTA estimates were largely dependent on the root profile information used for each cluster, using more than one root profile for a single growth form ROOTA estimate in a cluster ensures that the full extent of available information was used for these estimations. Therefore, the ROOTA of some clusters are characterised by a higher level of confidence than others due to the greater number of published root profiles for some growth forms as opposed to the very limited number for others. The number of root profiles assigned to each dominant growth form in the clusters ($n^{\#}$) is indicated in Tables 3.9 – 3.12, using four clusters in each of the four biomes as examples.

The root profiles allocated to each dominant growth form in a cluster were extrapolated to the EFRDEP of the specific growth form in the cluster to make the root profiles representative of the deeper rooting depths in clusters compared to the shallower sampled depths. Using the extrapolated root profiles together with the cluster's A-horizon depth, the growth form ROOTAs were derived. The growth form ROOTAs derived from the various root profiles were combined to determine the mean growth form ROOTA, which were weighted according to the dominance of growth forms in the clusters to determine the mean cluster ROOTA (Table 3.9 – 3.12). The ROOTA estimates for the clusters differed due to differences in MAP, dominant species compositions and depths of the A-horizons (Table 3.9 - 3.12; Table A3.1 of the Appendix). The extent to which these factors determined the variability of ROOTA estimates was dependent on the properties of the root profiles selected to represent each growth form. Given that a deeper EFRDEP would result in a greater vertical area covered by the fine roots, increasing the sampled rooting depths of the profiles to represent cluster roots resulted in a lower fraction of roots in the A-horizon. Therefore, growth forms with deeper EFRDEPs (such as trees and shrubs) generally had lower ROOTA estimates. Hence, clusters having a greater dominance of these deeper rooting trees and shrubs had a lower ROOTA than clusters having a greater dominance of shallower rooting grasses and forbs.

ROOTA estimates for grassland clusters

Gr_1 had the highest ROOTA estimate out of the four grassland clusters presented (Table 3.9), due to the high dominance of grass species, the absence of tree species and a relatively low dominance of shrubs. Gr_12 had the lowest ROOTA estimate out of the four clusters (Table 3.9), due to the high dominance of deep rooting trees and shrubs as well as the shallow depth of the A-horizon.

Table 3.9: ROOTA estimates for grassland clusters based on the mean of extrapolated root profiles for each growth form category.

Cluster code	**A-horizon (cm)**	**MAP (mm)**	**Dominant Growth forms***	**No. of dominant species (n)**	**Growth form Weighting (%)**	**n#**	**Growth form ROOTA (%)** ***(mean of root profiles)***	**Cluster ROOTA (%)**
Gr_1	29	633	Shrubs	1	11	1	86	**86**
			Grasses	8	89	5	87	
			Total	9	100	6		
Gr_7	28	1136	Trees	1	3	1	76	**83**
			Shrubs	6	19	2	76	
			Forbs	9	29	1	89	
			Grasses	15	48	3	84	
			Total	31	100	7		
Gr_12	24	583	Trees	3	10	3	80	**71**
			Shrubs	7	24	1	50	
			Forbs	1	3	1	65	
			Grasses	18	62	5	78	
			Total	15	100	10		
Gr_13	27	462	Trees	1	5	3	72	**81**
			Shrubs	5	24	2	69	
			Grasses	15	71	4	85	
			Total	21	100	9		

*Trees: tall trees and small trees; Shrubs: tall shrubs, low shrubs and woody climbers; Semi-shrubs: succulent shrubs; Forbs: herbs, geophytic herbs, herbaceous climber and succulent herbs; Grasses: graminoids; Succulents: succulent trees.

#Number of root profiles allocated to each dominant growth form in each cluster.

ROOTA estimates for savanna clusters

The two savanna clusters with the presence of shallow rooted succulent stem species, i.e. Sa_3 and Sa_4, had the highest ROOTA out of the four savanna clusters (Table 3.10). Sa_5 had a slightly lower ROOTA than Sa_1, despite having a higher dominance of shallow-rooting grass species, due to the shallower depth of the A-horizon for Sa_5.

Table 3.10 ROOTA estimates for savanna clusters based on the mean of extrapolated root profiles for each growth form category.

Cluster code	A-horizon (cm)	MAP (mm)	Dominant Growth forms*	No. of dominant species (n)	Growth form Weighting (%)	n[#]	Growth form ROOTA (%) *(mean of root profiles)*	Cluster ROOTA (%)
Sa_1	28	572	Trees	28	56	5	50	**61**
			Shrubs	10	20	2	65	
			Grasses	12	24	4	83	
			Total	50	100	11		
Sa_3	30	868	Trees	17	43	4	79	**78**
			Shrubs	6	15	1	60	
			Forbs	2	5	1	35	
			Grasses	14	35	5	89	
			Succulents	1	3	0	100	
			Total	40	100	11		
Sa_4	28	584	Trees	20	29	6	63	**66**
			Shrubs	17	25	1	57	
			Semi-shrubs	6	9	1	75	
			Forbs	6	9	2	43	
			Grasses	16	24	2	77	
			Succulents	3	4	0	100	
			Total	68	100	12		
Sa_5	26	870	Trees	7	35	1	42	**59**
			Shrubs	1	5	1	83	
			Grasses	12	60	2	66	
			Total	20	100	4		

*Trees: tall trees and small trees; Shrubs: tall shrubs, low shrubs and woody climbers; Semi-shrubs: soft shrubs, geoxylic suffrutex shrubs, succulent shrubs and woody succulent climbers; Forbs: herbs, geophytic herbs, herbaceous climber, succulent herbs and megaherbs; Grasses: graminoids; Succulents: succulent trees.

[#] Number of root profiles allocated to each dominant growth form in each cluster.

ROOTA estimates for forest clusters

Fo_3 had a higher ROOTA estimate than Fo_1, despite having similar MAP and the same A-horizon depths, due to the specific swamp forest root profiles that were allocated to the tree species in Fo_3 (Table 3.11). The ROOTA estimated for Fo_3 was thus directly linked to the properties of the root profiles. Despite Fo_2 having a similar MAP to Fo_1 and a similar A-horizon depth and high tree dominance to the other three forest clusters, the ROOTA of Fo_2 is lower. This can be explained by the tree root profile from the centre of a dense closed canopy thicket that was allocated to the trees in Fo_2 based on similarities in vegetation composition. Fo_2 is made up of afrotemperate and mistbelt forest vegetation units and there were no published root profiles available for these types of forests.

Table 3.11 ROOTA estimates for forest clusters based on the mean of extrapolated root profiles for each growth form category.

Cluster code	**A-horizon (cm)**	**MAP (mm)**	**Dominant Growth forms***	**No. of dominant species (n)**	**Growth form Weighting (%)**	**n#**	**Growth form ROOTA (%) *(mean of root profiles)***	**Cluster ROOTA (%)**
Fo_1	28	942	Trees	49	64	2	87	**78**
			Shrubs	8	11	1	56	
			Semi-shrubs	3	4	1	75	
			Forbs	12	16	1	54	
			Grasses	4	5	2	84	
			Total	76	100	7		
Fo_2	29	965	Trees	61	66	1	56	**62**
			Shrubs	13	14	1	58	
			Semi-shrubs	3	3	1	69	
			Forbs	8	9	1	89	
			Grasses	7	8	1	89	
			Total	92	100	5		
Fo_3	28	1007	Trees	40	65	2	94	**84**
			Shrubs	7	11	1	57	
			Semi-shrubs	1	2	1	67	
			Forbs	11	18	1	70	
			Grasses	3	5	1	70	
			Total	62	100	6		
Fo_4	29	650	Trees	18	60	4	82	**77**
			Shrubs	4	13	1	58	
			Forbs	3	10	1	89	
			Grasses	5	17	2	67	
			Total	30	100	8		

*Trees: tall trees, small trees and tree ferns; Shrubs: tall shrubs, low shrubs and woody climbers; Semi-shrubs: soft shrubs; Forbs: herbs, geophytic herbs, herbaceous climber, succulent herbs and megaherbs; Grasses: graminoids and climbing graminoids.

#Number of root profiles allocated to each dominant growth form in each cluster.

ROOTA estimates for desert clusters

De_1 had the lowest ROOTA estimate out of the four clusters due to the heavy weighting of semi-shrubs which are characteristically deeper rooting than the grass and succulent species (Table 3.12). De_4 had the highest ROOTA estimate as grass and succulent species (characteristically shallow-rooting) were the most heavily weighted in this cluster.

Table 3.12 ROOTA estimates for desert clusters based on the mean of extrapolated root profiles for each growth form category.

Cluster code	**A-horizon (cm)**	**MAP (mm)**	**Dominant Growth forms***	**No. of dominant species (n)**	**Growth form Weighting (%)**	**n#**	**Growth form ROOTA (%) *(mean of root profiles)***	**Cluster ROOTA (%)**
De_1	26	70	Semi-shrubs	9	82	1	63	**66**
			Grasses	1	9	1	59	
			Succulents	1	9	0	100	
			Total	11	100	2		
De_2	27	73	Shrubs	2	10	1	83	**88**
			Semi-shrubs	3	14	1	65	
			Forbs	1	5	1	55	
			Grasses	4	19	1	80	
			Succulents	9	43	0	100	
			Annuals	2	10	0	100	
			Total	21	100	4		
De_3	25	54	Shrubs	2	14	1	81	**84**
			Semi-shrubs	3	21	1	61	
			Grasses	3	21	1	77	
			Succulents	6	43	0	100	
			Total	14	100	3		
De_4	26	77	Shrubs	1	17	1	82	**90**
			Grasses	2	33	1	79	
			Succulents	3	50	0	100	
			Total	6	100	2		

*Shrubs: other shrubs; Semi-shrubs: leaf-succulent shrubs; Forbs: succulent herbs; Grasses: graminoids; Succulents: succulent trees, stem- and leaf-succulent shrubs, stem-succulent shrubs; Annuals: annual herbs.

#Number of root profiles allocated to each dominant growth form in each cluster.

3.4.3 Seasonal variations in monthly ROOTA estimates for grassland and savanna clusters

All 22 grassland clusters, and 19 of the 25 savanna clusters, received frost for durations within the requirements outlined in Section 3.3.3. The monthly ROOTA estimates for these frost-affected clusters, which are assumed to undergo senescence during these periods, were increased. These increases were according to the rules specified in Section 3.3.3, to either 1 to designate no transpiration, or to a lower ROOTA than 1 which implies a reduction in transpiration but to a lesser extent. Five grassland and three savanna clusters are given as examples in Table 3.13 to highlight the common patterns observed for the range of seasonal variations in monthly ROOTAs for the 22 grassland and 25 savanna clusters (Table A3.1 in Appendix).

Table 3.13: Selected examples to illustrate the monthly patterns of seasonal variations in ROOTA for grassland and savanna clusters under varying frost conditions

Cluster	Growing Season ROOTA	1st frost	last frost	Jan	Feb	Mar	Apr	May	Jun	Jul	Aug	Sep	Oct	Nov	Dec
Gr_11	0.82	18 May	7 Sep	0.82	0.82	0.82	0.82	0.98	1.00	1.00	1.00	0.95	0.82	0.82	0.82
Gr_7	0.83	4 May	3 Oct	0.83	0.83	0.83	0.83	1.00	1.00	1.00	1.00	1.00	0.95	0.83	0.83
Gr_21	0.82	11 Jun	1 Aug	0.82	0.82	0.82	0.82	0.82	0.98	1.00	0.95	0.82	0.82	0.82	0.82
Gr_18	0.79	21 Jun	11 Jul	0.79	0.79	0.79	0.79	0.79	0.95	0.98	0.79	0.79	0.79	0.79	0.79
Gr_9	0.90	23 Feb	26 Dec	0.90	0.90	0.95	1.00	1.00	1.00	1.00	1.00	1.00	1.00	0.95	0.90
Sa_7	0.67	27 Jun	27 Jun	0.67	0.67	0.67	0.67	0.67	0.67	0.67	0.67	0.67	0.67	0.67	0.67
Sa_4	0.66	21 Jun	12 Jul	0.66	0.66	0.66	0.66	0.66	0.80	0.83	0.66	0.66	0.66	0.66	0.66
Sa_12	0.71	22 May	6 Sep	0.71	0.71	0.71	0.71	0.80	0.85	0.85	0.85	0.80	0.71	0.71	0.71

The ROOTA estimates for most of the grassland clusters were increased to 1 for the winter months (June to August), as illustrated through the examples included in Table 3.13. Some grassland clusters, e.g. Gr_7, experience a longer frost season, while other grassland clusters only experience frost for one month of the year but nonetheless, a sufficient length of frost conditions to have an effect on transpiration (e.g. Gr_21). On the other hand, some grassland clusters, e.g. Gr_18 (Table 3.13), only experienced frost for half a month, or less. For these clusters, it is assumed that the plants in these clusters do not senesce long enough for transpiration to cease completely. Therefore, the ROOTA for these clusters were slightly increased to demonstrate the partial effect on transpiration, but was never increased to 1.

The only grassland clusters to vary beyond this was Gr_9, for which the Drakensberg Afroalpine Heathland is the only SANBI (2012) vegetation unit included. With the frequent occurrence of low temperatures (< 0^oC) throughout the year for this vegetation unit, frost can occur for more than half the year, including occasionally in summer (Mucina *et al.*, 2006). A detailed account of this vegetation unit and the conditions specific to its growth is provided by Robinson (2014). Based on expert consultation, the growing season for Gr_9 was assumed to be from November to March, with the occurrence of frost for more than half the year (April – October). The plants in this cluster, although slightly adapted to freezing temperatures, are assumed to undergo senescence throughout these six months. Given the shallow EFRDEP for Gr_9 of 52 cm (Appendix A3.1), together with the lack of root profiles to sufficiently represent the unique vegetation in Gr_9, the ROOTAs for the growing season were set to 0.95 for November and March, and 0.90 for December – February. During the months April – October the ROOTA was set to 1 (Table 3.13). Besides Gr_9, the ROOTA estimates for all grassland clusters for the growing season, summer months (November - March) remained unchanged.

Sa_8 was the only savanna cluster to not receive any frost throughout the year. As outlined in Section 3.3.3, a total of > 2 frost events was required for any increases to ROOTA, and > 1 month frost season duration required for ROOTA to increase to 1. Six savanna clusters did not meet the frost criteria of > 2 frost events, e.g. Sa_7 (Table 3.13), thus their ROOTAs remained unchanged. Six savanna clusters, e.g. Sa_4, had > 2 frost events, but the frost season duration was < 1 month, thus the ROOTA only increased to 0.80 and 0.83 for the months that received frost for longer and shorter periods, respectively, according to the rules outlined in Section 3.3.3. Five savanna clusters, e.g. Sa_12, experienced the longest frost season duration of the savanna clusters, resulting in the ROOTA being set to 0.85 for three months.

3.5 Discussion

With the limited availability of root measurements for total rooting depth and distribution in the topsoil horizon, and the challenges presented for field-based measurements, the root-specific below-ground ACRU Model parameters, EFRDEP and ROOTA, were derived using existing root information from previous studies together with physical cluster characteristics in various regression relationships. There are numerous factors that determine, either directly or indirectly, the root-specific below-ground parameters. Some of these factors include the availability of water (e.g. MAP), the above-ground vegetation biomass and structure, the soil properties and altitudinal factors such as frost. These factors cannot be considered on their own, as they are all intrinsically related to each other and the feedbacks and feedforwards between them co-determine the mass and distribution of roots. Therefore, the estimation of root parameters in this study, e.g. EFRDEP and ROOTA, were based on comprehensively accounting for all these factors in a repeatable methodology.

With the 128 clusters proposed as a new hydrological baseline land cover to be used by the DWS in South Africa, against which to assess land use impacts and particularly SFRAs of commercial forestry (Schulze, 2004a; Jewitt *et al.*, 2009) and to possibly reconsider candidate SFRA land uses such as sugarcane, the estimated ROOTA and EFRDEP parameters, as well as the repeatable methodology, derived in this study for the clusters in the grassland, savanna, forest and desert biomes, will contribute to the parameterisation of this improved and revised hydrological baseline. The ACRU Model is the hydrological model used in the SFRA Assessment Utility Tool (Jewitt *et al.*, 2009) thus, the improved parameterisation of the below-ground root parameters will contribute to improved ACRU Model simulations, and hence improved SFRA assessments. Although the root parameters in this study were derived for input to the ACRU Model and were based on the ACRU Model requirements, these parameters and/or the repeatable methodology developed to derive them, may be transferrable across space and time and may be applied and adapted in other similar hydrological models. The repeatable methodology, although developed for and applied to estimate root parameters for the four most commonly transformed natural vegetation types (grassland, savanna, forest and desert), is transferrable across regions and thus may be repeated in future analyses for the remaining biomes across South Africa, as well as for biomes in other regions of the world. Furthermore, as additional root measurements become available the root parameter estimates can be improved using the repeatable methodology.

The major determinant of root system dimensions and hence, the major factor influencing the estimations of root parameters in this study, are MAP and the plant’s demand for, and the availability of, soil water (Raz-Yaseef *et al.*, 2013). Therefore, fine roots which are responsible for water uptake, explore the spatial extent of the soil profile to reach depths that are sufficient for the provision of resource requirements (Schenk and Jackson, 2002a), within the constraints of the available soil water. Using MAP in the linear regression equation to estimate EFRDEP for specific growth forms, and using the MAP-influenced EFRDEP estimates to relate root profile distributions to cluster ROOTA for specific growth forms, ensured that these estimates not only reflect variability in root measurements due to the availability of water but also the use of available water by the roots of specific growth forms. The use of regression parameters derived for various growth form types (Schenk and Jackson, 2002a) ensured that the variability of root systems with MAP was specific to growth form types.

Within clusters, where the MAP is constant, variations between growth form EFRDEPs were due to differences in growth form regression parameters. Between clusters in a given biome, as well as between the four biomes, variations between the EFRDEPs for a single growth form, where the growth form parameters were constant, were due to differences in MAP. An increase in growth form EFRDEP was observed with an increase in MAP, which was in agreement with Holdo *et al.* (2018) who identified a strong and positive relationship between rooting depths and MAP for grasses and trees in an African Savanna. Between clusters in a given biome, variations in growth-form-weighted EFRDEP were due to differences in MAP, growth form regression parameters, as well as the weighting of dominant growth forms in the clusters. Comparing cluster EFRDEP estimates is more complicated than comparing growth form EFRDEP because the role of MAP becomes blurred as the variable dominance of plant growth forms plays a part too. For instance, clusters having similar MAP had contrasting EFRDEP estimates due to differences in dominance of plant growth forms. In clusters where the response of EFRDEP with MAP is less obvious or non-existent, the EFRDEP was governed by the vegetation composition and not the MAP.

The ranges of EFRDEP and ROOTA estimations between clusters within a biome varied substantially from those in other biomes. Clusters in the desert biome had the shallowest EFRDEP estimates and the deepest ROOTA estimates. Given the response of EFRDEP with MAP, the low EFRDEP estimates for the four low rainfall desert clusters (Table 3.8) confirm the shallow rooting depths that would be expected from such desert biomes characterised by markedly low rainfall. Clusters in the forest biome, which had the highest weighting of trees with the deepest EFRDEP of all the growth forms (i.e. EFRDEP = 300 cm), had the deepest EFRDEP estimates. However, the ROOTA for the clusters in the forest biome, bar Fo_2, were generally higher than in the savanna biome due to the mangrove and swamp type tree (characteristic of high ROOTAs) root profiles that were allocated to derive the ROOTA for the tree growth forms in the forest biome. The clusters in the savanna biome had the lowest ROOTA estimates due to the deep roots and high distribution of roots deeper in the soil profile associated with savanna vegetation, which was accounted for by the savanna case study root profiles allocated to the savanna clusters.

The median EFRDEP for perennial grasses in all clusters across the four biomes was 125 cm (Table 3.4) which corresponds with the median maximum rooting depth sampled, i.e. 90 cm, for the 15 perennial grass root profiles (Snyman, 2005, 2009a, 2009b; McNaughton *et al.*, 1998; Mordelet *et al.*, 1997; Le Roux *et al.* 1995; Scholes and Walker; 1993; February and Higgins; 2010; Okali *et al.* 1973) that were used for ROOTA estimations. The median maximum rooting depth of the case study root profiles were sampled from a range of grassland and savanna sites in African regions including sites in Tanzania (MAP 350 – 1200 mm; McNaughton *et al.*, 1998), Cote d'Ivoire (MAP 1200 mm; Mordelet *et al.*, 1997; Le Roux *et al.* 1995), Ghana (MAP 750 mm; Okali *et al.* 1973) and South Africa (MAP 547 – 737 mm; Snyman, 2005, 2009a, 2009b; Scholes and Walker; 1993; February and Higgins; 2010). The higher EFRDEP for the grasses in the clusters compared to the median rooting depth from the sampled root profiles may be due to the higher MAP of South African grassland clusters (MAP 400 – 1200 mm) and hence the generally deeper EFRDEP for grass species in grasslands which weight the overall median EFRDEP estimate for clusters quite heavily. Alternatively the lower median rooting depth for the root profiles may be due to the fact that some of the root profiles were not sampled to a depth at which no further roots were found. Hence, further emphasizing the need to extrapolate the root profiles to the EFRDEPs of the clusters.

Although EFRDEPs, A-horizon soil depths and growth form weighting of the clusters played an important role, the major and primary determinant of ROOTA estimates was the number and selection of published root profiles allocated to the dominant growth forms in the clusters. The use of field-based root distribution measurements from previous studies for natural ecosystems in Africa ensured that the clusters' ROOTA estimates were realistic and representative of root measurements for African-specific vegetation and climate. Therefore, those clusters that were allocated a larger number of root profiles have ROOTAs that are more realistic and representative of actual cluster conditions, as they are characterised by a higher level of confidence. The root profiles were difficult to allocate across all biomes except for the savanna biome as a high percentage of previous studies have been undertaken for a number of growth forms in a wide range of savannas in South Africa (e.g. Scholes and Walker, 1993; February and Higgins, 2010; Milne and Haynes; 2004; Knoop and Walker 1985; Smit and Rethman; 1998) and in other African regions (e.g. Mordelet *et al.*, 1997; Le Roux *et al.* 1995; Belsky; 1994; Lawson *et al.* 1970). Grasslands have been relatively well researched in South Africa but the focus has only been on the roots of the grasses and not of the other growth forms present (e.g. Snyman, 2005, 2009a, 2009b; Shackleton *et al.*, 1988). The limited number of forest case studies (only two – e.g. Clulow *et al.*, 2013; Milne and Haynes; 2004) and the lack of desert case studies, highlights the need for further research on natural forest and desert ecosystems in South Africa. This was previously recognised in the swamp and dune forest study by Clulow *et al.* (2013) who emphasized that most research on the comparative water use of introduced trees and the natural vegetation they replace in SA has been focused on transformations of natural grasslands and fynbos (Scott *et al.*, 2000; Dye and Versfeld, 2007; Dye, 2001; Gush *et al.*, 2002; Everson *et al.*, 2008) and very little has focused on that of natural forests (Gush and Dye, 2006, 2009; Everson *et al.*, 2011). Furthermore, where information is available, it is specific to the climate, season, geographical location, soil water availability and specific plant species of the transformed research site at the time of the research and thus, introduces doubt as to the transferability of these results to other locations (Clulow *et al.*, 2013). Dye *et al.* (2008) has also highlighted the general lack of information around the subject of natural tree water use in SA. The little information that is available from research on natural tree water use needs to be approached tentatively, as this information is often characterised by site specific climate, geographic location and soil water availability which may thus be subject to doubt as to the transferability of results across different areas (Clulow *et al.*, 2013).

Estimations of growth form ROOTA in grassland, forest and desert natural ecosystems would be more realistic if more published root profiles were available to use for the basis of these estimations. Furthermore, with regards to clusters such as Gr_9, if more results were available for such unique natural vegetation units in SA then the ROOTA estimates for such clusters may be more realistic and representative of the vegetation in these clusters. Nevertheless, the methodology set out in this study has been explicitly detailed in such a way that the methodology may be repeated for future estimations of ROOTA when new, or improved, natural vegetation root profiles become available. With more research to provide more knowledge about the distribution and depth of roots for a larger number and diversity of South African natural vegetation species, these estimations of ROOTA and EFRDEP for the clusters may be markedly improved. However, in dealing with the gap in knowledge that currently exists for root systems of South African vegetation, the best available information has been used for the estimations of ROOTA and EFRDEP in this study.

Of pertinence to the estimations of root parameters for hydrological modelling purposes is the methodological challenges and limitations posed by the ACRU Model structure, where certain internal assumptions and rules within the ACRU Model in terms of land cover conceptualisation need to be considered when deriving and assigning values to root parameters. Within the ACRU Model, senescence and more so, the absence of transpiration, is conceptualised by a monthly ROOTA parameter value of 1. On the other hand, given that the ROOTA parameter is defined in terms of the ACRU Model as the fraction of active roots appearing in the A-horizon soil depth, plants that characteristically have a shallow rooting depth (e.g. succulents; Schenk and Jackson, 2002a) which extends only within the depth of the A-horizon will have 100 % of their roots in the A-horizon, thus implying a ROOTA of 1. For these types of growth forms, a ROOTA of 1 does not mean "no transpiration", it only designates 100 % of roots in the A-horizon. This demonstrates the conflict between the definition of ROOTA to indicate the fraction of roots in the A-horizon and the internal function of the ROOTA parameter to "switch off" transpiration when set to a value of 1. This conflict has knock-on effects for the simulated hydrological response from the model, where, according to the results from McNamara and Toucher (2018), setting the ACRU ROOTA parameter to 1 results in large increases in the simulated streamflow and greater increases in the simulated baseflow. The conceptualisation of root distribution and the conflicting conceptualisation of the influence of root distribution on transpiration in ACRU needs to be reconsidered to improve the representation of vegetation water use in the model.

In terms of the grassland, savanna, forest and desert biomes in this study, all the clusters had more than one growth form thus, the markedly shallow EFRDEPs, and hence ROOTA of 1, for growth forms such as succulents never resulted in an overall growing season ROOTA of 1 for the cluster. Nevertheless, in other biomes such as the Succulent Karoo or Nama Karoo, where succulents may be the only growth form present in some of the clusters, the growing season ROOTA of 1 for these types of growth forms may result in an overall ROOTA of 1 for these clusters. Furthermore, if the clusters were to be further subdivided down, it may be that succulents (or other shallow rooting growth forms) are the only dominant growth form, thus resulting in a ROOTA of 1 for these clusters. Although the mis-conceptualisation of roots in

ACRU could not be seen for the clusters in this study, it did highlight the potential of this becoming a reality and thus needs to be resolved in future research.

Given the lack of information and limited measurements for roots and the important role that roots play in hydrological processes and in determining the water yield, it is important that roots are appropriately represented in hydrological models. Therefore, the conceptualisation of roots and root water uptake in ACRU may need to be revised and improved in order to improve hydrological simulations in ACRU. One way to do this would be to account for dynamic root growth, where the growth and architecture of fine (active) roots within the model changes dynamically with variations in the availability of water and nutrient resources in the soil profile (Postma *et al.*, 2013, 2017; Leitner *et al.*, 2010). The other would be the proposed method by Gao *et al.* (2014), Wang-Erlandsson *et al.* (2016) and Faridani *et al.* (2017) for models to allow root depth to adapt according to the variable volume of root zone soil water in order for plants to adapt and grow throughout periods of drought. These alternative approaches recommended to revise the conceptualisation of roots in ACRU would improve the knock-on effects of root growth on transpiration and other hydrological processes within the model. Additionally, the revised conceptualisation of roots may eliminate the issues around the lack of information on root measurements.

3.6 Conclusion

The concerns raised about the currently used hydrological baseline land cover of Acocks' (1988) Veld Types provided the opportunity to revise the baseline land cover for South Africa. Among the various vegetation and water use parameters required as input to the ACRU Model to represent this revised baseline land cover, this study focused on the root-specific below-ground parameters, ROOTA and EFRDEP, due to the general dearth of knowledge that was realised for these below-ground root structures. The parameters were derived using a repeatable methodology based on using various relationships that linked root measurements and observations from previous studies to the physical properties of the vegetation clusters. The root parameter database produced in this study will contribute to the revised parameterisation of South Africa's hydrological baseline land cover, and the repeatable methodology will improve estimations of root parameters for use in hydrological models.

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3.8 Appendix

Table A3.1: EFRDEP and monthly ROOTA input parameters for clusters in the grassland, savanna, forest and desert biomes for use in the ACRU Model.

	Cluster	**EFRDEP (cm)**	**Monthly ROOTA**											
			Jan	**Feb**	**Mar**	**Apr**	**May**	**Jun**	**Jul**	**Aug**	**Sep**	**Oct**	**Nov**	**Dec**
Grassland	**Gr_1**	137	0.86	0.86	0.86	0.86	0.95	1.00	1.00	1.00	0.95	0.86	0.86	0.86
	Gr_2	185	0.75	0.75	0.75	0.75	0.75	1.00	1.00	0.98	0.75	0.75	0.75	0.75
	Gr_3	174	0.80	0.80	0.80	0.80	0.98	1.00	1.00	1.00	1.00	0.80	0.80	0.80
	Gr_4	140	0.83	0.83	0.83	0.83	0.98	1.00	1.00	1.00	0.98	0.83	0.83	0.83
	Gr_5	131	0.81	0.81	0.81	0.81	0.81	1.00	1.00	0.98	0.81	0.81	0.81	0.81
	Gr_6	180	0.69	0.69	0.69	0.69	0.69	1.00	1.00	0.98	0.69	0.69	0.69	0.69
	Gr_7	198	0.83	0.83	0.83	0.83	1.00	1.00	1.00	1.00	1.00	0.95	0.83	0.83
	Gr_8	181	0.68	0.68	0.68	0.98	1.00	1.00	1.00	1.00	1.00	1.00	0.68	0.68
	Gr_9	52	0.90	0.95	1.00	1.00	1.00	1.00	1.00	1.00	1.00	1.00	1.00	1.00
	Gr_10	134	0.72	0.72	0.72	0.72	0.98	1.00	1.00	1.00	1.00	0.72	0.72	0.72
	Gr_11	134	0.82	0.82	0.82	0.82	0.98	1.00	1.00	1.00	0.95	0.82	0.82	0.82
	Gr_12	169	0.71	0.71	0.71	0.71	0.95	1.00	1.00	1.00	0.71	0.71	0.71	0.71
	Gr_13	148	0.81	0.81	0.81	0.81	0.95	1.00	1.00	1.00	0.95	0.81	0.81	0.81
	Gr_14	131	0.85	0.85	0.85	0.85	0.95	1.00	1.00	1.00	0.85	0.85	0.85	0.85
	Gr_15	135	0.83	0.83	0.83	0.83	0.98	1.00	1.00	1.00	1.00	0.83	0.83	0.83
	Gr_16	147	0.82	0.82	0.82	0.82	0.95	1.00	1.00	1.00	0.82	0.82	0.82	0.82
	Gr_17	162	0.79	0.79	0.79	0.79	0.79	0.98	1.00	0.95	0.79	0.79	0.79	0.79
	Gr_18	196	0.79	0.79	0.79	0.79	0.79	0.95	0.98	0.79	0.79	0.79	0.79	0.79
	Gr_19	152	0.83	0.83	0.83	0.83	0.83	0.98	0.98	0.83	0.83	0.83	0.83	0.83
	Gr_20	171	0.82	0.82	0.82	0.82	0.82	0.98	1.00	0.82	0.82	0.82	0.82	0.82
	Gr_21	162	0.82	0.82	0.82	0.82	0.82	0.98	1.00	0.95	0.82	0.82	0.82	0.82
	Gr_22	199	0.77	0.77	0.77	0.77	0.77	0.98	0.95	0.77	0.77	0.77	0.77	0.77
Savanna	**Sa_1**	245	0.61	0.61	0.61	0.61	0.61	0.85	0.85	0.80	0.61	0.61	0.61	0.61
	Sa_2	210	0.58	0.58	0.58	0.58	0.58	0.85	0.85	0.85	0.58	0.58	0.58	0.58
	Sa_3	225	0.78	0.78	0.78	0.78	0.78	0.80	0.80	0.78	0.78	0.78	0.78	0.78
	Sa_4	203	0.66	0.66	0.66	0.66	0.66	0.80	0.83	0.66	0.66	0.66	0.66	0.66
	Sa_5	202	0.59	0.59	0.59	0.59	0.59	0.80	0.59	0.59	0.59	0.59	0.59	0.59
	Sa_6	161	0.63	0.63	0.63	0.63	0.63	0.63	0.63	0.63	0.63	0.63	0.63	0.63
	Sa_7	224	0.67	0.67	0.67	0.67	0.67	0.67	0.67	0.67	0.67	0.67	0.67	0.67
	Sa_8	226	0.74	0.74	0.74	0.74	0.74	0.74	0.74	0.74	0.74	0.74	0.74	0.74
	Sa_9	201	0.65	0.65	0.65	0.65	0.65	0.65	0.65	0.65	0.65	0.65	0.65	0.65
	Sa_10	158	0.68	0.68	0.68	0.68	0.68	0.85	0.85	0.83	0.68	0.68	0.68	0.68
	Sa_11	208	0.58	0.58	0.58	0.58	0.58	0.85	0.85	0.80	0.58	0.58	0.58	0.58
	Sa_12	162	0.71	0.71	0.71	0.71	0.80	0.85	0.85	0.85	0.80	0.71	0.71	0.71
	Sa_13	198	0.62	0.62	0.62	0.62	0.80	0.85	0.85	0.85	0.80	0.62	0.62	0.62
	Sa_14	171	0.63	0.63	0.63	0.63	0.80	0.85	0.85	0.85	0.63	0.63	0.63	0.63
	Sa_15	229	0.64	0.64	0.64	0.64	0.64	0.80	0.80	0.64	0.64	0.64	0.64	0.64
	Sa_16	181	0.56	0.56	0.56	0.56	0.56	0.56	0.56	0.56	0.56	0.56	0.56	0.56
	Sa_17	225	0.52	0.52	0.52	0.52	0.52	0.52	0.52	0.52	0.52	0.52	0.52	0.52
	Sa_18	237	0.68	0.68	0.68	0.68	0.68	0.80	0.68	0.68	0.68	0.68	0.68	0.68
	Sa_19	230	0.72	0.72	0.72	0.72	0.72	0.80	0.72	0.72	0.72	0.72	0.72	0.72
	Sa_20	185	0.65	0.65	0.65	0.65	0.65	0.83	0.85	0.80	0.65	0.65	0.65	0.65
	Sa_21	198	0.63	0.63	0.63	0.63	0.63	0.83	0.63	0.63	0.63	0.63	0.63	0.63
	Sa_22	155	0.75	0.75	0.75	0.75	0.75	0.83	0.75	0.75	0.75	0.75	0.75	0.75
	Sa_23	208	0.62	0.62	0.62	0.62	0.62	0.83	0.85	0.62	0.62	0.62	0.62	0.62
	Sa_24	219	0.65	0.65	0.65	0.65	0.65	0.85	0.83	0.65	0.65	0.65	0.65	0.65
	Sa_25	208	0.60	0.60	0.60	0.60	0.80	0.85	0.85	0.85	0.60	0.60	0.60	0.60
Forest	**Fo_1**	264	0.78	0.78	0.78	0.78	0.78	0.78	0.78	0.78	0.78	0.78	0.78	0.78
	Fo_2	269	0.62	0.62	0.62	0.62	0.62	0.62	0.62	0.62	0.62	0.62	0.62	0.62
	Fo_3	268	0.84	0.84	0.84	0.84	0.84	0.84	0.84	0.84	0.84	0.84	0.84	0.84
	Fo_4	248	0.77	0.77	0.77	0.77	0.77	0.77	0.77	0.77	0.77	0.77	0.77	0.77
Desert	**De_1**	91	0.66	0.66	0.66	0.66	0.66	0.66	0.66	0.66	0.66	0.66	0.66	0.66
	De_2	55	0.88	0.88	0.88	0.88	0.88	0.88	0.88	0.88	0.88	0.88	0.88	0.88
	De_3	65	0.84	0.84	0.84	0.84	0.84	0.84	0.84	0.84	0.84	0.84	0.84	0.84
	De_4	59	0.90	0.90	0.90	0.90	0.90	0.90	0.90	0.90	0.90	0.90	0.90	0.90

CHAPTER 4: SYNTHESIS

The Department of Water and Sanitation (DWS) in South Africa currently uses natural vegetation in the form of the Acocks' (1988) Veld Types as the accepted baseline land cover against which land use impacts and particularly streamflow reduction activities (SFRAs) are assessed (Schulze, 2004a; Jewitt *et al.*, 2009). There have however been concerns raised about the use of the Acocks' (1988) Veld Types as the baseline vegetation in these assessments (Jewitt *et al.*, 2009). Given that important governmental and policy decisions are based on these assessments, the need to revise and improve the baseline land cover was recognised. A revised natural vegetation map for South Africa developed by Mucina and Rutherford (2006) and updated by the South African National Biodiversity Institute (SANBI, 2012) has been proposed as a new hydrological baseline land cover (Jewitt *et al.*, 2009; Warburton, 2012). In response, the WRC project (K5/2437) aims to assess this new baseline land cover to address the raised concerns. In order to do this, the proposed new baseline land cover needs to be parameterised for representation in a hydrological model, as this is the tool most commonly applied for assessing the hydrological impacts of land use change (Warburton *et al.*, 2010; Turner *et al.*, 1995; Bronstert *et al.*, 2002; De Fries and Eshleman, 2004; Samaniego and Bárdossy, 2006; Choi and Deal, 2008). The hydrological model in this case was the ACRU Agrohydrological Model as it is the model in the SFRA Assessment Utility Tool (Jewitt *et al.*, 2009) which is used by DWS. The ACRU Model is a physically-based conceptual model which directly links model parameters to catchment land cover characteristics (Bastola *et al.*, 2008; Li *et al.*, 2009) thus, is particularly sensitive to land use changes (Warburton *et al.*, 2010) and is an ideal tool to aid in the understanding of hydrological processes and for assessing land use impacts. This MSc project contributed to the larger WRC project through a sensitivity analysis of ACRU which identified CAY and PCSUCO as the land cover parameters to which the model output was most sensitive. Regardless of the sensitivity results, all vegetation and water use parameters need to be estimated to appropriately represent the baseline vegetation in ACRU, as all vegetation components play an important role in determining the hydrological responses. Given the disparity of information on root measurements, this MSc study focused on the root parameters and the estimations thereof. With the 450 vegetation units defined in the SANBI (2012) map being grouped into 128 hydrologically similar vegetation clusters, the root parameters needed to be estimated for all the clusters. The objective of this research was to develop a database of the EFRDEP and ROOTA parameters for each of the clusters in the grassland, savanna, forest and desert biomes, and in doing so producing a repeatable methodology. This repeatable methodology may then be applied to, among other things, estimate the root parameters for clusters in the remaining biomes. In terms of contributing to water resource management and land use change assessments in South Africa, the two major key findings from this study are the parameter sensitivities and the root parameter database. The other key findings are the repeatable methodology and the identified shortcomings in the conceptualisation of the roots in the ACRU Model.

4.1 ACRU Parameter Sensitivities and the Root Parameter Database

The sound management and protection of water resources requires the relatively accurate assessment of the hydrological impacts of land use and land use changes. The magnitude of such impacts is dependent, *inter alia*, on the hydrological response under baseline land conditions (Warburton *et al.*, 2012). Therefore, the establishment of an appropriate baseline land cover and the relatively accurate parameterisation thereof becomes imperative (Jewitt *et al.*, 2009). The SANBI (2012) natural vegetation units, grouped into 128 hydrologically similar clusters, are proposed as a revised hydrological baseline land cover for South Africa. Given that rooting depth and distribution play an important role in the partitioning of water and hence in determining the hydrological response from various land covers, the database of root parameters (ROOTA and EFRDEP) for the clusters in this study will contribute to parameterising the baseline and to improved estimations of baseline water use in land use change assessments.

In South Africa the ACRU Agrohydrological Model is used in the SFRA Assessment Utility Tool for assessing SFRAs of commercial forestry against the baseline land cover it replaces (Jewitt *et al.*, 2009), furthermore it is also commonly used for assessments of land use impacts. The results from the sensitivities of the land cover parameters determined in this study provide an understanding of the output from the ACRU Model that can be used to inform land use change assessments. The parameter sensitivities provide understanding of the conceptualisation of vegetation and its water use in ACRU, thereby highlighting the shortcomings within the ACRU Model's internal processes and parameterisation to provide an understanding of the uncertainties and challenges in ACRU Model simulations. Improving hydrological simulations in ACRU will improve SFRA assessments and other land use impact assessments. Further to this, the sensitivity study results may be used as guidelines in model predictions in ungauged basins, indicating that sensitive parameters must be estimated and quantified accurately. This information assists in prioritising the parameters and understanding the uncertainties in the output results. For instance, extreme sensitivity of baseflow output to CAY inputs and the high sensitivity of streamflow output to CAY inputs identified from the results, highlights the importance of accurate and representative CAY estimates for input to ACRU when simulating baseflow and streamflow volumes.

As the sensitivity study assessed a single land cover parameter at a time, one recommendation to further improve determinations of ACRU parameter sensitivities would be to assess several land cover parameters together, as a parameter may be found to be more sensitive when considered in conjunction with another parameter. Another recommendation would be to test the sensitivity of the parameters in different regions having a different climate and land cover to the fictitious grassland catchment used in this study. This would allow for different starting input values thus, providing the opportunity to possibly test the effect of increasing ROOTA and PCSUCO when the starting input values are lower. Nonetheless, the small window for testing the effect of percentage increases in ROOTA in this sensitivity study indicated a key shortcoming in the ACRU Model.

The scope of this project restricted the estimation of below-ground vegetation parameters to the two most important ACRU root-specific parameters that describe the water uptake functions of roots, which were EFRDEP and ROOTA. However, given more time, the other below-ground parameters should also be appropriately estimated for the proposed hydrological baseline of natural vegetation in order to further improve ACRU Model simulations of natural vegetation water use. These include (a) the percentage root colonisation in the A- and B-horizons (COLONA and COLONB) which is a root-specific parameter and (b) the fraction of PAW of the soil horizons when the onset of plant stress occurs, which is a non-root-specific parameter.

The root parameter database developed in this study will be useful in water resources management in South Africa, as it provides a look-up table product, from which to derive reliable and consistent model input parameters for the baseline land cover. This will ensure consistent applications of baseline parameters for simulating baseline hydrological responses. Furthermore, the root parameter estimations for clusters in this study were consistent across the biomes, thus applying the root parameters from the database for SFRA licencing determinations in different biomes would not lead to any discrepancies.

As the aim of the project was to develop a repeatable methodology, the root parameters were estimated for clusters in four biomes. The repeatable methodology developed in this study for estimations of root parameters was based on quantifying climatic (MAP and frost), genetic (above-ground phenology) and environmental (soil horizon depths) factors in terms of their influence on rooting depths and distributions, with each step documented in detail. In doing this, the methodology can be repeated to estimate root parameters for clusters in the remaining biomes, by using the climatic, genetic and environmental information specific to these. The development of the root parameter database emphasised the need for more research to produce information and measurements for roots of natural vegetation in South Africa, thus the documented repeatable methodology ensures that when more root information becomes available, this information may be used to improve the existing estimations. Given the detailed account of the repeatable methodology, the root parameters although estimated for input to the ACRU Model, may be used in other similar hydrological models.

4.2 The Importance of the Repeatable Methodology

The repeatable methodology developed in this study for estimations of root parameters is detailed and documented, making it understandable and accessible to all users, overcoming any doubt surrounding the parameter database. There is no room for ambiguity around the parameter database as the estimations were derived using a clearly documented methodology which was scientifically defensible, unlike the “opinion-based, rule-of-thumb” approach used previously. The methodology is open and flexible, encouraging adjustments and improvements in its development with the availability of new root measurements, and allowing for repetition in its application for estimating parameters in other biomes. The repeatable methodology has highlighted the challenges and uncertainties in estimating root parameters, indicating where there is room for improvement in the methods or in the tools used, such as ACRU.

The repeatable methodology also highlights the strengths in the methodology, such as the improvements and advancements made in root parameter estimations. Some of these include (a) the use of root measurements and observations from previous field studies together with physically measured catchment characteristics; (b) the use of EFRDEP estimates, thus incorporating MAP, in the extrapolation of case study root profiles and (c) the growth-form specific estimations contributing to the overall cluster estimations. These strengths highlighted in the methodology demonstrate that the scientifically defensible repeatable methodology developed in this study is certainly an improvement from the “expert-opinion-based working rules” approach that was used previously to derive root parameters for the Acocks’ (1988) baseline. The repeatable methodology is based on previous study finding using field observations and measurements, thus for a physically based model, this study has developed root parameter inputs that are based on physical measurements. With important water management and policy decisions based off of the root parameters estimated in this study, the detailed documentation of the repeatable methodology, and the physical measurements from previous field studies, used for these estimations, unlike the use of rules-of-thumb and expert opinion in the previous approach, ensures that there is no ambiguity. The strengths, challenges, uncertainties, assumptions made and shortcomings identified, as well as all the data used, have all been clearly and methodically documented in the repeatable methodology.

4.3 Conceptualisation of Roots in the ACRU Model

The shortcoming in the conceptualisation of roots in the ACRU Model was identified in the sensitivity study and was further explored in the estimations of the root parameters. The ROOTA parameter is defined as the fraction of active root mass in the topsoil horizon. According to the internal processes and rules within the model, it is this fraction of roots that determines, *inter alia*, the proportions of transpiration from each horizon (Schulze *et al.*, 1995) during the moisture growing season. Therefore, a ROOTA of 0.9, implying 90 % of active roots in the horizon, denotes that the transpiration proportion from the A-horizon is greater than from the subsoil horizon. Based on this and on the definition of the ROOTA parameter in ACRU, a ROOTA of 1 assigned to shallow rooting plants which have 100 % of their active roots in the A-horizon, would similarly mean, in logical terms that the plant water transpired is only from this horizon. However, this is not the case in the ACRU Model, whereby a ROOTA of 1 is assumed to denote periods of senescence, designating that effectively no transpiration is occurring (Schulze *et al.*, 1995). But the shallow rooted vegetation types that have a ROOTA of 1 throughout the year still continue to transpire throughout these months. Therefore, the internal assumption in ACRU for a ROOTA of 1 to “switch off” transpiration contradicts the definition of the ROOTA parameter to define the fraction of roots in the topsoil horizon and to use this fraction to determine transpiration rates from the soil horizons. The use of ROOTA to represent root water uptake and vegetation water use and thus to simulate the hydrological response in ACRU is not realistic or accurate. The unrealistic rule in ACRU which assumes a ROOTA of 1 denotes “no transpiration” confirms the conclusion by Taylor and Klepper’s (1978) that conceptualisation of root water uptake in most models is based on assumptions that are not strictly valid for everyday real-world scenarios in the field.

In response to the shortcoming identified in this study, the recommendation from this research is to revise and improve the conceptualisation of roots in the ACRU Model. It may not be enough to simply refine the existing root parameters required as input to ACRU. It may be necessary to move away from the rooting depths and distributions approach and re-think the overall conceptualisation of root water uptake in ACRU. To do this, the premise that rooting depth is governed by water availability (Schenk and Jackson, 2002a; Holdo *et al.*, 2018) needs to be maintained but also needs to be applied further to consider the variations in root growth with differential soil moisture storage and resource partitioning throughout the soil profile (Postma *et al.*, 2013, 2017; Gao *et al.*, 2014). Although plant root patterns are largely determined by the genetics of the species, it is generally the soil water availability that either limits or extends the root growth to a shallower or deeper depth to which the plant roots could genetically grow. While this concept is, in part, accounted for in the EFRDEP and ROOTA estimations by using MAP of the clusters, the single MAP measurement does not account for seasonality or type of rainfall experienced in the clusters (van Wijk, 2011), nor does is account for seasonal and extreme variations in the availability of water and nutrient resources across the soil profile. For example, plants in semi-arid to humid environments, which receive short, sporadic rainfall events, have a greater proportion of their fine root systems in the top soil horizons, as this is where the water is most readily available (Raz-Yaseef *et al.*, 2013). However, in arid environments receiving much fewer rainfall events, the roots tend to explore much deeper soil zones in order to access the required resources to carry the plants through drier periods. Additionally van Wijk (2011) found that the dynamics of resource availability within the soil may in fact shift the zone of maximum root activity (i.e. the depth at which 90 % of total active roots appear) rather than shifting the maximum rooting depth. Therefore, the conceptualisation of roots in the ACRU Model does not currently account for the responsive optimisation and adaptation of root growth and architecture in order to achieve resource use efficiency. Remembering that fine active roots will track the soil water (Schulze *et al.*, 1995), they will generally grow as deep as is required to meet evaporative and plant demands, naturally adapting to prevailing climates, soil heterogeneity and reduced water availability in order to carry the plants through drier periods (Meyer *et al.*, 1990; Gentine *et al.*, 2012; Sivandran and Bras, 2013). Hence, it is difficult and complicated to determine and generalise about rooting measurements at the catchment-scale.

These concepts have been explored and documented in recent studies (e.g. Leitner *et al.*, 2010; Postma *et al.*, 2013, 2017; Gao *et al.*, 2014; Faridani *et al.*, 2017; Wang-Erlandsonn *et al.*, 2017) which have moved the science along in terms of representing roots in models. It is recommended that the revised conceptualisation of root water uptake in ACRU consider the potential use of these approaches. One such approach would be accounting for dynamic roots such as in the global climate and vegetation models (e.g. Leitner *et al.*, 2010; Postma *et al.*, 2013, 2017). Dynamic root conceptualisation in models accounts for the dynamic interactions between the growth and structure of roots and the local soil properties and processes (Leitner *et al.*, 2010). During drier periods when the top soil dries out, models based on dynamic root growth can simulate compensatory water uptake and hydraulic redistribution by reducing water uptake from dry areas in the soil profile (Postma *et al.*, 2017). The concept of dynamic roots in models describes the ability of plants to optimise root growth and architecture in order to enhance resource use efficiency under challenges of soil heterogeneity and soil nutrient availability dynamics (Postma *et al.*, 2013). Another approach would be to do away with the rooting depths and distributions in ACRU and to rather consider the root zone storage capacity in order to simulate drought-related responses in root growth (Gao *et al.*, 2014; Faridani *et al.*, 2017; Wang-Erlandsonn *et al.*, 2017). In doing this, ACRU would allow the rooting depth to adapt and adjust to the soil water volume in order to carry the plants through dry periods. Gao *et al.* (2014) successfully tested the effect of treating the root zone as a reservoir, using effective rainfall and plant transpiration to estimate the catchment-scale root zone storage capacity. The concept of root zone storage in models describes the ability of ecosystems to dynamically design the plants' root systems in order to bridge droughts at a catchment-scale (Gao *et al.*, 2014).

According to the way the roots are currently conceptualised in ACRU and the misinterpretation of the link between ROOTA and transpiration (McNamara and Toucher, 2018), the simulated hydrological response was found to be only slightly sensitive or insensitive to the root parameters. However, revision of the conceptualisation of roots in the ACRU Model, thus improving the knock-on effects for determining transpiration rates and hence simulated streamflow (McNamara and Toucher, 2018) in future research, may result in the output from ACRU to be substantially more sensitive to the rooting land cover parameters. Despite the lack of information for root measurements, roots play an important role in the partitioning of rainwater to the components of the water budget. Therefore, the sound conceptualisation and parameterisation of roots in ACRU is imperative for simulating the hydrological response under various land uses. Furthermore, revising the conceptualisation of roots in ACRU my overcome the issues around the lack of root measurements.

4.4 Contributions of this Research

The following key findings from this research will contribute to land use impact assessments, particularly SFRA determinations, thus improving water resource management and planning in South Africa:

1. **The root parameter database** developed in this study will be used in SFRA determinations and other land use impact assessments in South Africa. Given that the proposed new baseline land cover for South Africa will pay an important role in land use impact assessments and particularly SFRA determinations, the development of the root parameter database for the baseline clusters in this study will contribute substantially to improving SFRA and other land use assessments, thus improving water resources management overall.
2. **The parameter sensitivity information** will provide ACRU Model users with an understanding of the uncertainties in model output. With the use of the ACRU Model in land use impact assessments, the sensitivities of the ACRU output to land cover parameters will guide the hydrological model simulations and will provide an understanding of the output used. The identification of parameter sensitivities in ACRU will improve hydrological model simulations. Given that the ACRU model is used in the SFRA Assessment Utility Tool, the improved hydrological simulations in ACRU will contribute to improved SFRA determinations.
3. **The repeatable methodology** will be applied to estimate ROOTA and EFRDEP parameters for the remaining biomes that make up the baseline land cover. The repeatable methodology that developed the database to be used in water resource management and SFRA determinations will contribute to ensuring consistency in terms of estimating baseline water use across various biomes. With the important management and policy

decisions based off the root parameter database, the documented repeatable methodology used for the parameter estimations will provide a clear understanding of the methodology to avoid ambiguity.

4. **The shortcoming in the conceptualisation of roots in the ACRU Model** highlighted in this study will provide ACRU Model users with an understanding of the uncertainties in the output from the model. The recommended improvements suggested in this study for re-visiting the root conceptualisation in ACRU will also improve future hydrological simulations of land use impacts and SFRAs in ACRU.

Ultimately, in line with the main aim of this study, the database of ACRU Model root parameters produced in this study for the proposed new baseline land cover for South Africa will contribute significantly to determining the water use of this new baseline, against which SFRAs and other land use impacts will be assessed. Further to this, the parameter sensitivities, the repeatable methodology and the identified shortcoming in ACRU's root conceptualisation will all contribute to improving these estimations using ACRU.

4.5 Conclusion

This study has addressed the ultimate aim of determining below-ground vegetation and water use input parameters for a revised hydrological baseline land cover in South Africa for use in the ACRU Agrohydrological Model. The sensitivity analysis resulted in an understanding of the ACRU Model's sensitivity to land use parameters, which addressed the first aim of this study. The sound and accurate assessment of land use change impacts is largely dependent on the hydrological response under baseline conditions and thus depends heavily on the parameterisation of the baseline land cover. Therefore, although the ACRU Model output was shown to be less sensitive to some of the land cover parameters, the estimation of all land cover input parameters are required for parameterising the baseline land cover. The rooting parameters gained priority in this study due to the general dearth of information for root measurements for natural vegetation in South Africa. The estimations of EFRDEP and ROOTA parameters for the baseline clusters addressed the second aim of this study, which led to achieving the primary objective to produce a database of root-specific below-ground parameters, from which to derive reliable hydrological model input parameters for use in the ACRU Model. The methodology developed in this study for estimations of root parameters is sound, scientifically defensible and repeatable, thus overcoming any possibility for ambiguity surrounding the parameter database, and enabling its future application for estimations in other biomes.

4.6 References

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