MODELLING THE IMPACTS OF CHANGES IN AGRICULTURAL MANAGEMENT PRACTICES ON WATER RESOURCES WITH DECLINING HYDROMETEOROLOGICAL DATA IN THE UTHUKELA CATCHMENT

Mlungisi M Shabalala

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Centre for Water Resources Research
School of Agricultural, Earth and Environmental Sciences
College of Agriculture, Engineering and Science
University of KwaZulu-Natal
Pietermaritzburg
South Africa

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PREFACE

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

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

Signed:……………………………….

Mlungisi Shabalala

Date:

Signed:……………………………….

Dr Michele Toucher (Supervisor)

Date:

DECLARATION 1: PLAGIARISM

I, *Mlungisi Maxwell Shabalala*, declare that:

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

(ii) this dissertation has not been submitted in full or in part for any degree or examination to any other university;

(iii) this dissertation does not contain other persons' data, pictures, graphs or other information, unless specifically acknowledged as being sourced from other persons;

(iv) this dissertation does not contain other persons' writing, unless specifically acknowledged as being sourced from other researchers. Where other written sources have been quoted, then:

  a) their words have been re-written but the general information attributed to them has been referenced;

  b) where their exact words have been used, their writing has been placed inside quotation marks, and referenced;

(v) where I have used material for which publications followed, I have indicated in detail my role in the work;

(vi) this dissertation is primarily a collection of material, prepared by myself, published as journal articles or presented as a poster and oral presentations at conferences. In some cases, additional material has been included;

(vii) this dissertation does not contain text, graphics or tables copied and pasted from the Internet, unless specifically acknowledged, and the source being detailed in the dissertation and in the References sections.

Signed:……………………………….

Mlungisi Shabalala

Date:

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Dr Michele Toucher (Supervisor)

Date:

DECLARATION 2: PUBLICATIONS

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

Chapter 2

*Shabalala, MM and Toucher, ML. 2018. The influence of declining hydrometeorological monitoring networks on hydrological modelling: a model confirmation case study from the uThukela catchment. *To be submitted to Physics and Chemistry of the Earth*.

This paper is investigates the impacts of the declining networks of observed hydrometeorological monitoring stations (rainfall and flow gauges) on hydrological modelling. The paper was entirely written by MM Shabalala and all figures and tables were produced by this author, unless otherwise referenced in the paper. All data assembling, extraction and analysis were entirely conducted by MM Shabalala through the use of various tools including, among others, GIS, hydrological models and Microsoft Office. Rainfall data was obtained from a national database by Lynch (2004), the South African Weather Service (SAWS) and the Agricultural Research Council (ARC), while daily observed streamflow data was obtained from the Department of Water and Sanitation (DWS). Land cover information was obtained from the Ezemvelo KZN Wildlife and the South African National Biodiversity Institute. Guidance and advice was provided by ML Toucher throughout the study, who was also responsible for editing of the paper. The paper was orally presented at the 18th WATERNET Symposium on 25th October 2017.

Chapter 3

*Shabalala, MM and Toucher, ML. 2018. The impacts of changes in agricultural land management practices on water flows at the uThukela catchment, South Africa. *To be submitted to Water SA.*

The paper addresses the potential impacts of changes in agricultural land management practices on water resources in the upper uThukela catchment in a scenario-based modelling methodology using the ACRU hydrological model. The study builds from Shabalala and Toucher (2017). Therefore, similar data sources were used, i.e. land cover information was obtained from the Ezemvelo KZN Wildlife, while rainfall data was extracted from a national database by Lynch (2004). The paper was entirely written by MM Shabalala, and guidance, advice and editing were provided by ML Toucher. All figures and figures were developed by MM Shabalala, unless otherwise referenced in the text. All assembling of input model data, hydrological modelling and processing of output was entirely conducted by this author.

ABSTRACT

In order to meet the country's growing demand for food, and to transform the economy of rural communities, the South African Government aims to develop the agricultural sector in the uThukela Catchment, KwaZulu-Natal Province. Intensification of agriculture will depend on the availability of water resources, with subsequent impacts on the quality and quantity of water resources. Therefore, the aim of this study was to investigate the impacts of proposed agricultural developments on the water flows in the upper uThukela Catchment using the multi-purpose, multi-soil-layered, daily time step ACRU model.

The first phase of the study was to confirm the model's ability to simulate flows in three, relatively small, gauged subcatchments of the uThukela catchment (Quaternary Catchments V11K, V14C and V31F), using current land cover and climate information extending to present day. However, the documented decline in the number of, and quality of data from, hydrometeorological stations, particularly since the year 2000, was concerning. Therefore, the impact of this decline on model performance was investigated in the selected subcatchments by comparing simulated flows to available observed flows in a confirmation study. Configuration of the model to present day conditions was restricted by the unavailability of rainfall stations. In cases where stations were available, there were no nearby stations to patch or compare to, when the record had missing or suspicious values. Given this, the model was set to run from 1960 to the latest record date available for catchments V14C and V31F. For V14C, the model performance decreased when the model was run from 1960 to 2012, compared to 1960-1999. Although a slightly better performance was obtained at V31F, the simulation time period was reduced to 1960-1999 for both catchments due to uncertainties with post 2000 rainfall and streamflow data. However, V14C continued to prove problematic and further investigation using of the Indicators of Hydrological Alteration software revealed a marked change in the flow characteristics between 1980 and 1981. No documentation of developments or substantial changes in the catchment could be sourced. Therefore, Quaternary Catchment (QC) V14C was excluded from further analysis. The ACRU model adequately simulated the flows for V11K and V31F, with the simulated flows being more representative of the observed flows in V31F. With the ability of the ACRU model to simulate the flows in the upper uThukela catchment under various land uses confirmed, the model could be used to investigate the impacts of agricultural land management scenarios on water flows.

The agricultural land management scenarios were developed from the national and local government's plan to expand agriculture to transform the socioeconomic status of the uThukela catchment. To develop scenarios for larger scale modelling, numerous scenarios were tested at QCs V31F and V11K. However, V11K was not responsive to changes in land use; therefore, results from the catchment were not used. For large scale modelling, the Upper uThukela (V1) Secondary Catchment was selected. The scenarios considered were: (i) increasing the fraction of irrigated commercial agriculture into currently dryland commercial fields, (ii) increasing subsistence agriculture through reduction of commercial agriculture (i.e. land reform), (iii) conversion of dryland commercial agriculture into crops with biofuel potential (iv) increased burning, (v) intensified land degradation and (vi) rehabilitation of degraded areas. These were developed from current land cover and compared to a simulation assuming natural conditions. The runoff components of interest were baseflow, quickflow and streamflow, as well as the low, median and high streamflows. Irrigation resulted in the highest flow reductions, with permanent cropping and planting two crops per year resulting in the largest decrease in streamflow at V31F and V1, when compared to natural conditions. These scenarios also had the greates impact on low flows. Plantation of biofuels increased flows, with soya beans having a higher impact on baseflows. Intensified burning and degradation increased quickflow and streamflow, while increasing subsistence agriculture and rehabilitation of degraded areas had little impact on flows. These results were generated from poor climate and land cover input information. Therefore, these results cannot be used at a definite decision-making tool, rather as an indication of the possible impacts of land use change on flows at the uThukela Catchment and similar regions. Efforts should be made to improve and maintain hydrometeorological monitoring stations. In addition, there should be more initiatives to collect land cover and water use data at various catchments in order to improve the quality of input data. Lastly, the current version of the ACRU model requires high computational power for large catchment simulations, lowering the model performance. Investigation into better versions or possible development of the current version should be conducted to enable modellers to finish large projects in allocated time.

ACKNOWLEDGMENTS

This research forms part of a larger project by the Water Research Commission (WRC), project number K5/2560, entitled “Modelling of water flows with change in land management in selected river catchments”. I would have not been able to complete the project without support from the following individuals/organisations:

Firstly, I would like to thank my family: my mother, father, sister Lindokuhle, cousin Nkanyiso and all my siblings for their unlimited emotional support throughout the project.

My deepest gratitude goes to my supervisor, Dr Michele Toucher, who was always available to guide and support me throughout the project, her comments and input were highly valuable. I would also like to thank her for understanding all the personal problems I encountered over the course of the study. She became my guardian.

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1. INTRODUCTION

Due to growing populations and subsequent increases in demands for natural resources, economic development and changes in national, regional and international policies, the Earth's natural landscape has been extensively modified by humans through processes such as deforestation, agriculture and urbanisation (Lomp *et al*., 1998; Legesse *et al*., 2003; Mustard *et al*., 2012; Hu *et al*., 2015). Changes in land cover and land use have direct and indirect spatial and temporal impacts both on the quantity and quality of water flowing in streams (Falkenmark *et al*., 1999; Wang *et al*., 2008; Li *et al*., 2009; Mango *et al*., 2011; Howells *et al*., 2013; Yan *et al*., 2013). For the purpose of this document, land cover refers to the biophysical attributes of the soil surface and immediate subsurface in the form of landscape and topography, above surface ecosystems, soil and subsurface ecosystems and surface and groundwater. Land use refers to the purpose and extent to which humans exploit and manage land cover (Lambin *et al*., 2000; Pielke *et al*., 2002). Approximately 40% of the world's terrestrial surface has been converted to agricultural land (Foley *et al*., 2005), with irrigation accounting for nearly 70% of freshwater resources (Howells *et al*., 2013). Therefore, agricultural activities have resulted in significant impacts on water quality and quantity. This study focuses on the impacts of changes in agricultural land management practices on water resources in the uThukela catchment, South Africa.

The South African agricultural sector is a dual, two-tiered system, consisting of well-established, large-scale commercial agricultural communities and small-scale, subsistence practitioners (Calzadilla *et al*., 2014; DEA, 2014). Agricultural activities are distributed, across the country, based on suitability: ranging from intensive crop production in the summer and winter rainfall regions (mostly rainfed), cattle farming in the bushveld and sheep farming in the more arid regions (Goldblatt, 2010). Due to soil and climate related limitations, only 12% of the country is potentially suitable for rainfed cropping and only one fifth of this area is considered to be fertile land (DEA, 2011; Dube *et al*., 2013). Most of South African land (approximately 70%) is suitable for grazing, making livestock farming the largest agricultural activity in the country (Goldblatt, 2010; Meissner *et al*., 2013). Most of the agricultural practices are concentrated in the east, wetter side of the country. About two thirds of the agricultural households are shared between three of the nine provinces, namely KwaZulu-Natal (24.4%), Eastern Cape (20.7%) and Limpopo (16.3%). The demand for agricultural products has shifted from grain field crops such as maize and wheat to poultry, specifically, chicken, due to the changing food preferences (Meissner *et al*., 2013). However, the industry has not been able to meet the rising demands (Goldblatt, 2010).

The agricultural sector accounts for about 3% of the country's GDP (Dube *et al*., 2013; Turpie and Visser, 2013; Musvoto *et al*., 2015), 10% of formal employment (Calzadilla *et al*., 2014) and 10% of the total value exports (Benhin, 2008). Owing to the recent drought in the country, the sector's contribution to the national GDP decreased by 6.5% in the first quarter of 2016 as the production of horticultural and field crops declined (StatsSA, 2016).

South Africa's population grows at an average 2% per annum; therefore, the recorded population of 49 million is expected to rise to approximately 82 million by 2035 (Goldblatt, 2010). This implies that food production has to double to meet the increasing demand within the same, if not fewer resources. In addition, a projected increase in citizen wealth will increase the demand for specific food products. This will exert more pressure on the already-limited natural resources.

Conversion of natural landscapes into agricultural fields has several impacts on various components of the hydrological cycle. For example, conversion of indigenous forests to agricultural fields can result in increased surface runoff and decreased groundwater recharge (Baker and Miller, 2013), while withdrawals for irrigation reduce the amount of water flowing in rivers (Hu *et al*., 2015). Through activities such as application of fertilizers, herbicides and pesticides, overgrazing and poor fire management practices, the agriculture sector has significant impacts on water quality. These changes have negative impacts for the ecological health of river systems. Given the potentially significant impacts of agricultural activities on water quantity and quality, it is important to understand the impacts at a catchment scale to assist in decision making, particularly land management planning. This is more important in areas facing water scarcity challenges such as the uThukela Catchment, where expansion in agriculture is proposed.

1.1 The Upper uThukela Catchment

The uThukela catchment is located in the KwaZulu-Natal province, South Africa (Figure 1.1). The catchment covers an area of 29 036 km^2, stretching from the high lying Drakensberg mountains, the largest mountain range in southern Africa, with several peaks above 3400 m, where the Thukela river and its tributaries begin to where it enters the Indian Ocean 85 km north of Durban (DWAF, 2003). The Drakensberg mountains also serve as an international border between South Africa and Lesotho, and a boundary between the KwaZulu-Natal and Free State provinces in the western parts of the catchment (OLM, 2016). The uThukela catchment is a source of water for the Gauteng Province, the country's economic hub (OLM, 2016). According to Nsuntsha (2000), the uThukela catchment produces enough water to provide for over one third of the country's water demand. For the purposes of this study, the focus will be on the Upper uThukela catchment. The upper catchment is predominantly rural, with a few urban areas in Bergville, Winterton, Cathkin and Khethani (OLM, 2016). A large part of the Upper uThukela catchment falls within the boundaries of the Okhahlamba Local Municipality (OLM), which is one of five Local Municipalities of the uThukela District Municipality.

According to Stats SA (2011), the population in the OLM is estimated to be around 132 068 people, with 27 576 households, the majority of whom are Black Africans (85%). The level of education in the municipality is relatively low, with only 22.5% of people over the age of 20 having education beyond primary school and 2% reaching tertiary level (OLM, 2016). This contributes to the high unemployment level in the municipality. 43.4% of the population has no form of employment, with 52.3% of the unemployed comprising of the youth (OLM, 2016). About 43% of the municipality receives no income, with 28% and 11% receiving between 1-400 ZAR[1] and 800-1600 ZAR per month, respectively. The municipality is also struck by high HIV/AIDS infections, which contributes to the high unemployment rate (Elleboudt, 2012).

Although the Local Government has made significant efforts to improve the provision of basic services since the end of the apartheid regime, a large portion of the households (75%) remains without access to basic sanitation, with 52% using pit toilets which results in contamination of surface and groundwater resources, thereby increasing the risks of waterborne diseases (Elleboudt, 2012). Rural communities mainly live in traditional houses built using mud blocks, and many lack access to bulk electricity supply.

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[1] South African rand, the currency of South Africa. On 22 February 2018, 1 ZAR= 0.086 USD.

Agriculture is the main land use in the region, with both commercial and small-scale, subsistence practitioners (Mander *et al*., 2008; Andersson *et al*., 2009; Ndoro *et al*., 2013; OLM, 2016). There exists a clear spatial distinction between the two sets of agricultural practitioners (Figure 1.1). Commercial farmers, who are predominantly White, own large properties on the lower and more fertile lands of the catchment, while subsistence farming activities are mainly limited to high elevation, less fertile areas at the foothills of the Drakensberg Mountains (Elleboudt, 2012; Pommerieux *et al*, 2014; OLM, 2016). This difference is mainly a result of segregation policies during the apartheid regime, which reserved fertile areas for White farmers, forcing the Black communities into less productive land (Durning, 1990; Arnalte, 2006; Kemerink *et al*., 2013; Pommerieux *et al*, 2014; OLM, 2016). Today, commercial agriculture covers an estimated 70% of the catchment's farmland (OLM, 2016).

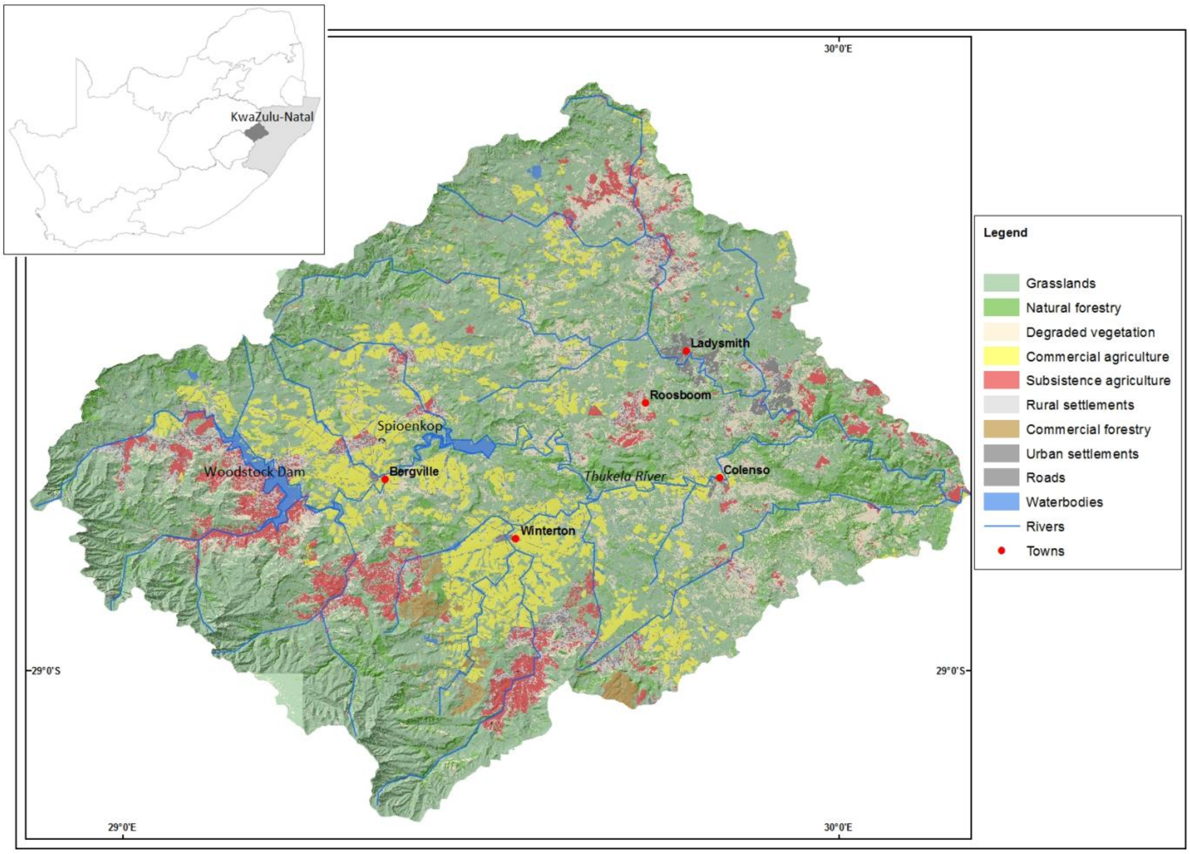

Figure 1.1: The spatial distribution of the major land uses within the Upper uThukela Catchment.

The commercial section of farmers grow rainfed crops in the form of maize, potatoes and soybeans during summer and irrigated wheat and vegetables during the winter season, while the small-scale practitioners mainly grow rainfed maize and, to a lesser extent, dry beans, sorghum, millet and potatoes (Andersson *et al*., 2009; Wood, 2011; OLM, 2016). Subsistence farmers generally own plots within the homesteads (<0.5 ha), and/or fields ranging between 1 and 5 ha at some distance from the homesteads (Bolliger, 2007; van Niekerk, 2007). Due to limited cropping resources as a result of financial constraints, subsistence farmers are limited to small vegetable gardens, which are mainly for household consumption (Elleboudt, 2012). According to Bolliger (2007), only the few, wealthier members of the community engage in cultivation of fields larger than 1 ha.

Both the commercial and subsistence farmers own livestock, with the commercial farmers at a larger scale (Mander *et al*., 2008; Andersson *et al*., 2009; Ndoro *et al*., 2013; OLM, 2016). Commercial farmers grow livestock mainly for beef and dairy products and, at a lower scale, mutton production (Wood, 2011; Mattews and Catacutan, 2012; OLM, 2016). Due to economic reasons, and the seasonal nature of climate in the upper uThukela region, commercial farmers grow irrigated pastures as supplement feed for their livestock (Elleboudt, 2012). With the support of the pre-democratic government, commercial farmers were able to raise funds to construct dams and install irrigation systems (Zunckel, 2003).

Subsistence livestock farming is mainly cattle, goats and to a lesser extent, sheep (OLM, 2016). This activity is largely restricted to community members with sufficient financial resources to purchase and maintain the animals (Elleboudt, 2012; Pommerieux *et al*, 2014). According to Chonco (2009), members of the community grow livestock for several reasons which can be categorized into agricultural, food and socio-cultural purposes. For example, oxen provide draught power for ploughing and transportation of manure and fertilizers. Livestock are also a source of food (meat and milk). In addition, cows and goats are slaughtered for various traditional and social events and, in some cases, these are sold for cash (Salomon, 2006). Elleboudt (2012) argues that livestock sale is far from being a business activity, but rather a buffer against adversity. The grazing and cropping cycles are interlinked. During the summer cultivation season, cattle, goats and sheep are moved away from the fields to higher surrounding grassland areas to graze freely. During the winter, post-harvest season, animals are allowed onto the fields to graze on crop residues, in addition to the rangeland (van Niekerk, 2007).

Both the commercial and subsistence farmers face several challenges, and both sets of farming activities impact on environmental ecosystems. These challenges and impacts are discussed below. In addition, a brief overview of the existing agriculture related development policies is presented.

1.1.1 Challenges facing the agriculture-sector in Upper uThukela

Commercial farmers within the Upper uThukela catchment are mainly faced with infrastructural and political issues such as lack of long-term planning and internal conflicts (Pommerieux *et al*, 2014). On the other hand, subsistence farmers are mainly affected by socioeconomic issues such as cattle theft, shortage of financial resources, poverty, disease and lack of education (Kemerink *et al*., 2013; Pommerieux *et al*, 2014; OLM, 2016). Even though some community members have been recipients of previously White-owned commercial land through the land reform programme[2] by the government, beneficiaries lack the necessary support and training to develop technical and managerial farming skills (OLM, 2016). The OLM reports that there have been 20 successful land reform cases in the municipality to date. However, due to financial limitations, subsistence farmers lack access to inputs such as improved seeds, pesticides, herbicides, fertilizer, and power machinery to improve production (Elleboudt, 2012; Pommerieux *et al*, 2014). In addition, subsistence farmers have limited credit access due to production of small volumes and scarcity of local markets. As a result, subsistence farmers cannot afford the high transportation costs, and are discouraged by the high price competition set by commercial farmers (Wood, 2011). These challenges are indirect drivers of the environmental impacts of the agriculture sector in the catchment.

1.1.2 The environmental impacts of agricultural activities in the Upper uThukela

Apart from the two sets of agricultural practitioners, a large proportion upper uThukela region is natural grasslands, with a number of conservation sites (Matthews and Catacutan, 2012; OLM, 2016). Places such as the Royal Natal National Park, Cathedral Peak and the Drakensburg World Heritage Site contribute to the region’s economy through tourism (OLM,

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[2] The land reform programme is a system where the Government buys previously White-owned land and redistribute it to previously disadvantaged individuals.

2016). However, these areas are endangered by potential threats posed by land management practices of the surrounding communities (Schulze and Horan, 2007; Matthews and Catacutan, 2012; Pommerieux *et al*, 2014). Thus, both commercial and subsistence agriculture directly and indirectly impact on natural ecosystems through land management practices. Therefore, it is important to quantify the effects of these activities on various natural resources.

Commercial agriculture mainly impacts on water quantity and quality (Matthews and Catacutan, 2012). The quantity of water is affected through construction of dams and abstractions for irrigation which reduce natural flow levels, and by replacing natural grassland by crops that use more water, therefore decreasing groundwater recharge (van Niekerk, 2007). Deterioration of water quality is mainly through the application of fertilizer, pesticides and herbicides (Elleboudt, 2012). In addition, water quality is affected by conventional cultivation and tilling methods, which cause erosion through crusting the soil, thus, resulting in sedimentation of water resources (Smith *et al*., 2005; Wood, 2011).

Subsistence agriculture is mainly sustained through natural resources, i.e. the use of natural grasslands to feed livestock and conversion of fertile land into cultivation (Elleboudt, 2012). However, due to lack of effective land management plans, subsistence practices have negative effects on conservation of natural resources. Small-scale farming mainly impacts the environment through land degradation, as a result of (i) livestock overstocking, leading to overgrazing, (ii) excessive conventional tillage practices and cropping on steep slopes, (iii) poor fire management, and (iv) harvesting of indigenous trees for firewood and other domestic purposes such as fencing and roofing (Schulze and Horan, 2007; van Niekerk, 2007; Blignaut *et al*., 2010; Nsuntsha, 2011; Wood, 2011; Pommerieux *et al*, 2014). Land degradation directly impacts the hydrological cycle as a loss of surface cover results in decreased infiltration rates, therefore reduced baseflow volumes, while stormflow volume is increased (Schulze and Horan, 2007; van Niekerk, 2007; Blignaut *et al*., 2010; Wood, 2011). In addition, degradation results in severe erosion, especially on mountainous parts of the catchment, where a large portion of small-scale farming is based. Subsistence farming is generally on relatively shallow, friable soils on steep terrains, making the fields highly susceptible to erosion (Schulze and Horan, 2007; Mander *et al*, 2008; Dlamini *et al*., 2011). This impacts the quality of downstream water resources through sedimentation.

Several land use impact studies have been conducted in the uThukela Catchment. For example, Schulze and Horan (2007) investigated the impacts of land degradation and uncontrolled burning activities on ecosystem services, and the potential economic implications of improved management in the headwaters of the uThukela Catchment. Dlamini *et al*. (2011) quantified sheet erosion and its impact on selected environmental aspects in a small agricultural catchment within the upper uThukela, while de Wienaar and Jewitt (2010) investigated the potential impacts of surface water harvesting on water resources in a small catchment within the Upper uThukela. In addition, Smith *et al*. (2005) investigated the practicality and potential impacts of adoption of conservational techniques by subsistence farmers within the uThukela Catchment.

1.1.3 Proposed development of agriculture in the Upper uThukela catchment

In 2013, the National Planning Commission (NPC, 2013) published a document entitled “National development Plan- Vision 2030” to guide the South African National Government in addressing the socioeconomic challenges facing the country. The National Development Plan (NDP), which has been adopted by the KwaZulu-Natal Provincial and Okhahlamba Local Governments (KZN, 2011; OLM, 2016), recognises the need to transform the socioeconomic status of rural communities through building an inclusive and integrated rural economy.

The NDP recognises agriculture as an important sector for economic development in rural areas, including the upper uThukela region. The NDP further recognises the need to increase food production to meet the demands of the growing population. To achieve sustainable rural economic development through the NDP, the Government aims to:

- Invest in irrigation and water storage infrastructure, where resource allows, in order to increase the amount of irrigated agriculture, supplemented by dryland cropping where feasible;
- Invest into research towards the development of new, efficient strategies to improve commercial agriculture, as well as the development of adaptation strategies and support services for small-scale, rural farmers;
- Provide adequate funding towards skills development to achieve improved and efficient management within the farming sector, and

- Accelerate the land reform programme and provide sufficient support for the beneficiaries.

The NDP also recognises the importance of sustainable management and development of natural resources. Therefore, the Government has committed to protection of conservation areas, as well as rehabilitation of degraded ecosystems.

Given these plans by the Government, there is a need to investigate the impacts of the proposed agricultural expansion on water resources by considering various possible land management scenarios. This will aid policy and decision makers to make informed water resources planning and management decisions to achieve maximum production in a sustainable manner.

1.2 Techniques for Assessing the Impacts of Agricultural Management Scenarios on Water Flows

There are three widely recognised methods of estimating/quantifying the impacts of land use change on water resources, namely paired-catchments experiments, time series analysis statistical methods and hydrological modelling (Li *et al*., 2009). Paired-catchment experiments make use of two relatively small catchments that are of relatively similar area, geology (soil and topography), climate (rainfall, temperature, and evaporation), hydrology and land cover (Brown *et al*., 2005). Both catchments are monitored for a period for calibration purposes, after which, the land use in one catchment is changed, while the other remains as a control (e.g. Nänni, 1970; Brown *et al*., 2005). After a period of monitoring, the relationship between the land use and hydrological response is established for those catchments (Li *et al*., 2009). Thus, paired-catchment experiments provide physically observed and measured evidence of the impacts of land use change on water resources. However, it is difficult to apply this method on medium or large catchments, for the catchments may change at different stages (Lørup *et al*., 1998, Shaw *et al*., 2014). In addition, the time required for paired-catchment experiments limits the use of the methodology for studies where imminent decisions are required (Andréassian, 2004; Ghaffari *et al*., 2010).

The time series approach makes use of statistical analysis to quantify the impacts of changes land use/cover on hydrological output (Li *et al*., 2009). This approach is easy to use and apply. However, the time series approach lacks definition of the physical relationships between the components of the hydrological cycle. Hence, there is a need to use a more physically based comprehensive tool to make the best use of limited datasets. Hydrological models provide a framework to conceptualize the relationships between humans, climate and the environment.

Hydrological modelling has been the more common and widely accepted approach for land use change impact assessment studies (De Fries and Eshleman, 2004; Ghaffari *et al*., 2010). Although significant research efforts have been dedicated to model development, specifically through the "Predictions in Ungauged Basins" theme by the International Association of Hydrological Sciences (Sivapalan, 2003; Hrachowitz *et al*., 2013), hydrological modelling is still faced with challenges including, among others, uncertainties in predictions at ungauged catchments (Hrachowitz *et al*., 2013; Knoche *et al*., 2014, Zhao *et al*., 2015, Engeland *et al*., 2016), insufficient understanding of catchment physical processes, and the inflexibility of many models (Hughes 2008; Mclntyre *et al*., 2014).). Despite these challenges, models which can adequately represent catchment hydrological and other terrestrial processes, and sensitive to changes in land use/cover have been widely accepted as tools to satisfactory assess the impacts of land use change on water resources (Turner *et al*., 1995; Ewen and Parklin, 1996; Lambin *et al*., 2000; Bronstert *et al*., 2002; De Fries and Eshleman, 2004; Samaniego and Bardossy, 2006, Choi and Deal, 2008). Thus, the physical-conceptual daily time step ACRU model was selected for the study. The model largely depends on the availability and quality of observed data records; therefore, the impact of declining data availability and quality on its performance was investigated.

1.3 Impacts of Hydrometeorological Data on Hydrological Modelling

South Africa is faced with a decline in hydrometeorological monitoring networks, which has impacts on hydrological modelling as the development and application of hydrological models depends on the availability and quality of observed datasets (van Rooyen and Versfeld, 2009; Pitman, 2011). The number of active rainfall stations monitored by the South African Weather Service (SAWS) has decreased from a peak of approximately 3000 stations in the 1970s to nearly 1200 by the year 2010 (Pegram *et al*., 2016). Pitman (2011) reports that the number of active flow gauging stations has also declined drastically. This decline in the number of hydrometeorological monitoring stations is due to declining resources to maintain the gauges and lack of skilled personnel; therefore, only a limited number of stations are useful for operational water resources assessment studies (Hughes, 2008; Van Rooyen and Versfeld, 2009, 2010; DWA, 2013).

Several studies have investigated the impacts of hydrometeorological data on hydrological modelling (Engel *et al*., 2007; Perrin *et al*., 2007; Liu and Gupta, 2007; Vaze *et al*., 2011; Emmanuel *et al*., 2015). Rainfall data availability and quality have been documented to have large impacts on the quality of output from hydrological models. Anctil *et al*. (2006) concluded that the use of more rainfall stations improves model simulation results, even though satisfactory results can be achieved with fewer stations. Due to limited rainfall data, many hydrological simulation studies have been completed using a single station which is either within, or outside the catchment of interest; therefore, misrepresenting the spatial variability of the catchment (Vaze *et al*., 2011). There has been limited documentation of studies investigating the impacts of streamflow data availability and quality on hydrological modelling. The few existing studies, however, conclude that a long streamflow record, representative of interseasonal variability is required for sound modelling (Sorooshian *et al*., 1983; Harlin, 1991; Yapo *et al*., 1996). In reality, only a limited number of catchments have long flow records; therefore, modellers are faced with the challenge of making use of short data records, with numerous gaps (Perrin *et al*., 2010; Mango *et al*., 2011). These data availability and quality challenges have been observed in several South African catchments; therefore, their impact on output from the ACRU model was investigated in the study.

1.4 Aims and Objectives

This study forms part of an ongoing larger project by the Water Research Commission (WRC Research Project K5/2560) titled “Modelling of water flows with change in land management in selected river catchments”. This dissertation focuses on assessing the impacts of various agricultural management scenarios on the water quantity in the upper uThukela river catchment, KwaZulu-Natal Province, South Africa, using the ACRU agrohydrological model.

With agriculture being the main sector for steering socioeconomic transformation of the uThukela Catchment, it is important to investigate the potential implications of development strategies provided by the NDP, as adopted by the OLM. According to the NDP, agriculture has the potential to increase in many rural communities. The OLM (2016) states that 23% of arable land within the municipality remains available for production, with considerable potential for irrigation development. Therefore, there is room for implementation of the NDP agricultural expansion goals within the uThukela Catchment. However, in addition to the political and socioeconomic challenges, the potential to achieve these in a sustainable manner, with limited degradation of environmental ecosystems remains in question. In this study, the potential impacts of the proposed agricultural development strategies on water resources within the uThukela Catchment using ACRU, a daily time-step hydrological model (Schulze, 1995; Smithers and Schulze, 2004) are explored. Thus, the questions that the study addresses include: what are the potential impacts of changes in agricultural land management on water resources if (i) the fraction of irrigated commercial agriculture was to be increased, (ii) subsistence agriculture was increased through reduction of commercial agriculture (i.e. land reform), (iii) current commercial dryland fields are used for crops with biofuel potential (iv) land degradation increases, or (v) the degraded areas are rehabilitated? With the decline in the monitoring of hydrometeorological stations, the study also aims to answer the following question: what are the impacts of the above-mentioned decline of hydrometeorological data quality and quantity on hydrological modelling?

As mentioned above, the main aim of the study is to quantify the impacts of changes in agricultural land management practices on water resources, particularly runoff components. This was completed through four objectives, which were:

- To investigate the impacts of declining hydrometeorological data availability and quality on hydrological modelling
- To confirm the adequacy of the ACRU model to simulate flows in two, relatively small subcatchments in the uThukela Catchment
- To use the ACRU model to simulate the impacts of changing agricultural management practices in the subcatchments selected for the confirmation study, so as to
- Simulate the impacts of the relatively significant agricultural land management scenarios at a larger scale (Upper uThukela).

This dissertation is structured as two research papers marked for publication in peer reviewed journals. This format has been accepted by the University of KwaZulu-Natal and each research paper is structured such that it can stand on its own. Therefore, there may be repetition of certain phrases, definitions and descriptions as the study was conducted in one area, using the same hydrological model. The referencing system for each paper adheres to the guidelines of the intended journal.

Following the introduction chapter, the two papers are presented in Chapters 2 and 3. Chapter 4 provides a synthesis of the papers, which highlights the main findings and conclusions drawn from the study, as well as recommendations going forward.

1.5 References

Anctil, F, Lauzon, N, Andréassian, V, Oudin, L and Perrin, C. 2006. Improvement of rainfall-runoff forecasts through mean areal rainfall optimization. *Journal of hydrology* 328(3): 717-725.

Andersson, L, Wilk, J, Graham, P and Warburton, M. 2009. Local Assessment of Vulnerability to Climate Change Impacts on Water Resources in the Upper Thukela River Basin, South Africa: Recommendations for Adaptation. Meteorological and Hydrological Institute. S-601 76 Norrköping, Sweden.

Andréassian, V. 2004. Waters and forests: from historical controversy to scientific debate. *Journal of hydrology* 291(1-2): 1-27.

Arnalte, L, 2006. Small farmers in the highest South African mountains. Dialogues, proposals, stories for global citizenship. Internet. Dialogues, proposals, stories for global citizenship. Almedio, Marseille, France. Available from: http://base.d-p-h.info/en/fiches/dph/fiche-dph-7074.html. Accessed: 20 August 2017.

Baker, TJ and Miller, SN. 2013. Using the Soil and Water Assessment Tool (SWAT) to assess land use impact on water resources in an East African watershed. *Journal of Hydrology* 486: 100-111.

Blignaut, J, Mander, M, Schulze, R, Horan, M, Dickens, C, Pringle, C, Mavundla, K, Mahlangu, I, Wilson, A, McKenzie, M and McKean, S. 2010. Restoring and managing natural capital towards fostering economic development: Evidence from the Drakensberg, South Africa. *Ecological Economics* 69(6): 1313-1323.

Bolliger, AM. 2007. Is zero-till and appropriate agricultural alternative for disadvantaged smallholders of South Africa?: a study of surrogate systems and strategies, smallholder sensitivities and soil glycoproteins. Unpublished Doctoral Dissertation, Department of Agricultural Sciences, University of Copenhagen, Denmark.

Bronstert, A, Niehoff, D and Bürger, G. 2002. Effects of climate and land-use change on storm runoff generation: present knowledge and modelling capabilities. *Hydrological processes* 16(2): 509-529.

Brown, AE, Zhang, L, McMahon, TA, Western, AW and Vertessy, RA. 2005. A review of paired catchment studies for determining changes in water yield resulting from alterations in vegetation. *Journal of hydrology* 310(1-4): 28-61.

Calzadilla, A, Zhu, T, Rehdanz, K, Tol, RS and Ringler, C. 2014. Climate change and agriculture: Impacts and adaptation options in South Africa. *Water Resources and Economics* 5: 24-48.

Chen, X, Yan, JF, Chen, Z. 2009. A spatial geostatistical analysis of impact of land use development on groundwater resources in the Sangong Oasis Region using remote sensing imagery and data. *Journal of Arid Land* 1(1): 1–8.

Choi, W and Deal, BM. 2008. Assessing hydrological impact of potential land use change through hydrological and land use change modeling for the Kishwaukee River basin (USA). *Journal of Environmental Management* 88(4): 1119-1130.

De Fries, R and Eshleman, KN. 2004. Land use change and hydrologic processes: a major focus for the future. *Hydrological processes* 18(11): 2183-2186.

Department of Water Affairs and Forestry (DWAF). 2003. *Thukela Water Management Area: Overview of Water Resources Availability and Utilisation*. Report No. P WMA 07/000/00/0203. http://www.dwa.gov.za/projects.aspx

Department of Water Affairs (DWA). 2013. *National Water Resource Strategy: Second Edition*. Pretoria, South Africa.

Dube, S, Scholes, RJ, Nelson, GC, Mason-D'Croz, D and Palazzo, A. 2013. South African food security and climate change: Agriculture futures. Economics: *The Open-Access, Open-Assessment E-Journal* 7(2013-35): 1-54.

Durning, AB. 1990. *Apartheid's environmental toll*. Washington, DC: Worldwatch Institute.

Elleboudt, R. 2012. Are conservation agriculture practices an interesting option for the smallholder farmer communities of the Okhahlamba Local Municipality, KwaZulu-Natal, South Africa? Unpublished Master's dissertation, University of Ghent, Belgium.

Emmanuel, I, Andrieu, H, Leblois, E, Janey, N and Payrastre, O. 2015. Influence of rainfall spatial variability on rainfall–runoff modelling: Benefit of a simulation approach? *Journal of hydrology* 531: 337-348.

Engel, B, Storm, D, White, M, Arnold, and Arabi, M. 2007. A Hydrologic/Water Quality Model Applicati1. *JAWRA Journal of the American Water Resources Association* 43(5): 1223-1236.

Engeland, K, Steinsland, I, Johansen, SS, Petersen-Øverleir, A and Kolberg, S. 2016. Effects of uncertainties in hydrological modelling. A case study of a mountainous catchment in Southern Norway. *Journal of Hydrology* 536: 147-160.

Ewen, J and Parkin, G. 1996. Validation of catchment models for predicting land-use and climate change impacts. 1. Method. *Journal of Hydrology* 175(1-4): 583–594.

Falkenmark, M, Andersson, L, Castensson, R, Sundblad, K, Batchelor, C, Gardiner, J, Lyle, C, Peters, N, Pettersen, B, Quinn, P, Rckström, J and Yapijakis, C. 1999. *Water: A Reflection of Land Use*. Swedish Natural Science Research Council, Stockholm, Sweden.

Foley, JA, DeFries, R, Asner, GP, Barford, C, Bonan, G, Carpenter, S. R and Helkowski, JH. 2005. Global consequences of land use. *Science* 309(5734): 570-574.

Ghaffari, G, Keesstra, S, Ghodousi, J and Ahmadi, H. 2010. SWAT-simulated hydrological impact of land-use change in the Zanjanrood basin, Northwest Iran. *Hydrological Processes* 24: 892–903.

Goldblatt, A. 2010. *Agriculture: Facts & Trends: South Africa*. World Wide Fund for Nature South Africa (WWF-SA), Cape Town, South Africa.

Harlin, J. 1991. Development of a process oriented calibration scheme for the HBV hydrological model. *Hydrology Research* 22(1): 15-36.

Howells, M, Hermann, S, Welsch, M, Bazilian, M, Segerström, R, Alfstad, T, Gielen, D, Rogner, H, Fischer, G, van Velthuizen, H, Wiberg, D, Young, C, Roehrl, RA, Mueller, A, Pasquale, S and Ramma, I. 2013. Integrated analysis of climate change, land-use, energy and water strategies. *Nature Climate Change* 3(7): 621.

Hrachowitz, M, Savenije, HHG, Blöschl, G, McDonnell, JJ, Sivapalan, M, Pomeroy, JW and Fenicia, F. 2013. A decade of Predictions in Ungauged Basins (PUB)—a review. *Hydrological sciences journal* 58(6): 1198-1255.

Hu, X, Lu, L, Li, X, Wang, J and Guo, M. 2015. Land Use/Cover Change in the Middle Reaches of the Heihe River Basin over 2000-2011 and its Implications for Sustainable Water Resource Management. *PloS one* 10(6): e0128960.

Hughes, DA. 2008. Modelling semi-arid and arid hydrology and water resources: the southern Africa experience. *Hydrological modelling in arid and semi-arid areas* 29-40.

Kemerink, JS, Méndez, LE, Ahlers, R, Wester, P and Van der Zaag, P. 2013. The question of inclusion and representation in rural South Africa: challenging the concept of water user associations as a vehicle for transformation. *Water Policy* 15(2): 2013; authors version (post-print).

Knoche, M, Fischer, C, Pohl, E, Krause, P and Merz, R. 2014. Combined uncertainty of hydrological model complexity and satellite-based forcing data evaluated in two data-scarce semi-arid catchments in Ethiopia. *Journal of hydrology* 519: 2049-2066.

KwaZulu-Natal Provincial Planing Commission (KZN). 2011. KwaZulu-Natal Provincial and Growth Development Strategy (PGDS). Pietermaritzburg, South Africa.

Lambin, EF, Rounsevell, MDA Geist, HJ. 2000. Are agricultural land-use models able to predict changes in land-use intensity? *Agriculture, Ecosystems & Environment* 82(1-3): 321-331.

Legesse, D, Vallet-Coulomb, C and Gasse, F. 2003. Hydrological response of a catchment to climate and land use changes in Tropical Africa: case study South Central Ethiopia. *Journal of Hydrology* 275(1-2): 67-85.

Leng C, Chen YN and Li XG. 2011. Evaluation of oasis stability in the lower reaches of the Tarim River. *Journal of Arid Land* 3(2): 123–131.

Li, Z, Liu, WZ, Zhang, XC and Zheng, FL. 2009. Impacts of land use change and climate variability on hydrology in an agricultural catchment on the Loess Plateau of China. *Journal of hydrology* 377(1-2): 35-42.

Liu, Y and Gupta, HV. 2007. Uncertainty in hydrologic modeling: Toward an integrated data assimilation framework. *Water Resources Research* 43(7): W07401.

Lørup, JK, Refsgaard, JC and Mazvimavi, D. 1998. Assessing the effect of land use change on catchment runoff by combined use of statistical tests and hydrological modelling: case studies from Zimbabwe. *Journal of Hydrology* 205(3-4): 147-163.

Mander, M, Blignaut, J, Schulze, R, Horan, M, Dickens, C, Pringle, C, Mavundla, K, Mahlangu, I, Wilson, A, McKenzie, M and McKean, S. 2008. *Payment for Ecosystem Services: Developing an Ecosystem Services Trading Model for the Mnweni/Cathedral Peak and Eastern Cape Drakensberg Areas*. INR Report IR281. Development Bank of Southern Africa, Department of Water Affairs and Forestry, Department of Environment Affairs and Tourism, Ezemvelo KZN Wildlife, South Africa.

Mango, LM, Melesse, AM, McClain, ME, Gann, D and Setegn, SG. 2011. Land use and climate change impacts on the hydrology of the upper Mara River Basin, Kenya:

results of a modeling study to support better resource management. *Hydrology and Earth System Sciences* 15(7): 2245.

Matthews, L and Catacutan, DC. 2012. *Context of uThukela watershed, KwaZulu Natal, South Africa*. Institute of Natural Resources, Pietermaritzburg, South Africa.

Meissner, HH, Scholtz, MM and Palmer, AR. 2013. Sustainability of the South African Livestock Sector towards 2050 Part 1: Worth and impact of the sector. *South African Journal of Animal Science* 43(3): 282-297.

Mustard, JF, Defries, RS, Fisher, T and Moran, E. 2012. Land-use and land-cover change pathways and impacts. In *Land change science* (pp. 411-429). Springer, Dordrecht.

Musvoto, C, Nortje, K, De Wet, B, Mahumani, BK and Nahman, A. 2015. Imperatives for an agricultural green economy in South Africa. *South African Journal of Science* 111(1-2): 01-08.

Nänni, UW. 1970. The effect of afforestation on streamflow at Cathedral Peak: *Report No. 1. South African Forestry Journal* 74(1): 6-12.

National Planning Commission (NPC). 2013. *National development plan vision 2030*. Pretoria, South Africa.

Ndoro, JT, Hitayezu, P, Mudhara, M and Chimonyo, M. 2013, September. Livelihood factors influencing market participation and supply volumes decisions among smallholder cattle farmers in the Okhahlamba Local Municipality, South Africa: Implications for agricultural extension programming. In *4th International Conference of the African Association of Agricultural Economists*, 22-25 September 2013, African Association of Agricultural Economists, Hammamet, Tunisia.

Nian, Y, Li, X, Zhou, J and Hu, X. 2014. Impact of land use change on water resource allocation in the middle reaches of the Heihe River Basin in northwestern China. *Journal of Arid Land* 6(3): 273-286.

Nsuntsha, ANM. 2000. Change and continuity in government institutional arrangements: implications for environmental management in the Upper Tugela area of KwaZulu-Natal. Unpublished Doctoral Dissertation, University of KwaZulu-Natal, Durban, South Africa.

Okhahlamba Local Municipality (OLM). 2016. Okhahlamba Integrated Development Plan Review 2016/2017. Okhahlamba Local Municipality, Bergville, South Africa.

Öztürk, M, Copty, NK and Saysel, AK. 2013. Modeling the impact of land use change on the hydrology of a rural watershed. *Journal of Hydrology* 497: 97-109.

Pegram, GGS, Sinclair, S and Bárdossy, A. 2016. *New methods of infilling Southern African raingauge records enhanced by annual, monthly and daily precipitation estimates tagged with uncertainty*. Report 2241/1/16. Water Research Commission, Pretoria, South Africa.

Perrin, C, Oudin, L, Andréassian, V, Rojas-Serna, C, Michel, C and Mathevet, T. 2007. Impact of limited streamflow data on the efficiency and the parameters of rainfall—runoff models. *Hydrological sciences journal* 52(1): 131-151.

Pielke, RA, Marland, G, Betts, RA, Chase, TN, Eastman, JL, Niles, JO and Running, SW. 2002. The influence of land-use change and landscape dynamics on the climate system: relevance to climate-change policy beyond the radiative effect of greenhouse gases. *Philosophical Transactions of the Royal Society of London A: Mathematical, Physical and Engineering Sciences* 360(1797): 1705-1719.

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

Pommerieux, M, Bourblanc, M and Ducrot, R. 2014. *Monitoring and evaluation of a participative planning process for the integrated management of natural resources in the uThukela District Municipality (South Africa)*. Working paper No. 2014/1, University of Pretoria, South Africa.

Samaniego, L and Bardossy, A. 2006. Simulation of the impacts of land use/cover and climatic changes on the runoff characteristics at the mesoscale. *Ecological Modelling* 196(1): 45-61.

Schulze, RE. (Ed.). 1995. *Hydrology and Agrohydrology: A Text to Accompany the ACRU 3.00 Agrohydrological Modelling System*. Water Research Commission, Pretoria, South Africa.

Schulze, RE and Horan, MJC. 2007. *Hydrological Modelling as a Tool for Ecosystem Services Trading: Case Studies from the Drakensberg Region of South Africa*. University of KwaZulu-Natal, Pietermaritzburg, School of Bioresources Engineering and Environmental Hydrology, *ACRUcons* Report 56. pp 71.

Sivapalan, M. 2003. Prediction in ungauged basins: a grand challenge for theoretical hydrology. *Hydrological Processes* 17(15): 3163-3170.

Smakhtin, VU. 2001. Low flow hydrology: a review. *Journal of hydrology* 240(3): 147-186.

Smithers, JC and Schulze, RE. 2004. *ACRU Agrohydrological Modelling System: User Manual Version 4.00.* School of Bioresources Engineering and Environmental Hydrology, University of KwaZulu-Natal, South Africa.

Sorooshian, S, Gupta, VK and Fulton, JL. 1983. Evaluation of maximum likelihood parameter estimation techniques for conceptual rainfall-runoff models: Influence of calibration data variability and length on model credibility. *Water Resources Research* 19(1): 251-259.

Statistics South Africa. 2016. cs2011.statssa.gov.za/

Turpie, J and Visser, M. 2013. The Impact of Climate Change on South Africa's Rural Areas. In: Technical Report: Submission for the 2013/14 Division of Revenue - For an Equitable Sharing of National Revenue. Midrand: Financial and Fiscal Comission, pp. 127-220. United Nations Environment Programme. 2006. *GEO Year Book 2006*: *An Overview of Our Changing Environment*, Nairobi, Kenya.

Turner, BL, Skole, B, Sanderson, S, Fischer, G, Fresco, L and Leemans, R. 1995. *Land-Use and Land-Cover Change: Science Research Plan*. IGBP Report, 35, IGBP, Stockholm, Sweden.

van Niekerk, K, Everson, T, Turpie, J, Scovronick, N, Mander, M, McKean, S. 2007. Identification of land use practices impacting on water related ecosystem services. In: (Ed), *Payment for Ecosystem Services: Developing an Ecosystem Services Trading Model for the Mnweni/Cathedral Peak and Eastern Cape Drakensberg Areas*. Maloti Drakensberg Transfrontier Project, Development Bank of Southern Africa, Department of Water Affairs and Forestry, Department of Environment Affairs and Tourism, Ezemvelo KZN Wildlife, South Africa.

Van Rooyen, JA and Versfeld, DB. 2009. *Strategic Planning for Water Resources in South Africa: A Situation Analysis 2009*. Report No. P RSA 000/00/7809. Department of Water Affairs, Pretoria, South Africa.

Van Rooyen, JA and Versfeld, DB. 2010. *Integrated Water Resource Planning for South Africa: A Situation Analysis 2010*. Report No. P RSA 000/00/12910. Department of Water Affairs, Pretoria, South Africa.

Vaze, J, Post, DA, Chiew, FHS, Perraud, JM, Teng, J and Viney, NR. 2011. Conceptual rainfall–runoff model performance with different spatial rainfall inputs. *Journal of Hydrometeorology* 12(5): 1100-1112.

Wagner, PD, Kumar, S and Schneider, K. 2013. An assessment of land use change impacts on the water resources of the Mula and Mutha Rivers catchment upstream of Pune, India. *Hydrology and Earth System Sciences* 17(6): 2233-2246.

Wang, S, Kang, S, Zhang, L and Li, F. 2008. Modelling hydrological response to different land use and climate change scenarios in the Zamu River basin of northwest China. *Hydrological Processes* 22(14): 2502-2510.

Wood, H.2011. *A Brief Overview of Farming Systems and Practices in the uThukela District*. KZN Department of Agriculture, Environment Affairs and Rural Development, Ladysmith.

Yan, B, Fang, NF, Zhang, PC and Shi, ZH. 2013. Impacts of land use change on watershed streamflow and sediment yield: an assessment using hydrologic modelling and partial least squares regression. *Journal of Hydrology* 484: 26-37.

Yapo, PO, Gupta, HV and Sorooshian, S. 1996. Automatic calibration of conceptual rainfall-runoff models: sensitivity to calibration data. *Journal of Hydrology* 181(1-4): 23-48.

Zhao, T, Wang, QJ, Bennett, JC, Robertson, DE, Shao, Q and Zhao, J. 2015. Quantifying predictive uncertainty of streamflow forecasts based on a Bayesian joint probability model. *Journal of Hydrology* 528: 329-340.

Zunckel, K. 2003. Managing and conserving southern African grasslands with high endemism: the Maloti–Drakensberg Transfrontier Conservation and Development Program. *Mountain Research and Development* 23(2): 113-118.

2. THE INFLUENCE OF DECLINING HYDROMETEOROLOGICAL NETWORKS ON HYDROLOGICAL MODELLING: A CASE STUDY FROM THE UTHUKELA CATCHMENT, SOUTH AFRICA

Mlungisi Shabalala[1*] and Michele Toucher[1,2]
[1]Centre for Water Resources Research, University of KwaZulu-Natal, Private Bag X01, Scottsville, Pietermaritzburg 3209, South Africa
[2]Grasslands-Wetlands-Forests Node, South African Environmental Observation Network (SAEON)

ABSTRACT

There has been a rapid decline in the number of functioning meteorological and flow gauging stations in South Africa. In addition, the quality of data from active stations has declined. This is concerning for hydrological modelling as hydrological models depend on the availability and quality of input hydrometeorological data to produce sound simulations. The study investigates the impact of declining hydrometerological monitoring networks on hydrological modelling, through a confirmation study in which streamflow simulated using a daily time-step, physical-conceptual model was compared to observed streamflow, in three Quaternary Catchments (V14C, V11K and V31F) of the uThukela Catchment, South Africa. Poor streamflow data for V14C resulted in no confirmation study being possible in the catchment. The model, however, adequately simulated flows for both V11K and V31F provided the simulation period was restricted to pre-2000 due to the lack of good quality rainfall and streamflow data extending beyond the year 2000.

2.1 Introduction

South Africa's growing population and associated economic growth, combined with the highly variable climate experienced and water scarcity, has increased the imperative for comprehensive management of South Africa's water resources (GreenCape, 2017; Pitman, 2011; Warburton *et al.*, 2010). Hydrological modelling has been widely accepted as a sound approach for use in water resources management and impact assessment studies, such as land use change impact assessments (De Fries and Eshleman, 2004; Ghaffari *et al.*, 2010; Vaze, 2011). However, in southern Africa, hydrological model application and development have been hampered by high spatial and temporal variability in climatic variables; lack of long, reliable records of hydroclimatic variables such as rainfall and streamflow; as well as political and socio-economic factors such as lack of skills development (Hughes, 2008). Despite these challenges, several hydrological models, e.g. Agricultural Catchments Research Unit (ACRU), Pitman and Soil and Water Assessment Tool (SWAT), have been shown to perform adequately in the region, and thus have been widely accepted as tools to assist in water resources management and assess the impacts of land use change on water resources (Turner *et al*., 1995; Ewen and Parklin, 1996; Lambin *et al*., 2000; Bronstert *et al*., 2002; De Fries and Eshleman, 2004; Samaniego and Bardossy, 2006, Choi and Deal, 2008; Vaze, 2011). However, these hydrological models remain dependent on the availability of good quality hydrometeorological data of adequate length to be able to produce sound results (Andréassian *et al*. 2001; Oudin *et al*. 2006; Beven, 2007; Engel *et al*., 2007; Perrin, *et al*., 2007; Segond *et al*. 2007; Arnaud *et al*., 2011; Pitman, 2011; Vaze *et al*., 2011).

Prior to 2000, there was a dense network of meteorological stations across South Africa. These were a combination of stations from the South African Weather Service (SAWS), the Agricultural Research Council (ARC) and private institutions. Since 2000, the number of meteorological stations has drastically declined (Pitman, 2011; Pegram *et al*., 2016), with the remaining stations being mainly owned by SAWS, and the ARC monitoring some catchments (Pegram *et al*., 2016). From a peak of approximately 3000 rainfall stations in the 1970s, SAWS now only monitors approximately 1200 active gauges (Figure 2.1), about the same number as in the early 1930s (Pitman, 2011; Pegram *et al*., 2016).

A similar trend is observed for the network of streamflow gauging stations (Figure 2.2), which are primarily the responsibility of the Department of Water and Sanitation (DWS) (Pitman, 2011; Pegram *et al*., 2016). The quality of data in active hydrometeorological stations has also drastically declined due to, among others, declining resources to maintain the gauges and lack of skilled personnel; therefore, only a limited number of stations are useful for operational water resources assessment studies (Van Rooyen and Versfeld, 2009, 2010; DWA, 2013).

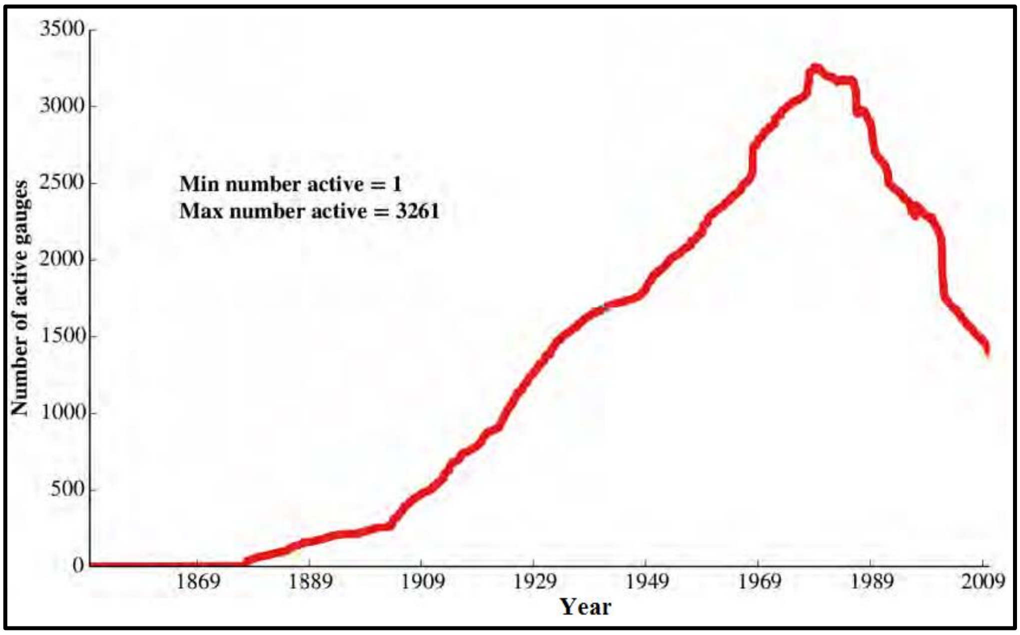

Figure 2.1: Number of active rain gauges in South Africa (Pegram *et al*., 2016).

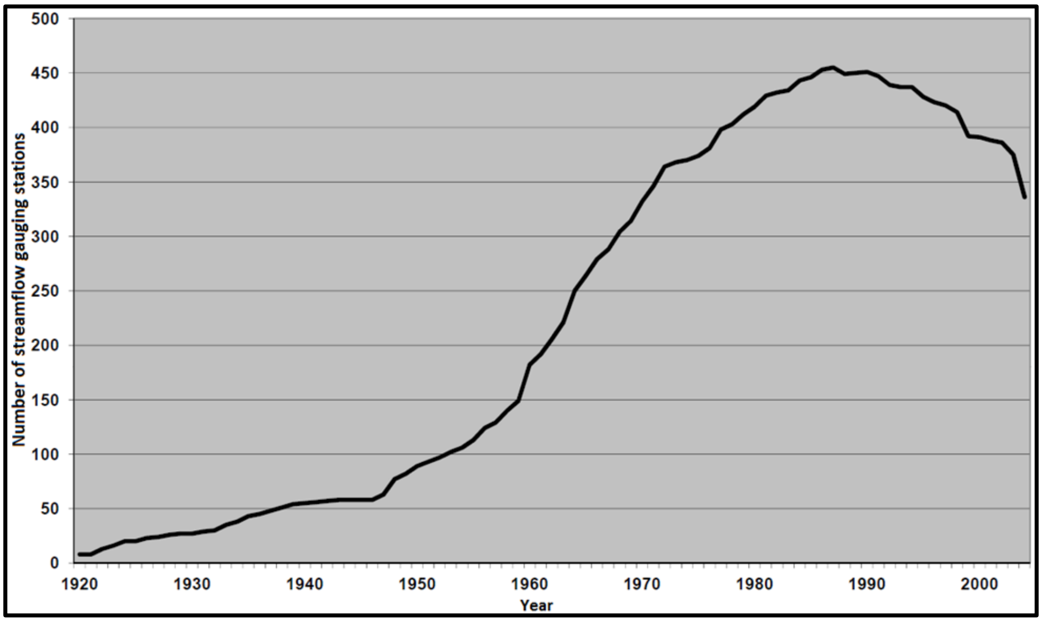

Figure 2.2: The number of useful flow gauging stations in South Africa (Pitman, 2011).

Daily water abstractions for various purposes (i.e. irrigation, industry, domestic) are also poorly monitored across the country, which is concerning for water resources management. Irrigation accounts for approximately 60% of the country's freshwater (Van Rooyen and Versfeld, 2010); however, daily abstraction records from rivers and farm dams, which are mainly monitored by individual farmers, are limited and seldom presented to the DWS (Pitman, 2011). According to the National Water Act (NWA, 1998), the Minister may require municipalities and public service providers, either on their own, or in conjunction with private institutions, to collect, store and manage municipal water use data. However, several municipalities have failed to timeously provide these records (DWA, 2013).

Given the extensive decline in the number of active hydrometeorological stations in South Africa and the decline in data quality, the impact of this on the ability of hydrological models to produce sound results needs to be investigated. Several international studies have shown the impacts of declining data quantity and quality on hydrological modelling (Andréassian *et al*., 2001; Anctil *et al*., 2006; Oudin *et al*., 2006; Segond *et al*., 2007). According to Vaze *et al*. (2011), in several modelling studies observed rainfall measurements are often at limited locations within, or outside the study catchment. This leads to the use of a single rainfall station to drive rainfall for large catchments, which is a misrepresentation of the spatial variability of precipitation within the catchment (Perrin *et al*., 2007; Vaze *et al*., 2011; Emmanuel *et al*., 2015). Increasing the number of rainfall stations increases the confidence in the model results (Anctcil *et al*., 2006; Vaze *et al*., 2011). Studies investigating the impact of streamflow data availability and quality have been limited. Nevertheless, it has been widely accepted that a long record of streamflow, representative of catchment seasonal variability, is required for sound modelling results (Sorooshian *et al*., 1983; Harlin, 1991; Yapo *et al*., 1996). In practice, however, modellers in data scarce regions are faced with the unavailability of gauging stations in many catchments. In cases where data are available, existing flow records are often of a short duration and flawed by gaps or suspicious values due to uncertainties related to extrapolation of rating curves (Perrin *et al*., 2007).

This paper aims to investigate the impacts of the availability and quality of observed hydrometeorological data on hydrological modelling, through a confirmation study where streamflow simulated using a physical, conceptual, daily time-step model is compared to observed streamflow in three Quaternary catchments of the uThukela Primary Catchment, KwaZulu-Natal Province, South Africa. For the purpose of the study, the argument by Oreskes *et al*. (1994) and Refsgaard and Henriksen (2004) that a physical, conceptual model representing a complex, open natural system where operative processes are incompletely understood, and the required empirical input data are incompletely known is confirmed rather than verified or validated, was adopted. According to Oreskes *et al*. (1994), the greater the number, and the wider the range of confirmation studies, the greater the confidence in the model.

2.2 Methodology

Following the description of the study area, the needed background to the ACRU model is discussed, prior to the configuration of the model and input data being detailed.

2.2.1 Study area

The uThukela catchment (Figure 2. 3) covers an area of 29 036 km^2, stretching from 27.41^o to 29.40^o S and 28.96^o to 31.44^o E. Elevations range from over 3 000 m in the Drakensberg Mountain range, where the uThukela River and its tributaries begin, to sea level where the river system enters the Indian Ocean, 85 km north of Durban (DWAF, 2003). The uThukela catchment is characterised by high spatial and temporal variability of climatic variables, with mean annual precipitation (MAP) ranging from nearly 2 000 mm in the high altitude areas in the west of the catchment to as low as approximately 600 mm in the low-lying valleys inland. Rainfall mainly occurs in summer (i.e. November to March), with January being the wettest month. Temperatures range from an average 2^{o}C per annum in the Drakensberg Mountains to 21^{o}C in the Valley region. The highest daily average temperatures are recorded in January, ranging from 26^{o}C to 32^{o}C in the valleys, while 20^{o}C is seldom exceeded in the Drakensburg Mountains. Winter temperatures range from below zero in the Drakensberg Mountains region, to an average 10^{o}C in the Valley region (DWAF, 2003).

Soils are predominantly deep, well-drained, highly weathered on flat slopes; while shallow, poorly drained soils dominate in areas of high relief. The main parent rocks are Basaltic lava of the Drakensberg, Stormberg and Beaufort beds, old granites and gneisses, beds of Table Mountain Sandstone and rocks of Dwyka and Ecca. The uThukela catchment is an intensive farming region, with both commercial and small-scale, subsistence farmers (Andersson *et al*., 2009). The commercial farmers grow rainfed maize during summer and irrigated wheat during the winter season, while the small-scale farmers only grow rainfed maize. Both sets of farmers are also cattle owners, with the commercial farmers at a larger scale than the subsistence.

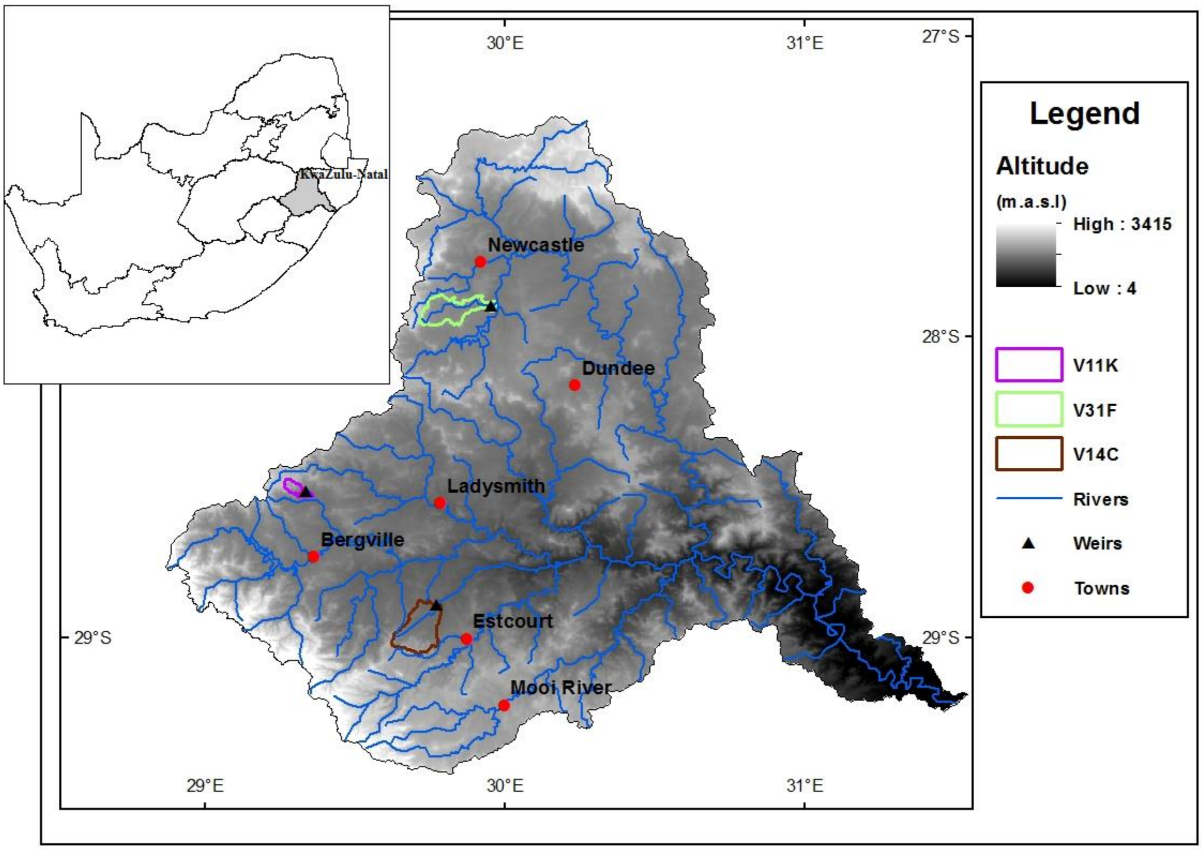

Figure 2.3: Location of the uThukela catchment, with altitude, river networks, selected Quaternary catchments, weirs and main towns shown.

Several reservoirs exist in the catchment, including the Woodstock Dam which is the main source of water for the Tugela-Vaal transfer scheme. Other dams include Spioenkop, Wagendrift, Bell Park; and many small farm dams which are mainly for irrigation purposes (DWAF, 2003). Other land uses in the catchment include natural grasslands, i.e. the Southern tall grassland, Natal sour sandveld, Valley bushveld, Highland sourveld and Dohne sourveld; nature conservation and tourism sites; commercial forestry, and large tracts of alien vegetation and bush encroachment in some parts of the catchment.

The Department of Water Affairs subdivided the Thukela Catchment into 86 operational Quaternary Catchments (QCs). To investigate the impact of the quality of hydrometeorological data on modelling, three QCs, namely V14C, V11K and V31F, were selected (Figure 2.3). These catchments were selected as streamflow records were available for the catchments, they were relatively small in size and their land uses are representative of the larger uThukela Catchment (Table 2.1).

2.2.2 The ACRU agrohydrological model

The ACRU agrohydrological model, developed at the University of KwaZulu-Natal, is a physical, conceptual, multi-purpose, multi-soil-layered, daily time-step model that is sensitive to changes in land use/cover (Schulze, 1995; Smithers and Schulze, 2004). ACRU has been applied in various hydrological and land use modelling studies in South Africa (for example, Tarboton and Schulze, 1990, 1991; Schulze *et al*., 1997; Kienzle *et al*., 1997; De Wiennaar and Jewitt, 2010; Warburton *et al*., 2012; Le Maitre *et al*., 2014). In addition, the model has been applied in studies outside South Africa; for example, in Zimbabwe (Butterworth *et al*., 1999), Germany (Herpertz, 2001), New Zealand (Kienzle and Schmidt, 2008; Schmidt *et al*., 2009), the USA (Martinez *et al*., 2008) and Canada (Forbes *et al*., 2010). The ACRU model is not a parameter-optimising model, where input parameters are adjusted and calibrated to produce a best fit; rather the model uses input variables measured or estimated from physically based characteristics of the catchment (Schulze 1995; Smithers and Schulze, 2004; Schulze and Pike, 2004). Being multi-level, ACRU allows for various pathways for input data depending on information available to the user, or the detail of output required (Schulze 1995; Schulze and Pike, 2004). Given this, the model is suitable to data constrained situations, thus it was selected for this study.

The conceptualisation of the hydrological cycle within the ACRU model is shown in Figure 2.4. As a minimum, the model requires daily rainfall, maximum and minimum temperature and A-pan reference evaporation as input climate information. In the absence of observed A-pan evaporation values, A-pan equivalent evaporation can be estimated through other methods (i.e. Penman, 1960; Penman-Monteith, (Allen *et al*., 1998); Hargreaves and Samani, 1985). Runoff in the ACRU model is a function of a daily multi-soil layer budgeting system (Figure 2.4). Precipitation, through rainfall or irrigation, is the main source of water into the system. Stormflow and interception are accounted for first from the incoming precipitation (Schulze, 1995), with the remainder infiltrating into the A horizon until the soil moisture content in this layer reaches field capacity. Water then moves into the B horizon as saturated drainage, when this layer is saturated, further percolation into the intermediate and groundwater store occurs, which contributes to runoff as baseflow. The model also takes into account unsaturated distribution of soil water up and down the soil profile, at a relatively slow rate (Schulze, 1995). The presence (or absence) of land cover controls the amount of water lost to the atmosphere through transpiration, evaporation from the soil and canopy interception. In ACRU, transpiration is a function of vegetation properties such as plant type, growth stage and critical leaf potential, and climate-related factors such as water availability and air temperature (Schulze, 2007). Monthly crop coefficients are used to estimate transpiration, and are required as input. Monthly canopy interception is determined by using input monthly leaf area indices (LAI), which are the ratio of the specific surface area of leaves to the ground surface below the canopy. Roots are the main mechanism through which water loss as transpiration by the plant occurs, and are responsible for nutrient uptake (Schulze, 1995). Thus, ACRU requires the fraction of active roots in the topsoil horizon (ROOTA) as input, from which the subsoil roots are calculated (ROOTB). These root distribution fractions integrate plant genetic and environmental factors including plant type and growth stage.

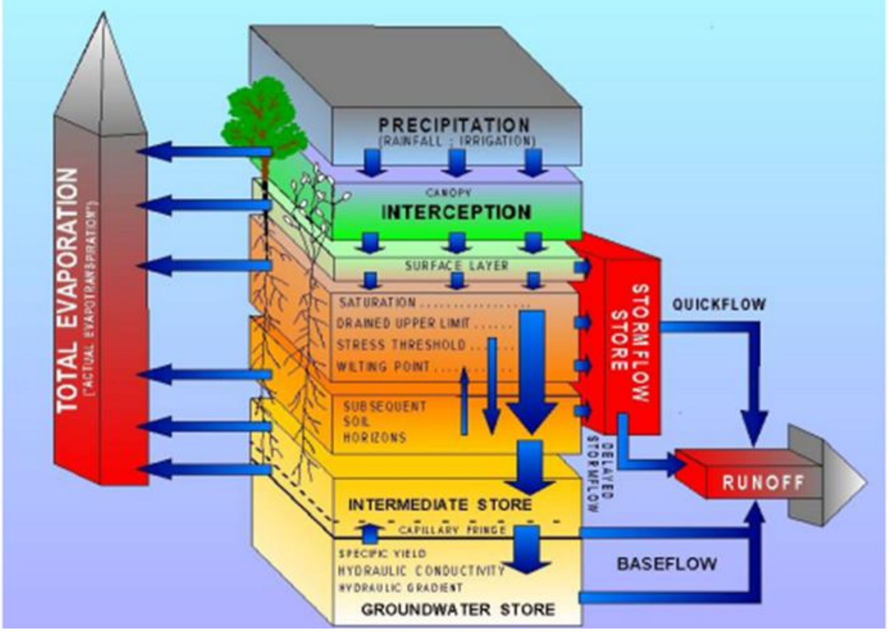

Figure 2.4: Layers and processes of the ACRU soil water budget system (Schulze, 1995; Smithers and Schulze, 2004).

2.2.3 ACRU model configuration

2.2.3.1 Subcatchment delineation

Quaternary Catchments V14C, V11K and V31F were delineated, using 1:50 000 topographic maps, into smaller subcatchments based on water movement, altitude and topography, land cover and the presence of hydrological structures such as gauging stations and reservoirs.

According to Schulze (1995), the ACRU model is best suited for catchments less than 50 km^2; therefore, V31F and V14C were divided into eight and nine subcatchments, respectively, while V11K was left as one subcatchment as it was less than 50 km^2. For modelling purposes, these subcatchments were further divided into homogeneous land use units, termed hydrological response units (HRUs). These HRUs were configured in a logical representation of river flow, i.e. an upstream HRU flows into the adjacent HRU downstream.

2.2.3.2 Climatic data

The ACRU model requires daily rainfall, maximum and minimum temperature as a minimum input. The updated rainfall database by Pegram *et al*. (2016) was investigated; however, this could not be used as it is only readily available as monthly values. For the years prior to 2000, high quality, patched daily rainfall data for 12 153 stations was available from a database developed by Lynch (2004). Similarly, quality controlled daily maximum and minimum temperatures were available from a 1’ by 1’ latitude/longitude gridded database developed by Schulze and Maharaj (2004). Stations were selected from these databases based on length and quality of the rainfall record, and the distance between the station and the catchment.

Rainfall and temperature data extending beyond the year 2000 were obtained from SAWS and ARC for the selected rainfall stations. However, many of the initially selected stations had ceased monitoring, or had numerous missing values. Further to this, there were no nearby stations available to use to patch with where the record had missing values. The next available stations, which were either at a large distance from the catchment, or at an altitude unrepresentative of the catchment, thus had to be used in the model or were used to patch missing values. To illustrate, the secondary catchment within which two of the study quaternaries fell was selected, *viz*. V1. Meteorological stations inside and within a radius of a 50 km distance from the catchment boundary were identified (Figure 2.5). Each station was assigned a quality code, i.e. active or discontinued; and good or poor quality. The code “discontinued” refers to stations that have ceased monitoring, while active stations record to present day (May 2016). A station was regarded as poor quality if the rainfall record had more than 50% missing values for the period 1960-1999, based on the Lynch (2004) database. From a fairly dense network of good quality stations inside and around V1 at the end of the year 2000, only four historically good quality stations remain active today inside the 7 600 km^2 catchment, and two more within 50 km (Figure 2.5).

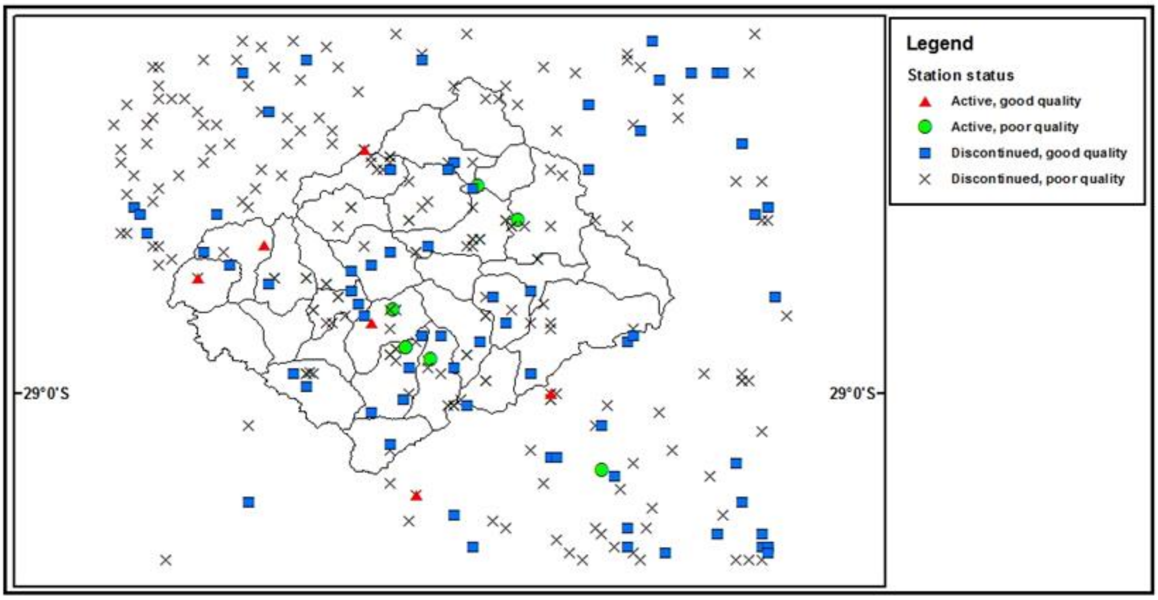

Figure 2.5: Active (1960-present) and discontinued rainfall stations inside and within 50 km from V1 secondary catchment, with a quality code assigned to each station.

In order to improve the representation of the catchments' aerial rainfall by the selected stations, the option to adjust daily rainfall by a month-by-month adjustment factor (CORPPT) was invoked in ACRU. This monthly adjustment factor was obtained by dividing the catchment's median monthly rainfall obtained from geographically weighted regression derived 1' by 1' raster surfaces of median monthly rainfall (Lynch, 2004) by the rainfall station's median monthly rainfall. From the input daily temperatures, daily A-pan equivalent evaporation was internally computed using the Hargreaves and Samani (1985) equation due to the unavailability of daily A-pan records in the study area. Average daily streamflow data for the Quarternary Catchments were obtained from DWS (http://www.dwa.gov.za/hydrology/).

2.2.3.3 Soils

Soil texture classes for each subcatchment were determined from the soil depth classes by Schulze (1995). Soils variables required for daily water budgeting were obtained from a gridded national database by Schulze and Horan (2007). From this source, the soil depth (m), porosity (m/m), field capacity (m/m) and permanent wilting point (m/m) estimates for the A and B horizons for each subcatchment were extracted. Estimates for the fraction of water that moves daily from the A to the B Horizon and from the B Horizon to groundwater were also obtained from Schulze and Horan (2007). The fraction of groundwater that contributes to runoff per day was set at 0.009 as recommended by Schulze *et al*. (1995) for South African catchments.

Stormflow response variables were also obtained from the database by Schulze and Horan (2007). The fraction of stormflow that is converted into runoff on the same day as the rainfall event (QFRESP) was 40% for V11K and 30% for V14C and V31F. The critical stormflow generation depth (SMDDEP) was set at the depth of the A horizon, as recommended by Schulze *et al*. (1995).

2.2.3.4 Land cover

To confirm the ACRU model for current conditions, the Ezemvelo KZN Wildlife (EKZN, 2011) database was used as the primary source of land cover information. Where necessary, the National Land Cover (NLC, 2000) map was used. The major land cover type in all three catchments was natural grassland, with large proportions of dryland commercial agriculture in V14C and V31F (Table 2.1).

Table 2.1: Proportions of different land uses in uThukela Primary Catchment and study Quartenary Catchments V11K, V14C and V31F.

Catchment	**uThukela**	**V11K**	**V14C**	**V31F**
Area (km^2)	29036	23	196	155
MAP (mm p.a)	810	912	772	811
Average Altitude (m.a.s.l)	1234	1431	1230	1323
Gauging Station	-	V1H030	V1H009	V3H009
Land use (%)				
Natural vegetation	57	92	50	63
Degraded areas	9	4	9	2
Water bodies	2	-	1	1
Wetlands	-	-	-	4
Commercial forests	4	-	8	7
Commercial agriculture				
- Dryland	6	4	18	18
- Irrigated	3	-	2	3
Subsistence agriculture	8	-	4	-
Residential & Urban areas	6	-	8	2

Where natural vegetation remained according to the EKZN (2011), the dominant Acocks (1988) Veld type for that area was deteremined. The dominant veld type in V31F was southern tall grassveld, while V11K and V14C were largely covered by Natal sour sandveld. Daily evapotranspiration was internally estimated from monthly above- and below-ground plant physiological variables. These were crop coeffients, interception storage (mm) and root distribution between the A and B horizons obtained from Schulze (2004) for each veld type. The effective rooting depth was set as the sum of the depth of the A and B horizon. Pastures were assumed to be irrigated from March to October. Through expert consultation, the assumed irrigation method was based on plant demand, allowing for plant available water to decrease to 80% before refilling the soil profile. Irrigation water was abstracted from dams. Based on field observation, the dryland agriculture activity was sugarcane in V31F and maize in V11K and V14C. There were no large reserviors in the study catchments; thus, the total volume of small farm dams was assumed to be one large dam at the bottom of each subcatchment. No environmental flows were released from the dams. Seepage was assumed to be 0.0006 of the total dam volume, as suggested by Schulze *et al*. (1995).

2.3 Results

2.3.1 Hydrometeorological data analysis

Rainfall is a primary driver of the hydrological cycle in the ACRU model, thus the availability and quality of rainfall data is important. It is imperative that rainfall stations with good quality data, which are representative of catchment conditions are used. Post-2000 climate records for the driver meteorological stations were requested from SAWS and ARC for the three study catchments. Due to the high climatic variability within the uThukela catchment, only the stations inside and within 50 km from the centroid of each study catchment were considered for use as model input. No meteorological station was available inside and within 50 km from V11K. In addition, streamflow record in the catchment was only available for period 1968-1993; therefore, the catchment was not included in the assessment of the impact of rainfall data availability on modelling. Both V14C and V31F had eight available stations for selection (Table 2.2 and 2.3).

Table 2.2: Stations that were active post-2000 inside and within 50 km from V14C.

Station	Source	MAP (mm)	Altitude (m)	Record length	Distance (km)	% missing
0268016 AX	SAWS	1004	1759	1903-2016	38	84.2
0268883 W	SAWS	753	1393	1903-2016	40	74.7
0299709 A	ARC	700	1244	2002-2010	34	1.5
0299797 A	ARC	679	1114	2012-2016	32	0
0299863 A	ARC	768	1100	1973-2015	24	0.9
0300085 A	ARC	710	1060	1998-2013	16	1.0
0300454 W	SAWS	750	1069	1993-2016	43	86.4
0300690 W	SAWS	669	1144	1882-2012	16	46.7

Table 2.3: Stations that were active post-2000 inside and within 50 km from V31F.

Station	Source	MAP (mm)	Altitude (m)	Record length	Distance (km)	% missing
0334663 A	ARC	798	1295	1975-2009	17	59.6
0335548 A	ARC	710	1219	2000-2016	50	7.2
0369777 A	ARC	681	1782	2000-2004	40	0
0370655 A	ARC	765	1311	1961-2009	2	25.9
0370807 W	SAWS	696	1247	1882-2016	11	0.7
0370856 W	SAWS	768	1189	1994-2016	20	7.4
0371437 W	ARC	576	1194	1882-2016	42	15.4
0371438 A	ARC	526	1210	1975-2016	42	62.9

To select a rainfall station best representative of each subcatchment within V14C and V31F, the record length, MAP, altitude, proximity and the fraction of missing values were considered. In addition, the monthly CORPPT values were considered, with a greater weighting placed on the representation of subcatchment summer (November to March) precipitation by each station as the catchment falls in a summer rainfall region. For V14C, station 0300690 W was best representative of precipitation for the low altitude subcatchments (i.e. 3, 4, 7, 8 and 9), while 0299863 A was best suited to drive rainfall for the high-altitude subcatchments (i.e. 1, 2, 5 and 6). The record from both these stations contained periods of missing data. In most cases, the periods of missing data at the gauges and nearby gauges corresponded, as a result 0300690 W was patched using data from a station with elevated precipitation and lower temperature values, while 0299863 A was patched using data from stations far away. Station 0300690 W record ended in February 2012, limiting the model confirmation length (Figure 2.6).

Station 0370807 W was selected to drive rainfall for V31F as it had the most consistent post-2000 rainfall record (Figure 2.7). However, the station recorded rainfall only; therefore, temperature estimates were obtained from station 0334663 A which was 14 km away from 0370807 W, with a record ending in March 2009 (Table 2.3). To extend the temperature record station 03780856 W was considered. However, there were 40 days with missing values between October 2009 and January 2010, restricting the confirmation to September 2009, further demonstrating the decline in available meteorological data.

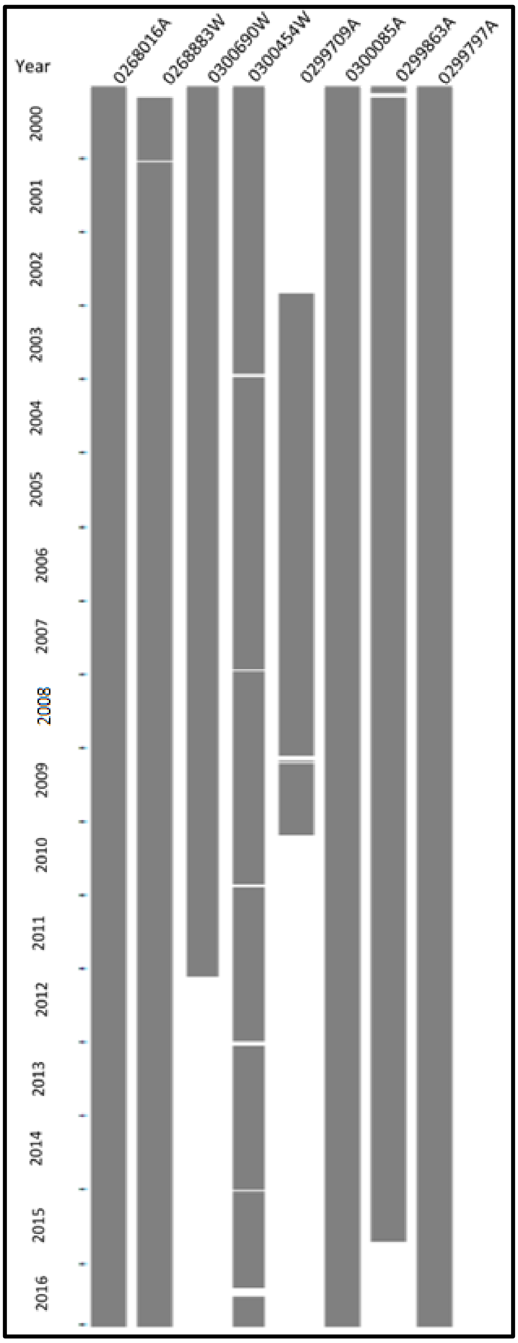

Figure 2.6: The amount of available rainfall data for stations with post-2000 data at QC V14C, with missing periods shown by gaps.

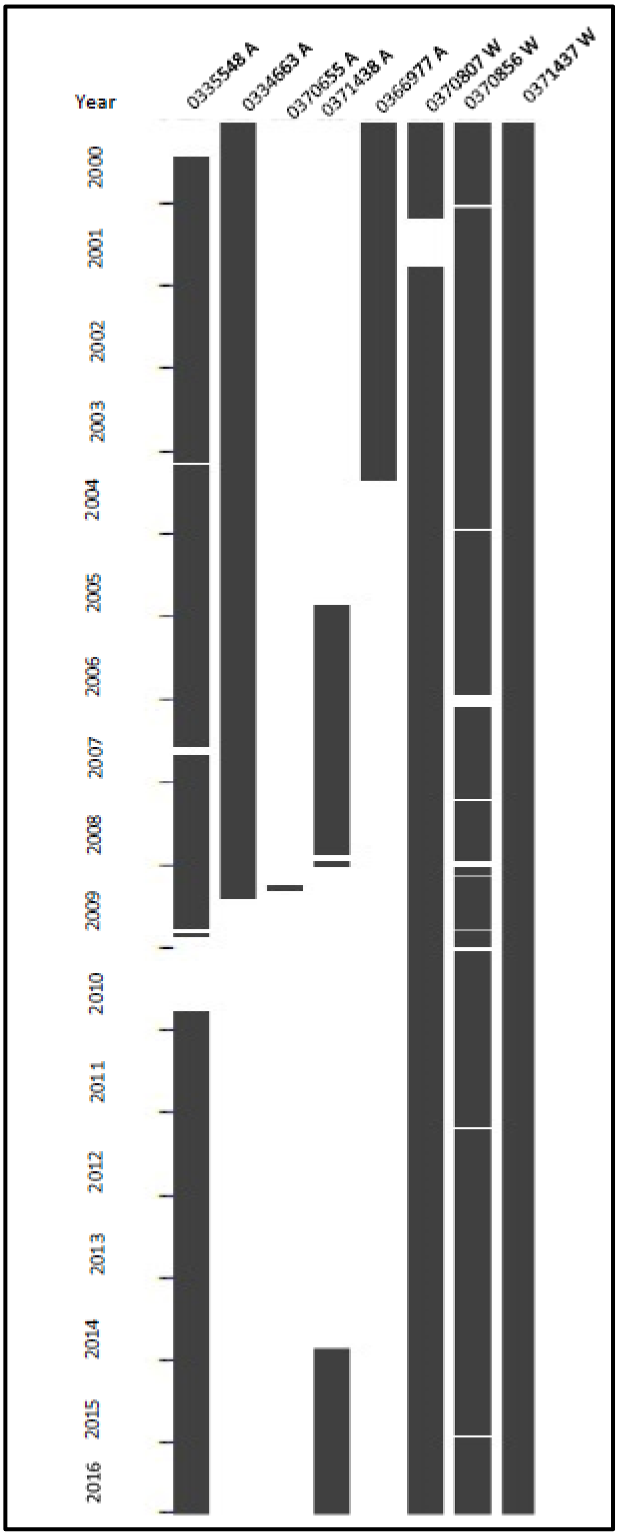

Figure 2.7: The amount of available rainfall data for stations with post-2000 data at QC V14C, with missing periods shown by gaps.

Model confirmation for current conditions was also limited by the availability and quality of streamflow data. For V11K, the streamflow record was only available between May 1968 and February 1993, and was characterized by numerous missing values (Table 2.4). The weirs at

V14C and V31F are remain active; however, a decline in quality of the data beyond 2005 for V14C (Table 2.4) was noted. Although the record for V31F had a significant amount of missing values between 1960 and 1965, it was more consistent, with few missing values beyond 1965.

Table 2.4: The fraction of missing values for Quaternary catchments V14C and V31F.

	Percentage missing streamflow		
Period	**V14C**	**V11K**	**V31F**
1960-1964	1.7	-	38.6
1965-1969	0.4	2.1	0.5
1970-1974	1	5.0	0
1975-1979	0.7	8.3	0.4
1980-1984	0.5	2.5	0.7
1985-1989	0.5	22.9	2.2
1990-1994	0.9	0	0
1995-1999	1.2	-	0
2000-2004	0.1	-	0
2005-2009	17.1	-	0
2010-2012	32.9	-	-

2.3.2 Data availability and quality impacts on model confirmation

2.3.2.1 Modelling with the longest record length

The ACRU model was configured to conduct a confirmation study in the three QCs, with the simulation length set to the period with available observed meteorological and streamflow data in each QC. The model confirmation objectives were set as a percentage difference less than 15% between observed and simulated conservation statistics (i.e. sum, mean and standard deviation of daily flows), a coefficient of determination (R^2) value above 0.7, a slope value close to 1 and a Nash-Sutcliffe efficiency index (Nash and Sutcliffe, 1970) (E_f) similar to R^2 (Smithers and Schulze, 2004; Warburton *et al.*, 2010).

Catchments V11K, V14C and V31F were configured to simulate for 1968 - 1993, 1960 - 2012 and 1960 - 2009, respectively. Results from the initial simulations indicated a systematic oversimulation of low flows at catchments V11K and V31F, while high flows were simulated well, with a slightly better simulation at V31F (Figure 2.8 and 2.10). At V14C, there was a systemetic oversimulation of both the low and high flows (Figure 2.9). As a result, the target objectives were not met in all catchments (Table 2.5). The model performed best in catchment V31F (Table 2.5), and this catchment had the lowest number of missing rainfall and flow values. The catchment characteristics, particularly the soil depth and depth at which stormflows are generated were reassessed and adjusted. However, this did not improve the simulated results when compared to the observed flows, particularly for catchment V14C. Therefore, as the poorest performance correlated to the catchments with the lowest quality hydrometeorological data available, the poor model performance was assumed to be largely a result of the quality of input data.

Further investigation of the weir records for V14C using the Indicators of Alterations (The Nature Conservancy, 2009) software was undertaken. The results indicated that in 1981 there was a change in the catchment which altered the flow regime. Post 1981, the one day, 7 day and 90 day maximum flows had greater variability (Figure 2.11). However, no documentation of the source of this inhomogeneity could be found. Given the problems with the data and the lack of documentation of the impacts in the catchments, V14C was excluded from further analysis.

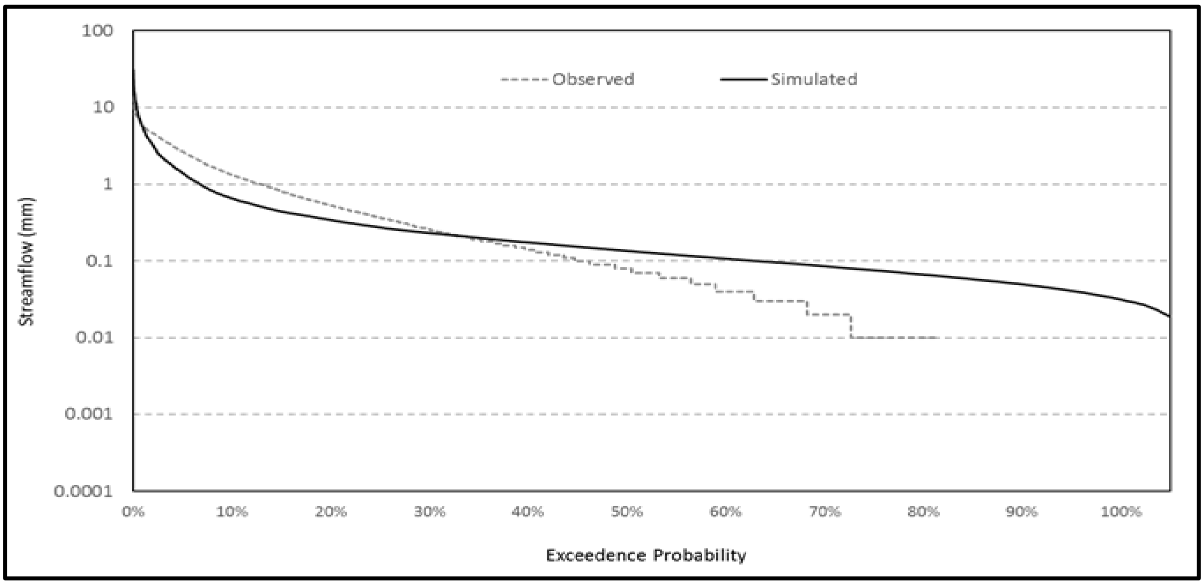

Figure 2.8: Flow duration curves showing the relationship between observed and simulated streamflow for V11K.

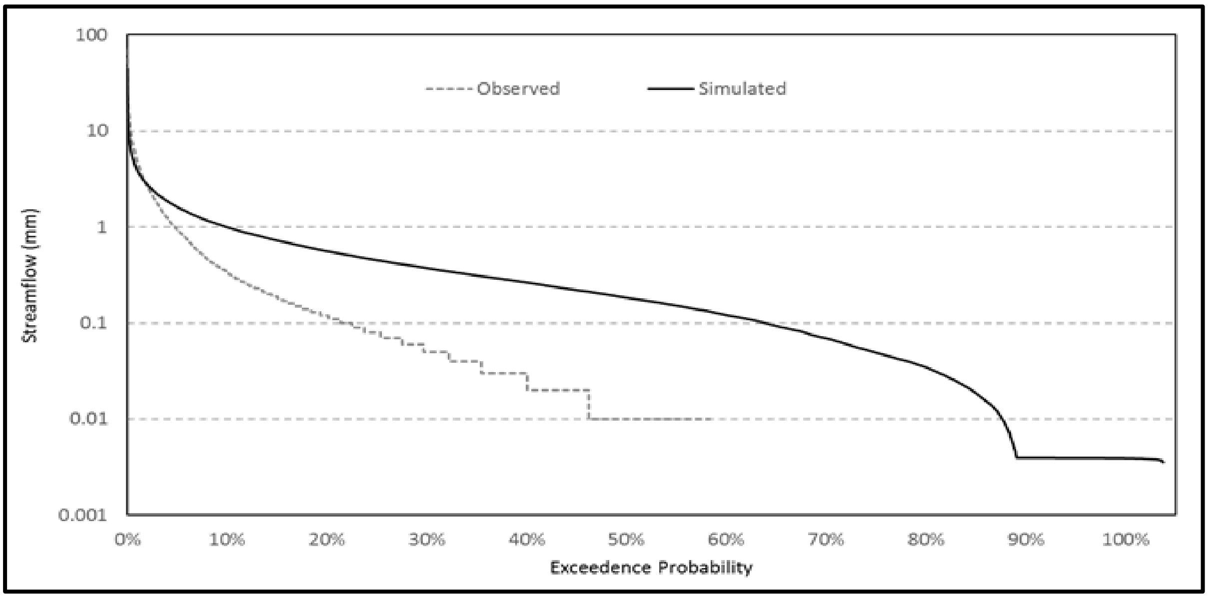

Figure 2.9: Flow duration curves showing the relationship between observed and simulated streamflow for V14C.

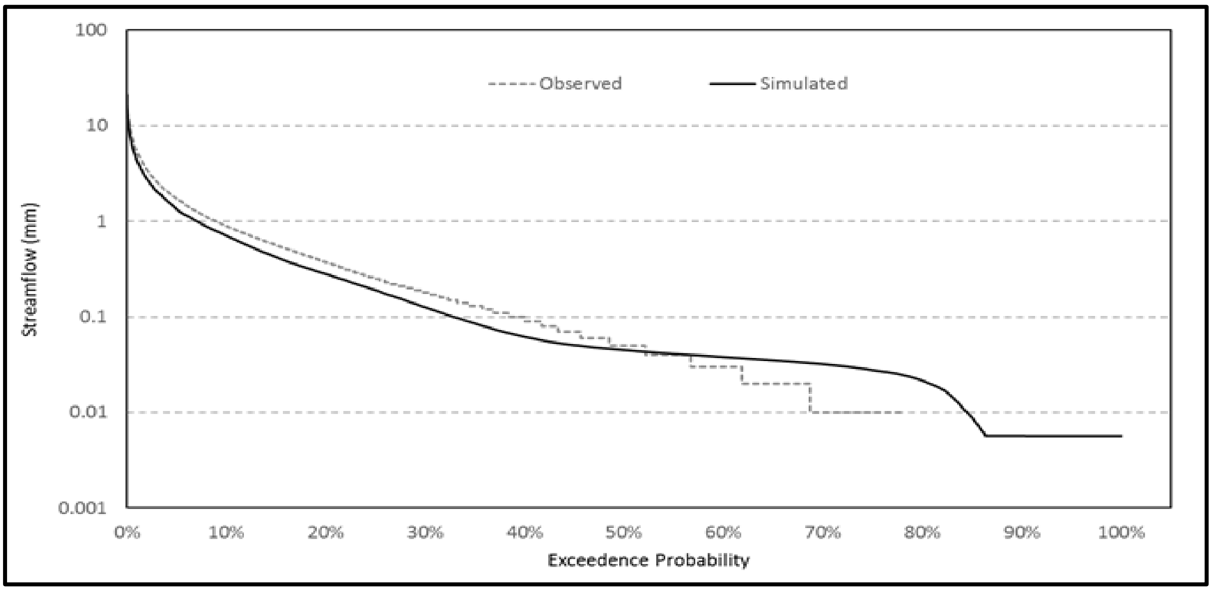

Figure 2.10: Flow duration curves showing the relationship between observed and simulated streamflow for V31F.

Table 2.5: Comparison of observed and simulated statistics between observed and simulated streamflow for the longest period with data.

	V11K **1968-1993**	**V14C** **1960-2012**	**V31F** **1960-2009**
Total observed flows (mm)	4101	4523	6466
Total simulated flows (mm)	2757	7691	5208
Ave. error in flow (mm/day)	-0.161	0.173	-0.072
Mean observed flows (mm/day)	0.491	0.247	0.372
Mean simulated flows (mm/day)	0.330	0.420	0.299
% Difference between means	32.8	-70.0	19.4
Variance of observed flows (mm)	1.326	1.866	1.127
Variance of simulated flows (mm)	0.995	0.844	0.845
% Difference between Variances	25.0	54.8	25.0
Std. Deviation of observed flows (mm)	1.152	1.366	1.061
Std. Deviation of simulated flows (mm)	0.997	0.918	0.919
% Difference between Std. Deviations	13.4	32.8	13.4
Correlation Coefficient: Pearson's R	0.539	0.562	0.583
Regression Coefficient (slope)	0.467	0.378	0.504
Regression Intercept	0.101	0.326	0.112
Coefficient of Determination: R^2	0.291	0.316	0.339
Nash—Sutcliffe Efficiency Index (E_f)	-0.114	0.288	0.254

Figure 2.11: The differences in 1 day, 7 day and 90 day maximum flows before and after 1981 at weir V1H009.

2.3.2.2 Modelling using good quality hydrometeorological data

To demonstrate the ability of the ACRU model to simulate streamflows adequately when good quality data is used, a confirmation study was undertaken using only the extensively checked, good quality hydrometeorological data available for V11K and V31F. This resulted in the simulation period being limited to 1970 - 1985 for V11K and 1970 - 1994 for V31F. The model confirmation objectives were set as a percentage difference less than 15% between observed mean, standard deviation and variance of daily flows, an average error of 0, a R^2 value above 0.7, a slope value close to 1 and a E_f similar to R^2 (after Smithers and Schulze, 2004; Warburton *et al*., 2010).

For both catchments, the low flows were well simulated in the initial simulation, while peak flows were systematically under simulated. The catchments were reassessed and the steepness related soil variables were adjusted. The percentage of stormflow that would leave the catchment on the same day as the rainfall event was increased to 50% in the steep subcatchments (subcatchments 1, 2 and 3) in V31F and to 40% in V11K. To account for the poor drainage of soils in V11K, the fraction of water that moves from the topsoil to subsoil and from the subsoil to groundwater when the soil is saturated was decreased. Lastly, the depth of the B-horizon in V11K was slightly reduced to account for the overall steepness of the catchment. In addition, SMDDEP was changed from the depth of the A-horizon to a uniform value of 0.2 m across V31F.

Following these adjustments, the ACRU model adequately simulated the flows measured at V1H030 and V3H009, with the differences between the conservation statistics below the 15% target objective (Table 2.6). The difference between the observed and simulated variances and means was approximately 9%, while the difference between the standard deviations was approximately 5% at V11K. The regression statistics, however, were below the objective target, with an R^2 value of 0.361 and a Nash-Sutcliffe Efficiency Index of 0.159. At V31F, the percentage differences between observed and simulated statistics were close to 0. The regression statistics also indicated a good simulation, with a slope value of 0.824, an intercept close to 0 and an R^2 value of 0.679. The Nash-Sutcliffe Efficiency Index was close to the R^2 value, which indicates a good simulation.

Table 2.6: Summary of simulation statistics for catchments V11K and V31F.

	V11K 1970 - 1985	V31F 1970 - 1994
Total observed flows (mm)	3059	2531
Total simulated flows (mm)	2764	2512
Ave. error in flow (mm/day)	-0.053	-0.003
Mean observed flows (mm/day)	0.553	0.367
Mean simulated flows (mm/day)	0.500	0.364
% Difference between means	9.66	0.74
Variance of observed flows (mm)	1.486	1.185
Variance of simulated flows (mm)	1.633	1.186
% Difference between Variances	-9.88	-0.07
Std. Deviation of observed flows (mm)	1.219	1.089
Std. Deviation of simulated flows (mm)	1.278	1.089
% Difference between Std. Deviations	-4.83	-0.03
Correlation Coefficient: Pearson's R	0.601	0.824
Regression Coefficient (slope)	0.630	0.824
Regression Intercept	0.151	0.062
Coefficient of Determination: R^2	0.361	0.679
Nash—Sutcliffe Efficiency Index (E_f)	0.159	0.648

A time series of monthly flows for V11K indicated a good simulation of the regression limb of the hydrograph (Figure 2.12). However, low flows appeared to be oversimulated systematically, while peak flows were under simulated for most of the confirmation period. The oversimulation of the low flows was also evident from the flow duration curve (Figure 2.13). However, there was a good correspondence between the accumulated magnitude of the observed and simulated flows.

The time series of monthly flows indicates that the model adequately simulated flows for V31F (Figure 2.14). The flow duration curve indicates a general oversimulation of low flows (Figure 2.15). However, the accumulated total flows were well simulated. Based on these results, the ACRU model was deemed to be able to adequately simulate flows for subcatchments V11K and V31F.

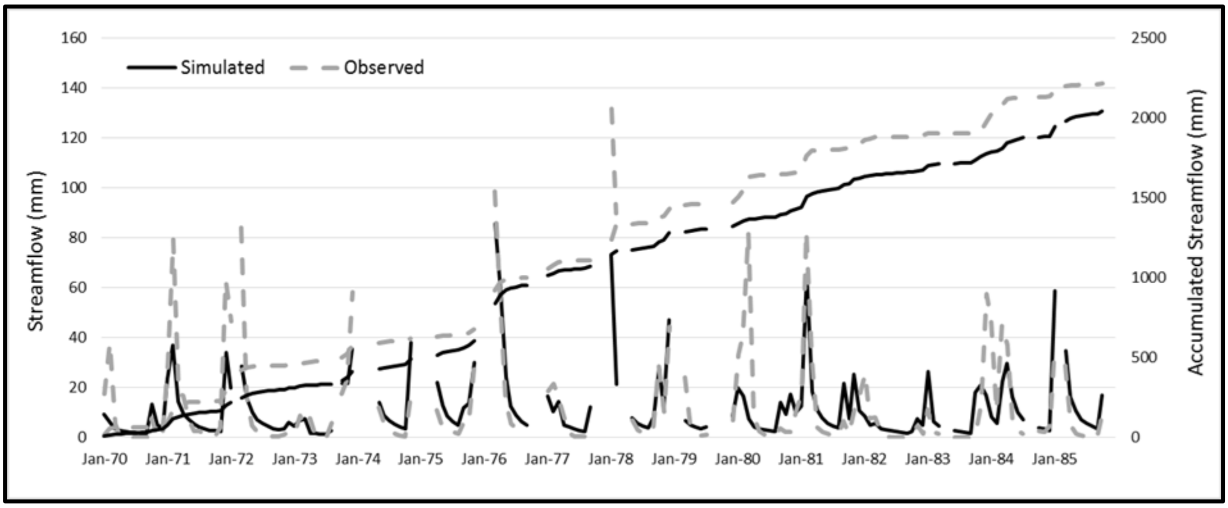

Figure 2.12: Comparison between observed and simulated total monthly flows and accumulated flows for the verification period (1970-1985) in V11K.

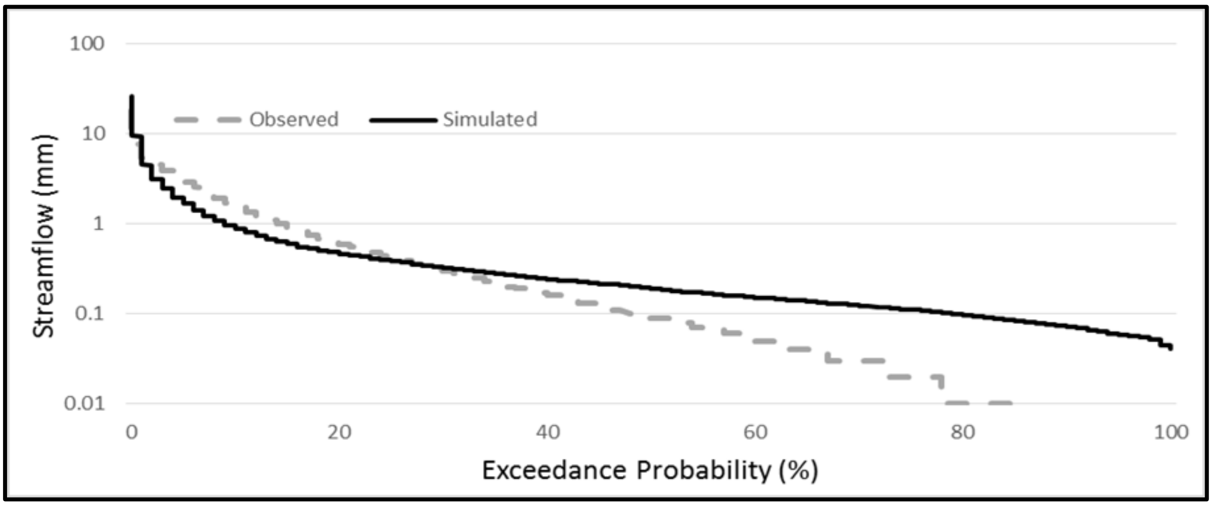

Figure 2.13: Comparison of flow duration curves between simulated and observed flows for V11K.

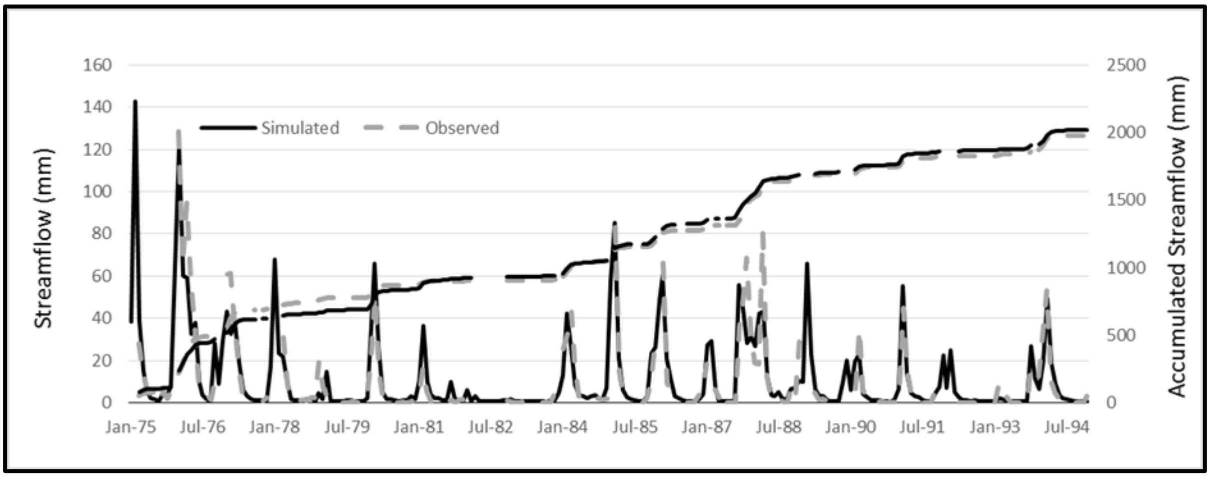

Figure 2.14: Comparison between observed and simulated total monthly flows and accumulated flows for the verification period (1970-1994) in V31F.

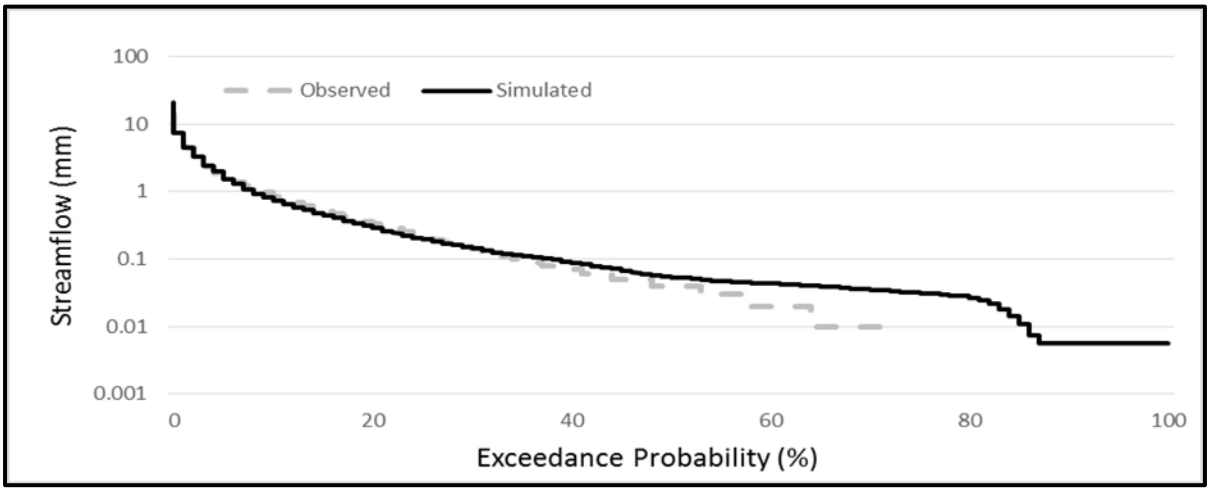

Figure 2.15: Comparison of flow duration curves between simulated and observed flows for V31F.

2.4 Discussion

This study aimed to investigate the impact of rainfall and streamflow data availability on model confirmation in three Quaternary Catchments within the uThukela Primary Catchment, *viz*. V11K, V14C and V31F, using the physical, conceptual daily time step ACRU model. Confirmation of the ability of the model to simulate observed flows could not be carried out for current conditions due to the decline in the number of rainfall stations in the study catchments and poor confidence in the quality of the hydrometeorological data available after the year 2000.

Catchments V14C and V31F were configured to simulate streamflow for periods 1960- 2012 and 1960- 2009, respectively, with the simulation length limited by rainfall data availability. The target objectives were not met at either catchment; however, the model performance was better for V31F. The poor model performance may be due to the use of a limited number of stations to drive the rainfall in both catchments, which may have misrepresented the rainfall spatial variability across the catchments. Two rainfall stations were used for V14C, while one station was used for V31F at a distance of approximately 15 kilometres from the catchment. Therefore, rainfall measured at this station may not be a true representation of precipitation within the catchment, even though MAP, altitude and monthly median rainfall corresponded between the catchment and the station. A study by Vaze *et al*. (2011) in 240 Australian catchments using four different hydrological models concluded that the use of more rainfall stations improved the representation of rainfall spatial variability; thus, improving model performance. Similarly, a study by Anctil *et al*. (2006) in a mountainous catchment in France showed that increasing the number of rainfall stations improves streamflow simulation, with certain raingauge combinations performing better than others. Therefore, both the number of stations and quality of data in the record are important.

The most readily available high quality, patched daily rainfall data for South Africa can be obtained from a database developed by Lynch (2004), which only extends to year 2000. Although a database of high quality, patched daily rainfall to 2012 has been developed by Pegram *et al*. (2016) it is not readily available. This creates room for the potential for using other rainfall estimation techniques to be investigated; for example, ground-based radar and remote sensing (Smith *et al*., 2007; Cole and Moore, 2008, 2009; Seo *et al*., 2012; He *et al*., 2013; Clark, 2015; Suleman, 2017). Although several studies have investigated the impact of the use of ground-based radar data on model performance, the technique has been documented to produce poor estimates for low rainfall events (Wetchayont *et al*., 2013). Suleman (2017) explored the potential for the use of satellite rainfall data to simulate streamflow in three South African catchments with varying climatic and land cover conditions (including the uThukela catchment) using the ACRU model. The model performance results were generally poor, which was attributed to poor observed rainfall and streamflow data quality. This is only the second study investigating the potential for incorporation of remotely sensed rainfall data into the ACRU model after Clark (2015). Therefore, there is still room for further research into the technique.

Although remote sensing and radar techniques have the potential to improve rainfall estimation, these require calibration and validation using observed rainfall. Therefore, the need for improving and maintaining rainfall and streamflow monitoring across South Africa remains (Suleman, 2017).

Beyond the use of traditional hydrometeorological monitoring methods, there is room for the use of citizen science techniques in the generation of hydrometeorological data (Buytaert *et al*., 2014). Although citizen science has become a popular tool for monitoring and knowledge generation in several scientific disciplines (e.g. ecology and biogeography), its adoption in hydrological sciences and water resources management has been limited (Buytaert *et al*., 2014). This is mainly due to the technological complexity and expensive nature of traditional data collection tools. Additionally, the large temporal variability of the hydrological cycle requires repeated measurements of variables to generate long time series of hydrological states and fluxes (Herschy, 2009). However, the development of robust, cheaper and low maintenance sensing equipment provides an opportunity for monitoring of hydrometeorological variables in a citizen science context. For example, disdrometers (Löffler-Mang and Joss, 2000) and cellular communication (Overeem *et al*., 2013) are increasingly being used for precipitation data collection. In the context of streamflow monitoring, camera-based level measurements have been shown to have good correlation with traditional stage measurements (Royem *et al*., 2012). This technique, combined with the emergence of remote sensing methods, such as high resoulution digital elevation and river bed mapping from space measurements (Alsdorf *et al*., 2007; Smith and Pavelsky, 2008, Sampson *et al*., 2013), provides an opportunity for incorporation of citizen science into steamflow monitoring.

In an ongoing study entitled “Increasing Resilience to Water-Related Risks in the UK Fresh Fruit and Vegetable System”, McCosh (2018) reports that a number of farmers in the Groot Letaba catchment (Limpopo Province) own meteorological stations with record extending to present day. In addition, the commercial forestry sector monitors climatic variables, mainly to inform the fire danger index, while the sugar industry also monitors climate around farmed areas. Future studies should consider investigating the availability of privately owned meteorological stations in other parts of the country. Such information could be useful in extending climate records; thus, enabling hydrological models to produce sound results.

Hydrological modelling studies conducted with higher confidence in input data would enable water resources managers and policy-makers to make more informed decisions.

Streamflow data quality had a significant impact on the study, particularly for catchment V14C. This catchment was excluded from model confirmation due to uncertainties in observed streamflow post-1981. The ratings curve for gauge V1H009 was updated in 1954, 1987 and 1988, respectively. Smithers *et al.* (2013) compared observed and simulated streamflow using the ACRU model at the catchment for period 1958-1999 and attributed apparent pre-1989 flow oversimulation to changes in the ratings table. However, the IHA model indicates flow increases to be from 1981. Therefore, further investigation into the catchment streamflow is required to draw concrete conclusions.

In many parts of the world, hydrological models have become the main tools for water resources management (Beven, 2007). However, many of these models were developed with incomplete understanding of catchment hydrological behaviour. Vrugt *et al.* (2008) argue that hydrological models, whether physically-based or conceptual, represent complex vegetation and subsurface catchment systems as homogeneous units with particular hydrological behaviour. Non-linearity’s related to spatial complexities of catchment biophysical processes such as topography, soil, vegetation, and climatic characteristics such as rainfall, temperature and evaporation imply that the catchment hydrological response cannot be perfectly simulated by hydrological models (Beven, 1989; Oreskes *et al.*, 1994; Refsgaard and Henriksen, 2004). This introduces uncertainties in hydrological modelling. As a consequence, there have been several attempts to reduce these uncertainties to improve confidence in hydrological models (for example, Beven and Binely, 1992; Perrin *et al.*, 2003; Vrugt *et al.*, 2008; Song *et al.*, 2015; Zhao *et al.*, 2015). Vrugt *et al.* (2008) suggest that sources of model uncertainty should be treated separately. Sources of modelling uncertainty can be grouped into four forms: (i) input data, (ii) model parameter values, (iii) model structure and (iv) observed streamflow used to test model performance (Beven, 1989; Perrin *et al.*, 2003; Engeland *et al.*, 2016). In order to improve streamflow simulation by rainfall-runoff models, adjustments are made to what the modeller perceives as the main source of uncertainty. This paper mainly focused on using the ACRU model as a tool. A detailed investigation into the mathematical relationships in the model structure was not carried out. However, several validation and verification studies have been carried out using the model in different climatic regions. For example, Schulze (1995) reports 11 verification studies for different internal components of the model. Schulze and Pike (2004) list 10 additional verification studies, both for internal variables and simulated output. The model has also been verified in other countries, for example, Zimbabwe (Butterworth *et al*., 1999), Canada (Kienzle and Schmidt, 2008) and New Zealand (Kienzle, 2011). Thus, the main source of uncertainty was assumed to be input data, particularly rainfall and streamflow. McMillan *et al*. (2010) found uncertainties related to observed streamflow to lead to increased parameter uncertainty, while Peña-Arancibia *et al.* (2015) report these uncertainties to have insignificant effects on model parameters. Engeland *et al.* (2016) conclude that the impact of streamflow uncertainties on model parameters depends on the modelling approach followed. Perrin *et al*. (2003) suggest that, for daily time step rainfall-runoff models, a small number of parameters (3-5) is sufficient to provide sound simulations.

Configuration of the ACRU model is associated with a number of parameters (more than 5); therefore, poor model performance may be due to uncertainties related to these parameters. For example, the systematically over-estimation of low-flows throughout the simulation period at catchment V14C could be due to input soil parameters (e.g. the amount of water that is transported from the topsoil to the subsoil, and from the subsoil to groundwater). However, ACRU model parameters have a physical meaning as they are derived from experimental information. Thus, poor model performance was largely due to uncertainties in input streamflow and rainfall data.

With the confirmation length shortened to periods with consistent, relatively good quality data, the ACRU model was able to adequately simulate flows at two, relatively small subcatchments of the uThukela Catchment (V11K and V31F). The target objective for the percentage differences between simulated and observed flows was achieved for conservation statistics in both subcatchments. However, a low R^2 value was obtained at V11K. This may be due to the short duration of the confirmation period, as well as the number of missing values in the record. Several studies have investigated the impact of the length of input data on model performance, mostly focusing on model calibration (Harlin, 1991; Yapo *et al*., 1996; Anctil *et al*., 2004; Mathevet, 2005; Perrin, *et al*., 2007). These studies concluded that model performance is improved with increasing calibration length, however the minimum period required for sound modelling results differed from one to eight years. Mathevet (2005), on the other hand, concluded that a longer period is required as model complexity increases. ACRU can be considered a fairly complex model, thus the 15-year confirmation period used for V11K may have contributed to the poor model performance. Whereas, the model performance was better for V31F where a 25-year record period was used. Further to this, the performance of the ACRU model is affected by the period required for starting-up, which could be up to nine years (Kunz, 2018). Further investigation into the minimum confirmation period required for confirmation of the ACRU model at catchments with varying physical and climatic conditions should be carried out.

The EKZN Wildlife (2011) and NLC (2000) land cover maps were used as the primary sources for land cover in the study, while the confirmation period was 1970-1985 for V11K and 1975-1994 for V31F. A review study by Engel *et al*. (2007) argues that the time difference between observed streamflow and land use data may result in misrepresentation of the land uses during the observed flow. Although ACRU simulated flows well for V31F, this may have contributed to the poor performance at V11K. In addition, exact figures of in-field management practices (i.e. irrigation, planting dates, grazing) could not be obtained in the study, as several attempts to get a hold of land owners failed. To improve this, DWS aims to develop a standardised system for various stakeholders and municipalities to share water use data (DWA, 2013). This will improve the confidence in model input information to produce sound results, aiding policy-makers to make more informed water resources management decisions.

Historical hydrometeorological records remain essential for water resources management and planning. Pitman (2011) argues that after all human interference is removed, water resources will remain the same. Therefore, it is important to improve hydrometeorological monitoring networks to understand anthropogenic impacts on water resources, particularly in the age of climate change, where future water resources management decisions have to be made with reference to historical conditions. Hydrometeorological monitoring in South Africa faces two main socio-economic challenges: (1) lack of sufficient skills and (2) lack of financial resources to improve water resources monitoring. Herold (2010) reports that only 39% of DWS's engineering posts were filled. Pitman (2011) suggests that this situation will be exacerbated by retirement of senior personnel. Improving traditional monitoring techniques and exploring some of the above-mentioned techniques will require skills development and financial support. Therefore, improving the water resources planning management will require recruitment of personnel with suitable skills and sufficient financial support.

2.5 Conclusion

The documented decline in the number of, as well as quality of data in existing, hydrometeorological stations was evident in the uThukela Catchment. As a result, confirmation of the ACRU model could not be extended to current conditions. With the confirmation length limited to periods with the most consistent good quality data, the ACRU model adequately simulated flows.

2.6 References

Acocks, JPH. 1988. Veld Types of southern Africa. Botanical Research Institute, RSA. *Botanical Survey of South Africa Memoirs* 57: 146.

Allen, RG, Pereira, LS, Raes, D and Smith, M. 1998. *Crop Evapotranspiration: Guidelines for Computing Crop Water Requirements*. FAO Irrigation and Drainage Paper No. 56, Rome, Italy.

Alsdorf, DE, Rodriguez, E and Lettenmaier, DP. 2007. Measuring surface water from space. *Reviews of Geophysics* 45(2).Anctil, F, Lauzon, N, Andréassian, V, Oudin, L and Perrin, C. 2006. Improvement of rainfall-runoff forecasts through mean areal rainfall optimization. *Journal of hydrology* 328(3): 717-725.

Andersson, L, Wilk, J, Graham, P and Warburton, M. 2009. Local Assessment of Vulnerability to Climate Change Impacts on Water Resources in the Upper Thukela River Basin, South Africa: Recommendations for Adaptation. Meteorological and Hydrological Institute. S-601 76 Norrköping, Sweden.

Andréassian, V, Perrin, C, Michel, C, Usart-Sanchez, I and Lavabre, J. 2001. Impact of imperfect rainfall knowledge on the efficiency and the parameters of watershed models. *Journal of Hydrology* 250(1): 206-223.

Arnaud, P, Lavabre, J, Fouchier, C, Diss, S and Javelle, P. 2011. Sensitivity of hydrological models to uncertainty in rainfall input. *Hydrological Sciences Journal* 56(3): 397-410.

Beven, K. 1989. Changing ideas in hydrology - the case of physically-based models. *Journal of hydrology* 105(1-2): 157-172.

Beven, K. 2007. Towards integrated environmental models of everywhere: uncertainty, data and modelling as a learning process. *Hydrology and Earth System Sciences* 11(1):460-467.

Beven, K and Binley, A. 1992. The future of distributed models: model calibration and uncertainty prediction. *Hydrological processes* 6(3): 279-298.

Bronstert, A, Niehoff, D and Bürger, G. 2002. Effects of climate and land- use change on storm runoff generation: present knowledge and modelling capabilities. *Hydrological processes* 16(2): 509-529.

Butterworth, JH, Schulze, RE, Simmonds, LP, Moriarty, P and Mugabe, F. 1999. Hydrological processes and water resources management in a dryland environment IV: Long-term groundwater level fluctuations due to variation in rainfall. *Hydrol. Earth Syst. Sc.* 3: 353–361.

Buytaert, W, Zulkafli, Z, Grainger, S, Acosta, L, Alemie, TC, Bastiaensen, J, De Bievre, B, Bhusal, J, Clark, J, Dewulf, A, Foggin, M, Hannah, DM, Hergarten, C, Isaeva, A, Karpouzoglou, T, Pandeya, B, Paudel, D, Sharma, K, Steenhuis, T, Tilahun, S, Van Hecken, G and Zhumanova, M. 2014. Citizen science in hydrology and water resources: opportunities for knowledge generation, ecosystem service management, and sustainable development. *Frontiers in Earth Science* 2: 26.

Choi, W and Deal, BM. 2008. Assessing hydrological impact of potential land use change through hydrological and land use change modeling for the Kishwaukee River basin (USA). *Journal of Environmental Management* 88(4): 1119-1130.

Clark, DJ. 2015. Development of a methodology for water use quantification and accounting. In ed: Clark, DJ. 2015. *Development and assessment of an integrated water resources accounting methodology for South Africa*. Water Research Commission, Pretoria, South Africa, Report K5/2205.

Cole, SJ and Moore, RJ. 2008. Hydrological modelling using raingauge-and radar-based estimators of areal rainfall. *Journal of Hydrology* 358(3-4): 159-181.

Cole, SJ and Moore, RJ. 2009. Distributed hydrological modelling using weather radar in gauged and ungauged basins. *Advances in Water Resources* 32(7): 1107-1120.

De Fries, R and Eshleman, KN. 2004. Land-use change and hydrologic processes: a major focus for the future. *Hydrological Processes* 18: 2183–2186.

De Wiennaar, G and Jewitt, G. 2010. Ecohydrological implications of runoff harvesting in the headwaters of the Thukela River basin, South Africa. *Physics and Chemistry of the Earth, Parts A/B/C* 35(13): 634-642.

Department of Water Affairs (DWA). 2013. *National Water Resource Strategy: Second Edition*. Pretoria, South Africa.

Department of Water Affairs and Forestry (DWAF). 2003. *Thukela Water Management Area: Overview of Water Resources Availability and Utilisation*. Report No. P WMA 07/000/00/0203. http://www.dwa.gov.za/projects.aspx

Emmanuel, I, Andrieu, H, Leblois, E, Janey, N and Payrastre, O. 2015. Influence of rainfall spatial variability on rainfall–runoff modelling: Benefit of a simulation approach? *Journal of hydrology* 531: 337-348.

Engel, B, Storm, D, White, M, Arnold, and Arabi, M. 2007. A Hydrologic/Water Quality Model Applicati1. *JAWRA Journal of the American Water Resources Association* 43(5): 1223-1236.

Engeland, K, Steinsland, I, Johansen, SS, Petersen-Øverleir, A and Kolberg, S. 2016. Effects of uncertainties in hydrological modelling. A case study of a mountainous catchment in Southern Norway. *Journal of Hydrology* 536: 147-160.

Ewen, J and Parkin, G. 1996. Validation of catchment models for predicting land-use and climate change impacts. 1. Method. *Journal of Hydrology* 175(1-4): 583–594.

Ezemvelo, KZN Wildlife, EKZN. 2011. KwaZulu-Natal Land Cover 2008 V1. 1. *Unpublished GIS Coverage [Clp_KZN_2008_LC_V1_1_grid_w31. zip],* Biodiversity Conservation Planning Division, Ezemvelo KZN Wildlife, PO Box, 13053.

Forbes, KA, Kienzle, SW, Coburn, CA, Byrne, JM and Rasmussen, J. 2011. Simulating the hydrological response to predicted climate change on a watershed in southern Alberta, Canada. *Climatic Change* 105(3): 555-576.

Ghaffari, G, Keesstra, S, Ghodousi, J and Ahmadi, H. 2010. SWAT-simulated hydrological impact of land-use change in the Zanjanrood basin, Northwest Iran. *Hydrological Processes* 24: 892–903.

GreenCape. 2017. *Water: Market intelligence Report 2017*. Cape Town, South Africa.

Hargreaves, GH and Samani, ZA. 1985. Reference crop evapotranspiration from temperature. *Applied engineering in agriculture* 1(2): 96-99.

Harlin, J. 1991. Development of a process oriented calibration scheme for the HBV hydrological model. *Hydrology Research* 22(1): 15-36.

He, X, Sonnenborg, TO, Refsgaard, JC, Vejen, F and Jensen, KH. 2013. Evaluation of the value of radar QPE data and rain gauge data for hydrological modeling. *Water Resources Research* 49(9): 5989-6005.

Herold, CE. 2010. The water crisis in South Africa. *Civil Engineering* 18(5): 6-15. http://www.civils.org.za/Publications/CivilEngineeringMagazine/MonthlyIssues/tabid/84/Default.aspx.

Herpertz, D. 2001. Schneehydrologische Modellierung im Mittelgebirgsraum. Unpublished PhD thesis, Bonn University, Germany.

Herschy, R. 2009. *Streamflow Measurements, 3rd Edn*. Taylor & Francis, London, UK.

Hughes, DA. 2008. Modelling semi-arid and arid hydrology and water resources: the southern Africa experience. *Hydrological modelling in arid and semi-arid areas* 29-40.

Kienzle, SW, Lorentz, SA and Schulze, RE. 1997. *Hydrology and water quality of the Mgeni Catchment*. Report No. TT87/97, Water Research Commission, Pretoria, South Africa.

Kienzle, SW and Schmidt, J. 2008. Hydrological impacts of irrigated agriculture in the Manuherikia catchment, Otago, New Zealand. *Journal of Hydrology (New Zealand*) 47(2): 67.

Kunz, RPZ. 2018. Personal communication. Centre for Water Resources Research, School of Agricultural, Earth and Environmental Sciences, University of KwaZulu-Natal, Pietermaritzburg, South Africa, 16 March 2018.

Lambin, EF, Rounsevell, MDA and Geist, HJ. 2000. Are agricultural land-use models able to predict changes in land-use intensity? *Agriculture, Ecosystems & Environment* 82(1): 321-331.

Le Maitre, DC, Kotzee, IM and O'Farrell, PJ. 2014. Impacts of land-cover change on the water flow regulation ecosystem service: Invasive alien plants, fire and their policy implications. *Land Use Policy* 36: 171-181.

Löffler-Mang, M and Joss, J. 2000. An optical disdrometer for measuring size and velocity of hydrometeors. *Journal of Atmospheric and Oceanic Technology* 17(2): 130-139.

Lynch, SD. 2004. *Development of a Raster Database of Annual, Monthly and Daily Rainfall for Southern Africa*. Report No. 1156/1/03, Water Research Commission, Pretoria, South Africa.

Martinez, CJ, Campbell, KL, Annable, MD and Kiker, GA. 2008. An object-oriented hydrologic model for humid, shallow water-table environments. *Journal of Hydrology* 351(3): 368-381.

Mathevet, T. 2005. Quels modeles pluie-debit globaux au pas de temps horaire? Développements empiriques et intercomparaison de modeles sur un large échantillon de bassins versants. Unpublished PhD thesis, ENGREF, Paris, France.

McCosh, J. 2018. Personal communication. Institute of Natural Resources, Pietermaritzburg, South Africa, 25 July 2018.

McMillan, H, Freer, J, Pappenberger, F, Krueger, T and Clark, M. 2010. Impacts of uncertain river flow data on rainfall-runoff model calibration and discharge predictions. *Hydrological Processes: An International Journal* 24(10): 1270-1284.

Nash JE and Sutcliffe, JV. 1970. River flow forecasting through conceptual models, part I - A discussion of principles. *Journal of Hydrology* 10: 282–290.

National Land Cover (NLC). 2000. Council for Scientific and Industrial Research and Agricultural Research Council Consortium. Pretoria, South Africa.

National Water Act (NWA). 1998. RSA Government Gazette No. 36 of 1998: 26 August 1998, No. 19182. Cape Town, RSA.

Oreskes, N, Shrader-Frechette, K and Belitz, K. 1994. Verification, validation, and confirmation of numerical models in the earth sciences. Science 263(5147): 641-646.

Oudin, L, Perrin, C, Mathevet, T, Andréassian, V and Michel, C. 2006. Impact of biased and randomly corrupted inputs on the efficiency and the parameters of watershed models. *Journal of Hydrology* 320(1): 62-83.

Overeem, A, Leijnse, H and Uijlenhoet, R. 2013. Country-wide rainfall maps from cellular communication networks. *Proceedings of the National Academy of Sciences* 110(8): 2741-2745.

Pegram, GGS, Sinclair, S and Bárdossy, A. 2016. *New methods of infilling Southern African raingauge records enhanced by annual, monthly and daily precipitation estimates tagged with uncertainty*. Report 2241/1/16. Water Research Commission, Pretoria, South Africa.

Peña-Arancibia, JL, Zhang, Y, Pagendam, DE, Viney, NR, Lerat, J, van Dijk, AI and Frost, A. J. 2015. Streamflow rating uncertainty: characterisation and impacts on model calibration and performance. *Environmental Modelling & Software* 63: 32-44.

Perrin, C, Michel, C and Andréassian, V. 2003. Improvement of a parsimonious model for streamflow simulation. *Journal of hydrology* 279(1-4): 275-289.

Perrin, C, Oudin, L, Andréassian, V, Rojas-Serna, C, Michel, C and Mathevet, T. 2007. Impact of limited streamflow data on the efficiency and the parameters of rainfall—runoff models. *Hydrological sciences journal* 52(1): 131-151.

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

Refsgaard, JC and Henriksen, HJ. 2004. Modelling guidelines - terminology and guiding principles. *Advances in Water Resources* 27(1): 71-82.

Royem, AA, Mui, CK, Fuka, DR. and Walter, MT. 2012. Proposing a low-tech, affordable, accurate stream stage monitoring system. *Transactions of the ASABE*, 55(6): 2237-2242.

Samaniego, L and Bardossy, A. 2006. Simulation of the impacts of land use/cover and climatic changes on the runoff characteristics at the mesoscale. *Ecological Modelling* 196(1): 45-61.

Sampson, CC, Fewtrell, TJ, Duncan, A, Shaad, K, Horritt, M. S and Bates, PD. 2012. Use of terrestrial laser scanning data to drive decimetric resolution urban inundation models. *Advances in water resources*, 41: 1-17.

Schmidt, J, Kienzle, SW and Srinivasan, MS. 2009. Estimating increased evapotranspiration losses caused by irrigated agriculture as part of the water balance of the Orari Catchment, Canterbury, New Zealand. *Journal of Hydrology (NZ)* 48: 89-94.

Schulze, RE. (Ed.). 1995. *Hydrology and Agrohydrology: A Text to Accompany the ACRU 3.00 Agrohydrological Modelling System*. Water Research Commission, Pretoria, South Africa.

Schulze, RE, Angus, GR and Guy, RM. 1995. Soils. In: ed. Schulze, RE. *Hydrology and Agrohydrology: A Text to Accompany the ACRU 3.00 Agrohydrological Modelling System*, Chapter 5, AT5-1-28. Water Research Commission, Pretoria, South Africa.

Schulze, R, Summerton, M, Meier, K, Pike, A and Lynch, S. 1997. The ACRU*forest* Decision Support System to Assess Hydrological Impacts of Afforestation Practices in South Africa. In: *Proceedings of the Eighth South African National Hydrology Symposium*, Pretoria, South Africa.

Schulze, RE. 2004. Determination of baseline land cover variables for applications in addressing land use impacts on hydrological responses in South Africa. In: eds. Schulze, RE, and Pike, A. *Development and Evaluation of an Installed Hydrological Modelling System*. Report No. 1155/1/04, Water Research Commission, Pretoria, South Africa, Chapter 3, pp. 37–50.

Schulze, RE and Maharaj, M. 2004. *Development of a Database of Gridded Daily Temperatures for Southern Africa*. Report No. 1156/2/04, Water Research Commission, Pretoria, South Africa.

Schulze, RE and Pike, A. 2004. *Development and Evaluation of an Installed Hydrological Modelling System*. Report No. 1155/1/04, Water Research Commission, Pretoria, South Africa.

Schulze, RE and Horan, MJC. 2007. Soils: Hydrological Attributes. In: ed. Schulze, RE. *South African Atlas of Climatology and Agrohydrology*. Report No. 1489/1/06, Water Research Commission, Pretoria, South Africa, Section 4.2.

Segond, ML, Wheater, HS and Onof, C. 2007. The significance of spatial rainfall representation for flood runoff estimation: A numerical evaluation based on the Lee catchment, UK. *Journal of Hydrology* 347(1): 116-131.

Seo, Y, Schmidt, AR and Sivapalan, M. 2012. Effect of storm movement on flood peaks: Analysis framework based on characteristic timescales. *Water Resources Research* 48(5).

Smith, JA, Baeck, ML, Meierdiercks, KL, Miller, AJ and Krajewski, WF. 2007. Radar rainfall estimation for flash flood forecasting in small urban watersheds. *Advances in Water Resources* 30(10): 2087-2097.

Smith, LC and Pavelsky, TM. 2008. Estimation of river discharge, propagation speed, and hydraulic geometry from space: Lena River, Siberia. *Water Resources Research*, 44(3).

Smithers, JC and Schulze, RE. 2004. *ACRU Agrohydrological Modelling System: User Manual Version 4.00.* School of Bioresources Engineering and Environmental Hydrology, University of KwaZulu-Natal, South Africa.

Smithers, JC, Chetty, KT, Frezghi, MS, Knoesen, DM and Tewolde, MH. 2013. Development and assessment of a daily time-step continuous simulation modelling approach for design flood estimation at ungauged locations: ACRU model and Thukela Catchment case study. *Water SA* 39(4): 467-476.

Song, X, Zhang, J, Zhan, C, Xuan, Y, Ye, M and Xu, C. 2015. Global sensitivity analysis in hydrological modeling: Review of concepts, methods, theoretical framework, and applications. *Journal of hydrology* 523: 739-757.

Sorooshian, S, Gupta, VK and Fulton, JL. 1983. Evaluation of maximum likelihood parameter estimation techniques for conceptual rainfall- runoff models: Influence of calibration data variability and length on model credibility. *Water Resources Research* 19(1): 251-259.

Suleman, S. 2017. Assessment of satellite derived rainfall and its use in the ACRU hydrological model. Unpublished MSc Hydrology Dissertation, Centre for Water Resources Research, University of KwaZulu-Natal, Pietermaritzburg, South Africa.

Tarboton, KC and Schulze, RE. 1990. Impacts of increased afforestation and farm dams on water resources of the upper Mgeni catchments. *Agricultural Engineering in South Africa* 22: 201–215.

Tarboton, KC and Schulze, RE. 1991. The ACRU modelling system for large catchment water resources management. *Hydrology for the Water Management of Large River Basins* 219-232.

The Nature Conservancy. 2009. *IHA Software Version 7.1 User's Manual*. The Nature Conservancy, Virginia, United States.

Turner, BL, Skole, B, Sanderson, S, Fischer, G, Fresco, L and Leemans, R. 1995. *Land-Use and Land-Cover Change: Science Research Plan*. IGBP Report, 35, IGBP, Stockholm, Sweden.

Van Rooyen, JA and Versfeld, DB. 2009. *Strategic Planning for Water Resources in South Africa: A Situation Analysis 2009*. Report No. P RSA 000/00/7809. Department of Water Affairs, Pretoria, South Africa.

Van Rooyen, JA and Versfeld, DB. 2010. *Integrated Water Resource Planning for South Africa: A Situation Analysis 2010*. Report No. P RSA 000/00/12910. Department of Water Affairs, Pretoria, South Africa.

Vaze, J, Post, DA, Chiew, FHS, Perraud, JM, Teng, J and Viney, NR. 2011. Conceptual rainfall–runoff model performance with different spatial rainfall inputs. *Journal of Hydrometeorology* 12(5): 1100-1112.

Vrugt, JA, Ter Braak, CJ, Clark, MP, Hyman, JM and Robinson, B.A. 2008. Treatment of input uncertainty in hydrologic modeling: Doing hydrology backward with Markov chain Monte Carlo simulation. *Water Resources Research* 44(12).

Warburton, ML, Schulze, RE and Jewitt, GP. 2010. Confirmation of ACRU model results for applications in land use and climate change studies. *Hydrology and Earth System Sciences* 14(12): 2399.

Warburton, ML, Schulze, RE and Jewitt, GP. 2012. Hydrological impacts of land use change in three diverse South African catchments. *Journal of Hydrology* 414: 118-135.

Wetchayont, P, Hayasaka, T. Satomura, T, Katagiri, S, and Baimoung, S. 2013. Retrieval of Rainfall by Combining Rain Gauge, Ground-Based Radar and Satellite Measurements over Phimai, Thailand. *SOLA* 9(0): 166-169.

Yapo, PO, Gupta, HV and Sorooshian, S. 1996. Automatic calibration of conceptual rainfall-runoff models: sensitivity to calibration data. *Journal of Hydrology* 181(1-4): 23-48.

Zhao, T, Wang, QJ, Bennett, JC, Robertson, DE, Shao, Q and Zhao, J. 2015. Quantifying predictive uncertainty of streamflow forecasts based on a Bayesian joint probability model. *Journal of Hydrology* 528: 329-340.

3. THE IMPACTS OF CHANGES IN AGRICULTURAL LAND MANAGEMENT PRACTICES ON WATER FLOWS AT THE UTHUKELA CATCHMENT, SOUTH AFRICA

Mlungisi Shabalala[1*] and Michele Toucher[1,2]
[1]Centre for Water Resources Research, University of KwaZulu-Natal, Private Bag X01, Scottsville, Pietermaritzburg 3209, South Africa
[2]Grasslands-Wetlands-Forests Node, South African Environmental Observation Network (SAEON)

ABSTRACT

The South African Government aims to transform the socioeconomic status of the uThukela Catchment through development of agriculture within the region. Intensification of agricultural activities will depend on the availability of water resources. These activities pose a threat to the quantity and quality of water flowing in streams. Thus, the aim of this paper was to investigate the potential impacts of the proposed development of the agricultural sector through a scenario-based study using the ACRU Agrohydrological model. The scenarios considered were: (i) expansion of irrigated agriculture, (ii) conversion of commercial agriculture to subsistence practices (i.e. land reform), (iii) conversion of dryland commercial agriculture into crops with biofuel potential, (iv) changed burning practices, (v) intensified land degradation and (vi) rehabilitation of degraded areas. The impacts of these activities on accumulated baseflow, quickflow and streamflow were first investigated at a Quaternary Catchment scale (V31F), then up scaled to the upper uThukela Catchment (V1). Irrigation resulted in the highest streamflow reductions, with the permanent pasture and double cropping scenarios resulting in a 79% and 21% reduction in streamflow at the outlet of V31F and V1, respectively. Planting of soya bean as a biofuel crop increased baseflows by 20% and 25% at the outlet of V31F and V1 respectively, when compared to natural conditions. Further degradation of the catchments and severe burning practices increased quickflows and streamflows, however land tenure change and rehabilitation of degraded vegetation had little impact on flows. These scenarios were generated from limited climate, water use and land cover information; therefore, cannot be used to make final decisions on

land management issues. However, they can be used as an indication of the possible impacts of certain land management decisions on water resources.

3.1 Introduction

For many decades, humans have modified natural landscapes through activities such as deforestation, agriculture and urbanisation (Foley *et al*., 2005; Baker and Miller, 2013; Rulli *et al*., 2013; Yan *et al*., 2013). In this paper, land use change is referred to as the exploitation and utilization of land resources by humans (Pielke *et al*., 2002). The main drivers for land use change include population growth, which increases the demand for food, water and energy resources; economic growth and changes in national, regional and international policies (Headey and San, 2008; Godfray *et al*., 2010; Parajul *et al*., 2013; Watanabe and Ortega, 2014). Of particular concern in this paper are agricultural land uses.

Increasing agriculture has resulted in substantial improvements in global food security through increases in production (Gordon *et al*., 2010). However, expansion of agricultural activities has led to significant impacts on the hydrological cycle through changes in river flow patterns and wetlands (Finlayson and D’Cruz, 2005; Choi and Deal, 2008; Baker and Miller, 2013; Öztürk *et al*., 2013; Hu *et al*., 2015). This has resulted in depletion of several large rivers around the world (Falkenmark and Lannerstad, 2005; Fang *et al*., 2007). Agricultural activities have also resulted in redistribution of global total evaporation (ET) patterns: with decreases in areas associated with large-scale deforestation, and increases in many irrigation regions (Gordon *et al*., 2010). Through application of chemicals such as fertilizers, herbicides and pesticides, agricultural activities have resulted in the doubling of nitrogen fixation (Galloway *et al*., 2004) and tripling of phosphorus use (Bennett *et al*., 2001), leading to increased eutrophication (Diaz, 2001). These modifications in water quantity and quality have several social, environmental and ecological impacts such as a decline in fisheries, waterborne diseases and loss of wetlands and coastal ecosystems (Hu *et al*., 2015). Some agricultural-induced changes in natural ecosystems have negative impacts on agricultural ecosystems themselves, with some changes seemingly irreversible or at least difficult to reverse (Kremen *et al*., 2002; Bossio *et al*., 2007; Gordon *et al*., 2010). Therefore, it is important to investigate the impacts of agricultural activities on environmental ecosystems to achieve sustainable production.

Agriculture, at both commercial and subsistence scales has been documented to impact on both water quantity and quality. Commercial agriculture, through the development of dams and irrigation systems alters the natural flow regime, impacting on downstream ecosystems (Pommerieux *et al*, 2014). In addition, the pesticides, herbicides and fertilizers used in commercial agriculture deteriorate the quality of water through percolation into groundwater, or as surface runoff (Elleboudt, 2012; Merchán *et al.*, 2013). Subsistence agriculture mainly impacts the environment through land degradation, as a result of (i) livestock overstocking, leading to overgrazing, (ii) excessive conventional tillage practices and cropping on steep slopes, (iii) poor fire management, and (iv) harvesting of indigenous trees for firewood (Nsuntsha, 2000; Blignaut *et al*., 2010; Wood, 2011; Chaplot *et al*., 2012). These impact both on water quantity and quality, with the former being affected through increased stormflow and decreased baseflow recharge (Schulze and Horan, 2007; Wood 2011). The quality of water is also impacted through sedimentation, as a result of severe erosion from the fields (Dlamini *et al*., 2011).

South Africa's uThukela catchment in the KwaZulu-Natal (KZN) Province is the second largest river system in the country (DWAF, 2003). The catchment is an important source of water for the Gauteng Province, the country's economic hub, through inter-basin transfers (OLM, 2016). The region is predominantly rural, with the majority of the population living on communal lands (OLM, 2016). Agriculture is the main economic activity and land use in the uThukela catchment, with large scale commercial agricultural and small-scale subsistence farmers (Andersson *et al*., 2009; Ndoro *et al*., 2013). According to Hu *et al*. (2015), changes in land use are often correlated with implementation of national policy. In order to meet the country's food demands, and develop the region's economy, the South African Government aims to transform the agricultural sector in the uThukela catchment (National Planning Commission, NPC, 2013). The sector has not reached its potential in the catchment, particularly in the case of the small-scale farmers (OLM, 2016). The subsistence farmers lack the infrastructural and financial resources to maximise production, and experience social issues such as lack of education and support, poverty and disease (Kemerink *et al*., 2013; OLM, 2016; Wood, 2011). The Government aims to improve the state of subsistence farming in the region through provision of the necessary financial resources for infrastructural and skills development (NPC, 2013; OLM, 2016). In addition, the Government aims to transfer previously commercial land to small-scale practitioners through intensification of the land reform programme. The Government, alongside this, aims to improve commercial agriculture through provision of support for improved technologies, research and increased irrigation where resources allow (NPC, 2013). These proposed development strategies will be largely limited by resource availability.

Several land use change studies have been carried out in the uThukela catchment, mostly focusing on the impacts of land degradation by subsistence farmers (Smith *et al.*, 2005; Schulze and Horan, 2007; Blignaut *et al.*, 2010; Wood, 2011; Chaplot *et al.*, 2012, 2016; Dlamini *et al*, 2011, 2014). However, none of these studies investigate the potential impacts of expansion of agriculture within the catchment. Thus, this study aims to investigate the impacts of the proposed agricultural development strategies on the water resources of the upper uThukela catchment. The study focused on three runoff components, *viz*. baseflow, quickflow and streamflow. The impacts were quantified through a scenario-based modelling approach using the daily-time step, soil water budget sensitive ACRU model (Schulze, 1995; Smithers and Schulze, 2004). The scenarios that were established were: (i) increasing the fraction of irrigated commercial agriculture into currently dryland commercial fields, (ii) increasing subsistence agriculture through reduction of commercial agriculture (i.e. land reform), (iii) conversion of dryland commercial agriculture into crops with biofuel potential (iv) increased burning, (v) intensified land degradation and (vi) rehabilitation of degraded areas.

3.2 Methodology

3.2.1 Study area

The study site (Figure 3.1) was the upper region of the uThukela Primary Catchment (27.41^{o} to 29.40^{o} S and 28.96^{o} to 31.44^{o} E), KZN Province, South Africa. The most notable feature of the upper uThukela catchment is the Drakensburg Mountain Range, which is the source of water for the Thukela River, the largest river system in the province. The mountains also act as an international border between South Africa and Lesotho, as well as a local boundary separating KZN from the Free State and Eastern Cape Provinces. The upper uThukela is a summer rainfall catchment, characterized by high climatic variability. Mean annual precipitation (MAP) ranges from nearly 2 000 mm.yr^{-1} in the high-altitude region to as low as approximately 600 mm.yr^{-1} in the low-lying interior region. Temperatures range from an average 2°C per annum in the Drakensberg Mountains to 21°C in the Valley region (DWAF, 2003).

The main land use in the catchment is agriculture, at both commercial and subsistence scales, with protected areas in some parts of the catchment. Several large dams have been constructed in the catchment, including Woodstock Dam (380 million cubic metres) which is a source of water for the Gauteng Province through the Tugela-Vaal Water Transfer Scheme. Water from the dam is also used for electrical power generation during times of shortage through the Tugela-Vaal Pumping Scheme. A number of small farm dams, mainly used for irrigation, are also found in the catchment. The land uses and climatic conditions in the upper uThukela are representative of the larger uThukela catchment (Table 3.1). Therefore, the catchment was deemed adequate for modelling purposes.

3.2.2 Model selection and configuration

The multi-purpose, multi-soil-layered, daily time-step, physical-conceptual ACRU Agrohydrological Model (Schulze, 1995; Smithers and Schulze, 2004) was selected. The ACRU model has been applied in several land use change studies within South Africa (Tarboton and Schulze, 1990, 1991; Schulze *et al*., 1997; Kienzle *et al*., 1997; De Wiennaar and Jewitt, 2010; Warburton *et al*., 2012; Le Maitre *et al*., 2014). The model has also been applied in other countries such as Zimbabwe (Butterworth *et al*., 1999), Germany (Herpertz, 2001), Canada (Forbes *et al*., 2010), New Zealand (Kienzle and Schmidt, 2008; Schmidt *et al*., 2009) and the USA (Martinez *et al*., 2008). A full description of the model physical processes is given in the companion paper on the model confirmation by Shabalala and Toucher (2018; Chapter 2).

The Department of Water Affairs and Forestry (DWAF, 2003) divided the country's Primary Catchments into Quaternary Catchments (QCs) for water management purposes. Schulze and Horan (2011) divided each QC into three fifth order quinary catchments based on altitude. This study was divided into two phases. Following confirmation of the ACRU model's ability to simulate streamflow for QCs V11K (26 km^2) and V31F (156 km^2) by Shabalala and Toucher (2018), these QC catchments (Figure 3.1), with the configuration used in the confirmation study, were used to simulate the impacts of potential land use change scenarios on runoff components (accumulated baseflow, quickflow and streamflow). The impacts of land uses that resulted in significant changes in the runoff components were then investigated at a larger catchment scale. Quaternary Catchment V11K was not responsive to changes in land cover, due to the small size of the catchment. Therefore, results from this catchment were excluded. Secondary Catchment V1 in the upper uThukela (Figure 3.1), which is composed of 29 QCs was selected for the upscaling of the selected land management scenarios. Modelling of V1 was performed at a quinary scale, i.e. 87 quinary catchments. Each quinary catchment was divided into homogenous hydrological response units (HRUs) based on land cover.

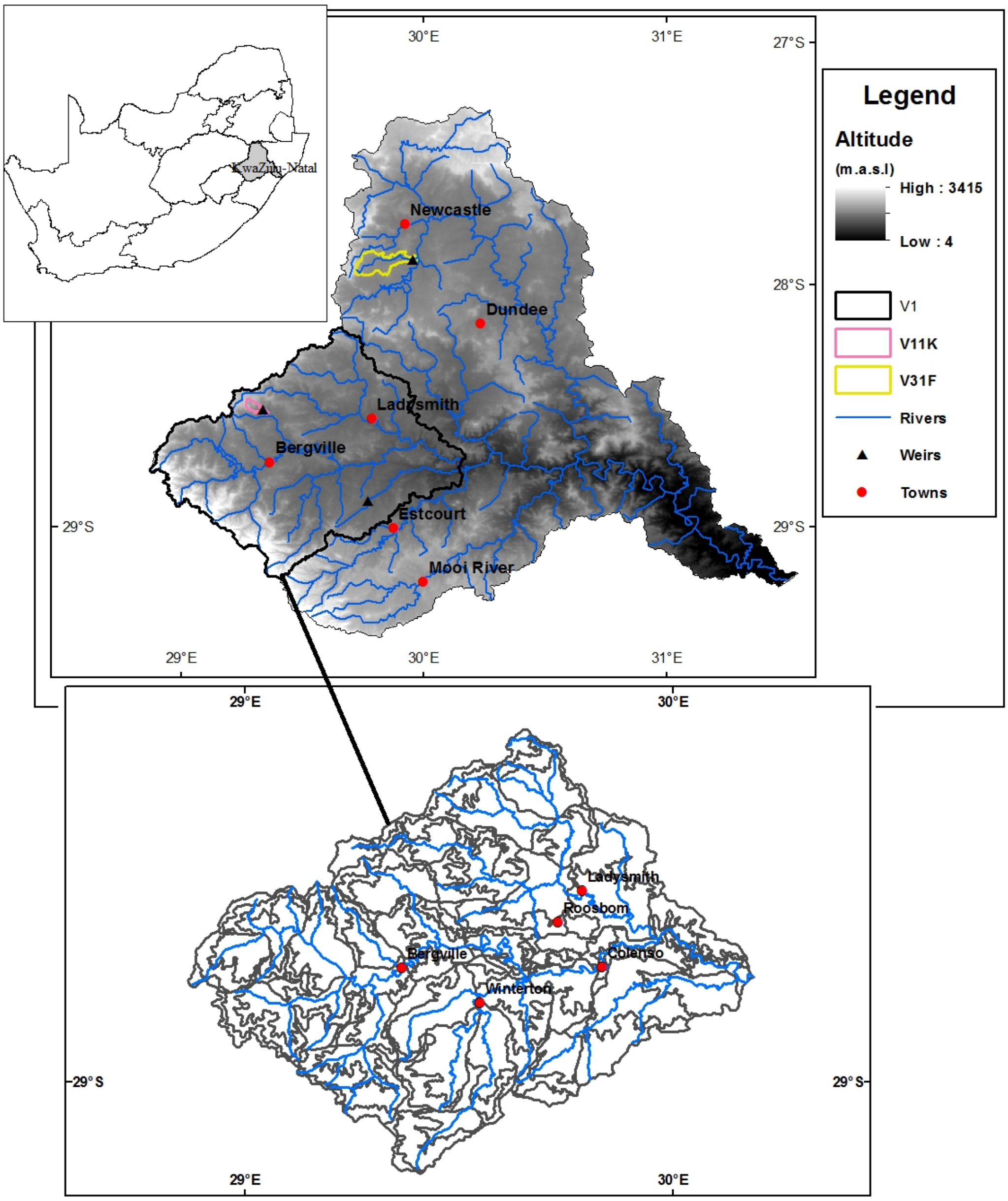

Figure 3.1: Location of the study catchments Quaternary Catchments V31F and V11K and Secondary Catchment V1 with altitude, rivers and towns displayed.

Due to unavailability of good quality rainfall data extending to present day (Shabalala and Toucher, 2017), daily rainfall for 1960 - 2000 for a representative station for each quinary catchment was obtained from a national database (Lynch, 2004). Daily minimum and maximum temperature estimates for this period were obtained from a 1' by 1' latitude/longitude gridded database (Schulze and Maharaj, 2004). Reference evaporation was estimated using the Hargreaves and Samani (1985) equation.

The ACRU model requires A and B horizon soil variables as input. These include soil depth (m), field capacity (m/m), porosity (m/m), permanent wilting point (m/m) and the fraction of water that is drained from the A to the B horizon, and from the B horizon to groundwater when the soil is saturated. Estimates for these variables were obtained from a gridded database by Schulze and Horan (2007). The model also accounts for the amount of groundwater that contributes to daily runoff; this was set at 0.9%, as recommended by Schulze *et al*. (1995) for South African catchments.

Configuration of the ACRU model includes consideration of stormflow generation variables, *viz.* the fraction of stormflow that is converted into runoff on the same day as the rainfall event (QFRESP) and the critical stormflow generation depth (SMDDEP). QFRESP was exctracted from the Schulze and Horan (2007) gridded database, while SMDDEP was set at the depth of the A horizon, as recommended by Schulze *et al*. (1995).

The primary source of land cover information was the Ezemvelo KZN Wildlife (EKZN, 2011), supplemented with information from the National Land Cover (NLC, 2000). The general proportions of the land uses in the study catchments are shown in Table 3.1 below.

Table 3.1: Study catchment details and land use percentages.

Catchment	**uThukela**	**V31F**	**V1**
Area (km^2)	29036	148	7647
MAP (mm p.a)	810	811	864
Average Altitude (m.a.s.l)	1234	1323	787
Land use (%)			
Natural vegetation	57	63	65
Degraded areas	9	2	7
Water bodies	2	1	2
Wetlands	-	4	1
Commercial forests	4	7	1
Commercial agriculture			
- Dryland	6	18	7
- Irrigated	3	3	3
Subsistence agriculture	8	-	5
Residential & Urban areas	6	2	9

For modelling purposes, the Acocks (1988) Veld Type was determined for where areas of natural grasslands and forest remained. The dominant veld types in the study area were the southern tall grassveld and the Natal sour sandveld. The mode of irrigation used in the study was based on expert consultation. Irrigation occurred once the plant available water (PAW) had been depleted by 20%. Based on field visitation, the irrigated crop was set as pastures growing between March and October, with irrigation water drawn from dams. Commercial dryland agriculture was chosen to be sugarcane for QC V31F and maize, planted on 15th November, growing over 140 days, was selected for V1. For each vegetation type, the ACRU model requires above (crop coefficients, coefficient of initial abstraction and interception storage) and below-ground (root distribution between the A and B horizons) physiological variables to estimate daily water use. These were obtained from a database by Schulze (2004). The onset of plant stress was set to 40% of plant available water, as suggested by Schulze (1995). Subsistence farming in the uThukela catchment is associated with land degradation due poor management (Schulze and Horan, 2007; Dlamini *et al.*, 2011, 2014; Elledbout, 2012; Chaplot *et al.*, 2012, 2016). To account for management practices such as overgrazing and erosion, disjunct impervious areas were assumed to flow into subsistence agricultural areas. There was no information on the specific volumes and water movement from the dams within the study area; therefore, the total volume of all small farm dams was assumed to be one dam at the bottom of each quinary catchment. Daily seepage was assumed to be 0.0006 of the total dam volume, as suggested by Schulze *et al.* (1995). No environmental flows were released from the dams, and inter-basin transfers were not included in the modelling.

3.2.3 Land use/management change scenarios

The land management scenarios considered were based on the proposed socio-economic development plan of the uThukela region, as provided by the National Development Plan (NPC, 2013) and the integrated development plans of the uThukela District and Okhahlamba Local Municipalities (KZN, 2016; OLM, 2016). The uThukela District and Okhahlamba Local Municipalities have identified primary, secondary and tertiary nodes and corridors for socio-economic development. With agriculture being the main economic activity in the region, the Government aims to intensify commercial agricultural activities (i.e. irrigated and dryland cropping, as well as beef and dairy production) and subsistence farming (i.e. dryland cropping and cattle ranching) which is prevalent in traditional areas. Furthermore, the local Government recognises the need to intensify Land Reform and Restitution projects, and provision of the necessary support to new land owners. In addition, the Municipality aims to maintain the integrity of protected areas such as the uKhahlamba Drakensberg Park through the reduction of current environmental degradation resulting from activities such as overgrazing, uncontrolled burning and accelerated soil erosion. Thus, the selected scenarios included (i) conversion of commercial dryland agriculture to irrigation, subsistence and biofuel cropping, (ii) intensified burning, expanding into natural grasslands, (iii) increased degradation of natural grasslands and (iv) rehabilitation of already-degraded grassland.

It is important to establish a baseline condition against which the impacts of land use/management change on water resources are assessed. The Department of Water and Sanitation (DWS) supports the use of natural vegetation as a baseline against which the impacts of land use/management change on streamflow are assessed (Schulze, 2004; Jewitt *et al*., 2009). The Acocks (1988) Veld Type maps have been the widely used as a baseline against which to determine hydrological response to land use change South Africa (Schulze, 2004; Warburton *et al*., 2012). Thus, the impacts of changes in agricultural management practices on streamflow were assessed relative to a baseline hydrology simulation under the Acocks Veld Types (1988).

The Year 2011 land use map was assumed to represent the current state. Therefore, the Year 2011 land uses were adjusted to develop the land use management scenarios. The same climatic data for the period 1960-1999 was used in the simulations of the baseline, current and proposed land management change scenarios.

Four irrigation scenarios were modelled in the study: (i) maize planted on 15th October, growing for 140 days (irrigated from November to February) was selected for summer irrigation; (ii) wheat planted on 01 May growing for 110 days, irrigated from June to August, was selected for winter irrigation; (iii) double cropping of maize and wheat, irrigated from November to March and June to September, respectively, was referred to as 'All Year' in the results and (iv) permanent pastures irrigated throughout the year (referred to from here on as permanent pastures). To investigate the impacts of the conversion of commercial agricultural land to subsistence farming, commercial sugarcane and maize were replaced with subsistence sugarcane and maize at catchments V31F and V1, respectively. To consider the impacts of biofuel cropping, two biofuel crops were considered, *viz*. sweet sorghum and soya beans. Two burning scenarios were considered, namely annual (June) and biennial severe burning. These scenarios were represented by adjusting the vegetation water use parameters (CAY, VEGINT, COIAM, ROOTA and ROOTB, see Appendix A) and the areas of the HRU's. The vegetation water use parameters for each land use/management change scenario were extracted from the Schulze (2004) database.

The expansion of irrigation, subsistence agriculture, burning, degradation and rehabilitation were modelled through 10% increments of the specific land use up to 50%. Irrgation and subsistence agriculture were expanded into commercial dryland agriculture. Based on field visitation and expert consultation, plantation of biofuels was considered to be 100% replacement of current commercial dryland agriculture. Due to the significant land degradation associated with subsistence farming practices in the uThukela catchment, for each 10% increase in subsistence cropping, 2.5% was assumed to be disjunct impervious areas.

The impacts of the land management scenarios on accumulated baseflow, quickflow and streamflow over 40 years (1960-1999) were quantified. In addition, the impacts of the scenarios on low (90th percentile), median (50th percentile) and high (10th percentile flow) flows were quantified.

3.3 Results

Accumulated baseflow, quickflow and streamflow simulated for V31F under year 2011 land use conditions are lower, by 14%, 12% and 39% respectively, in comparison to the flows simulated under baseline vegetation. Whereas for V1, the flows simulated under year 2011 land use are higher than those simulated under baseline vegetation by 21%, 28% and 2% respectively (Table 3.2). Similarly, the accumulated baseflow, quickflow and streamflow simulated under the considered land management scenarios were lower than those simulated under the baseline land cover at QC scale (V31F). However, the flows simulated under the scenarios were higher than those simulated under the baseline land cover at Secondary Catchment scale (V1), except for the irrigation scenarios (Table 3.2). The impacts of each of these scenarios on flows will be further explored in the sections that follow.

Table 3.2: Percentage changes in simulated accumulated baseflow, quickflow and streamflow under year 2011 land use and the land management scenarios considered, relative to the flows simulated under Acocks (1988) Veld Types.

Scenario	V31F (% difference)			V1 (% difference)		
	Baseflow	Quickflow	Streamflow	Baseflow	Quickflow	Streamflow
Year 2011 Land use	-14	-12	-39	21	28	2
Summer irrigation	-19	-14	-55	23	27	-6
Winter irrigation	-12	-11	-38	26	27	6
All year irrigation	-19	-14	-72	23	27	-18
Pasture irrigation	-19	-17	-79	24	25	-21
Subsistence agriculture	-15	-10	-38	24	27	4
Soya beans	20	-3	-21	25	28	6
Sweet sorghum	4	-10	-31	21	28	6
Annual burning	-3	-11	-34	22	26	2
Biennial severe burning	1	3	-26	22	38	7
Degradation	2	3	-26	22	38	8
Rehabilitation	-15	-12	-39	21	26	1

3.3.1 Irrigation

The scenarios were developed from the Year 2011 land use, which implies that the irrigation areas present in 2011 were expanded in the scenarios in 10% increments, as well as various timings/crops considered. Increasing the area under irrigation from the 2011 land use (0 on x-axis; Figure 3.2) resulted in a decrease in the simulated accumulated baseflow, quickflow and streamflow relative to flows under baseline vegetation from both V31F and V1, regardless of the irrigation timing/crop. The decreases in accumulated streamflow were significant, whereas the changes in baseflows and quickflows were negligible. The all year and permanent pastures irrigation scenarios resulted in the largest declines in streamflows relative to those simulated under baseline conditions both at the QC and Secondary catchment scales, with a lesser impact at the secondary catchment scale. Irrigation of a summer crop reduced accumulated streamflows by 55% and 6% relative to flows simulated under baseline vegetation for V31F and V1, respectively. While, the smallest impacts on flows were noted under the scenario which considered irrigation of a winter crop.

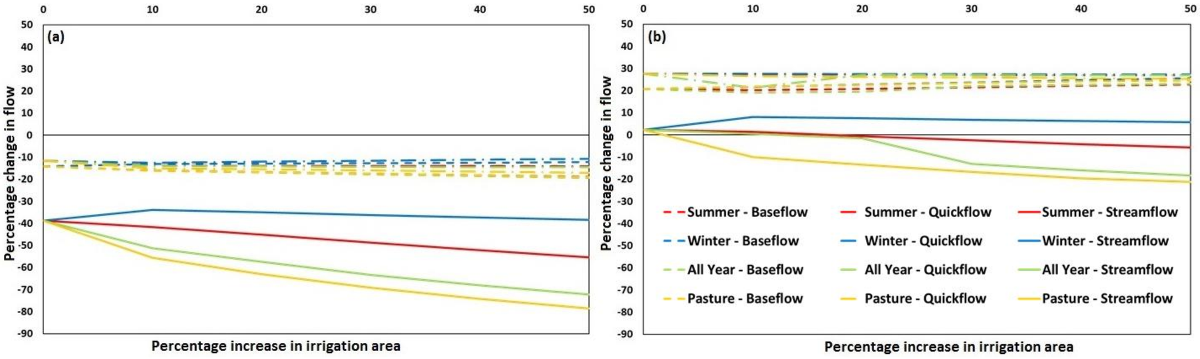

Figure 3.2: Percentage change in accumulated baseflow, quickflow and streamflow (1960-1999) under various irrigation scenarios with increases in the area irrigated (50% increase) relative to baseline vegetation (0 on x-axis point is Year 2011 land use) at catchment V31F (a) and V1 (b).

The impacts of the Year 2011 land use and the various scenarios on the monthly low (90th percentile; Figure 3.3), median (50th percentile; Figure 3.4) and high (10th percentile; Figure 3.5) were considered. Under the Year 2011 land use, the low flows simulated were less than those simulated under the baseline vegetation for both V31F and V1. Similarly, the median and high flows simulated under the Year 2011 land use were lower than those simulated under the baseline land cover for V31F. However, the median and high flows under the Year 2011 land use were greater than those simulated under the baseline vegetation during the summer months for V1. The irrigation scenarios had the largest impact on the low flows, and the impacts were far greater at the smaller QC scale than at the Secondary catchment scale. Of the scenarios, the all year irrigation scenarios of double cropping and permanent pastures had the greatest impacts on the flows. The summer irrigation decreased low and median flows at both scales, and high flows at the QC scale during the summer months. The winter irrigation scenario decreases low, median and high flows across both scales in the winter months.

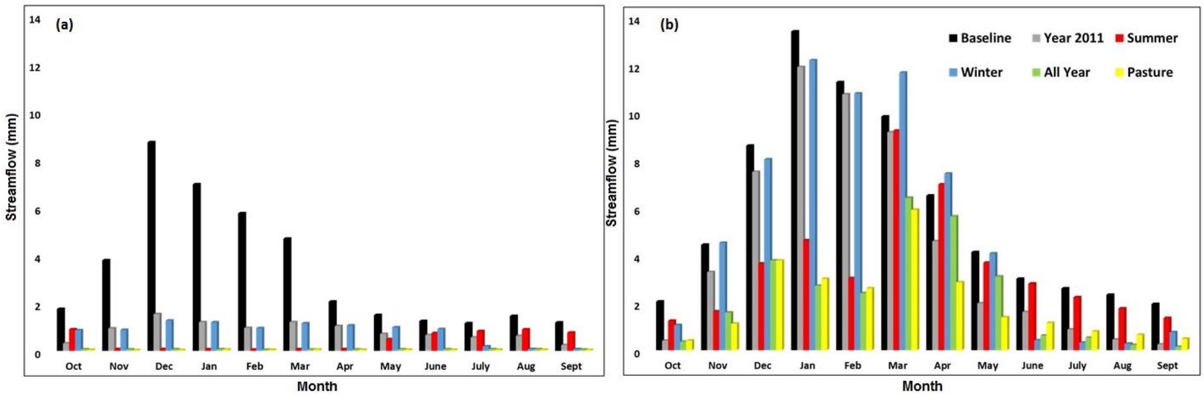

Figure 3.3: Monthly low flows (90th percentile) under baseline vegetation, year 2011 land use and various irrigation scenarios for catchment V31F (a) and V1 (b) for the period 1960-1999.

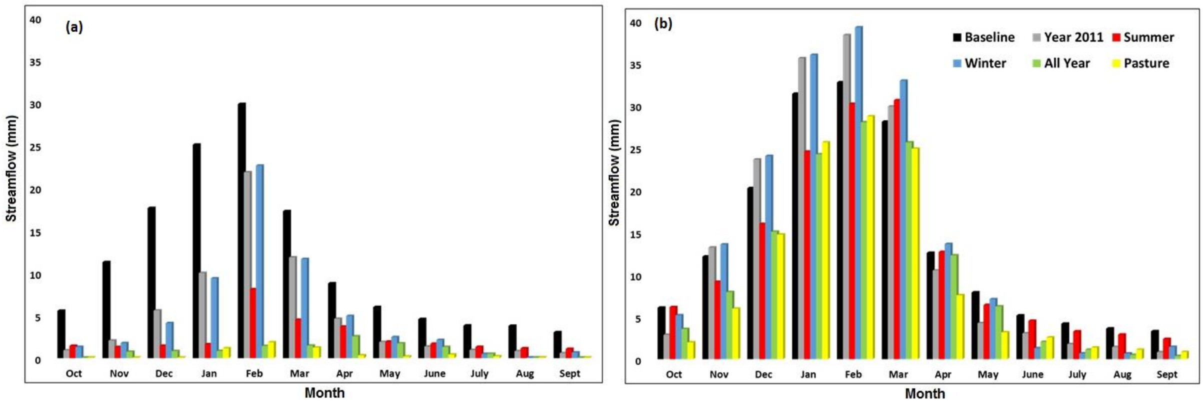

Figure 3.4: Monthly median flows (50th percentile) under baseline vegetation, year 2011 land use and various irrigation scenarios for catchment V31F (a) and V1 (b) for the period 1960-1999.

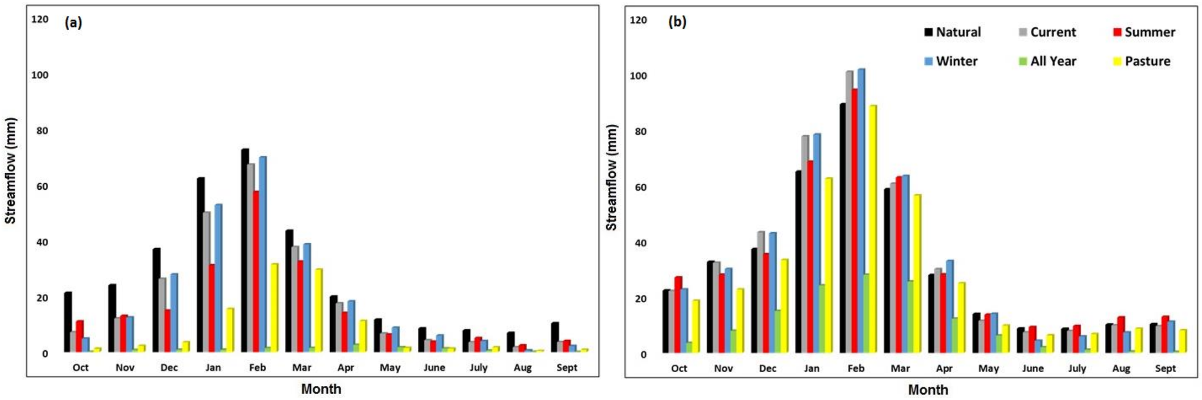

Figure 3.5: Monthly high flows (10th percentile) under baseline vegetation, year 2011 land use and various irrigation scenarios for catchment V31F (a) and V1 (b) for the period 1960-1999.

3.3.2 Subsistence agriculture

Increasing the area under subsistence agriculture in 2011 by 10% increments to a 50% increase in area, resulted in negligible changes in the simulated accumulated streamflows, quickflows and baseflows at both the QC and Secondary catchment scale (Figure 3.6). Similarly, increasing the area under subsistence agriculture in 2011 by 50% had no further impact than the Year 2011 land use on the low, median and high flows (Figure 3.7).

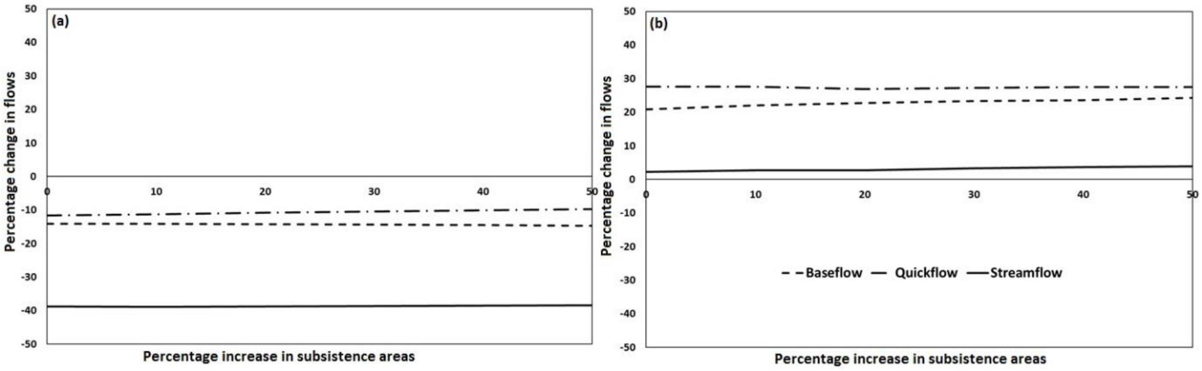

Figure 3.6: Percentage change in accumulated baseflow, quickflow and streamflow (1960-1999) with increasing subsistence agriculture areas relative to baseline vegetation (0 x-axis point is Year 2011 land use) at catchment V31F (a) and V1 (b).

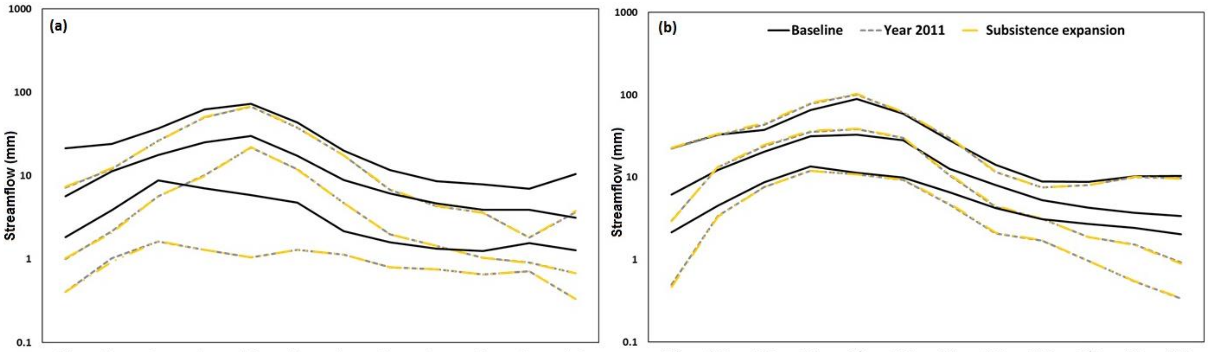

Figure 3.7: Monthly low (90th percentile), median (50th percentile) and high (10th percentile flows) under baseline vegetation, year 2011 land use and a 50% increase in subsistence agricultural areas for catchment V31F (a) and V1 (b), for the period 1960-1999.

3.3.3 Biofuels

Replacing commercial dryland fields present in 2011 completely (100%) with soya beans and sweet sorghum resulted in increased accumulated baseflow, quickflow and streamflow across both catchment scales. The increases at the Secondary catchment scale were negligible; however, the increases at the QC scale were substantial (Figure 3.8). The increases due to a change to soya beans were greater than those under sweet sorghum. Further to this, the increases in the baseflow were the greatest, with the accumulated baseflow under soya bean being 20% and 34% more than baseflows simulated under baseline and Year 2011 land uses for V31F, respectively. While accumulated streamflow simulated under soya beans for V31F was 7% and 20% greater than streamflow simulated under than baseline and Year 2011 land uses, respectively.

Only at the QC catchment scale did replacing commercial dryland crops with biofuel potential crops have a different impact on monthly low, median and high flows than the Year 2011 land use, relative to baseline vegetation. At the QC scale, both soya beans and sweet sorghum increased the monthly low, median and high flows across all months (Figure 3.9), with the largest increases in high flows. During the summer months, the increases in low, median and high flows under soya beans were greater than under sweet sorghum.

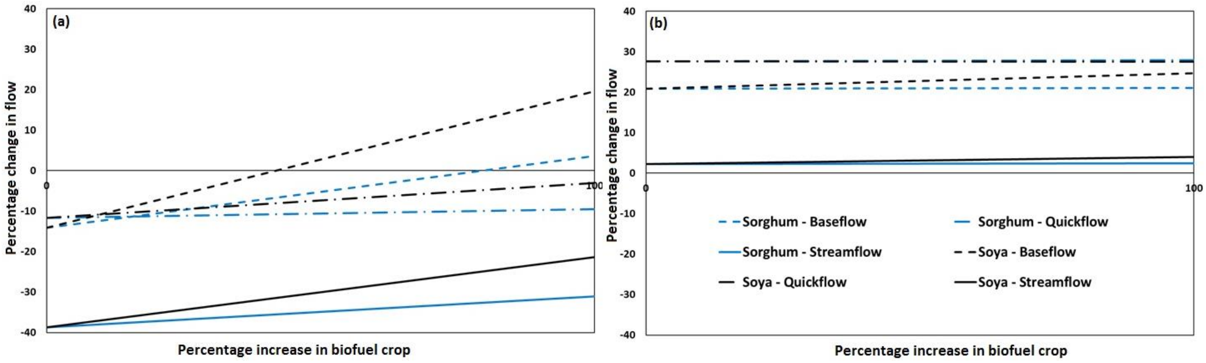

Figure 3.8: Percentage change in accumulated baseflow, quickflow and streamflow (1960-1999) due to conversion of commercial dryland agriculture to crops with biofuel potential, relative to baseline vegetation (0 x-axis point is Year 2011 land use) at catchment V31F (a) and V1 (b).

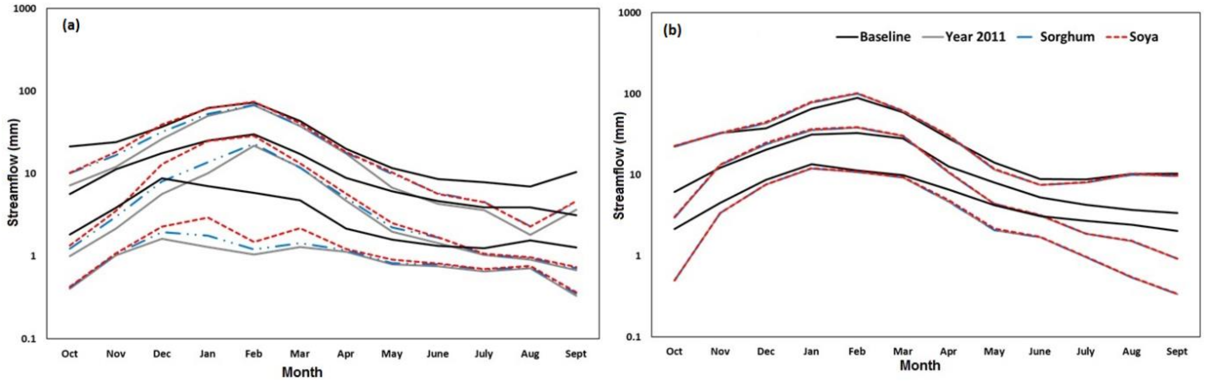

Figure 3.9: Monthly low (90th percentile), median (50th percentile) and high (10th percentile flows) under baseline vegetation, year 2011 land use and a conversion of dryland crops to those with biofuel potential for catchment V31F (a) and V1 (b), for the period 1960-1999.

3.3.4 Degradation and rehabilitation

Increasing the degraded areas in V31F and V1 in 10% increments, till the area had increased by 50%, resulted in increases in the accumulated baseflow, quickflow and streamflow from both catchments (Figure 3.10). The increases at the QC scale were slightly greater than those simulated for V1 for accumulated streamflow and quickflow. The marked difference between the two catchment scales was in the response of the accumulated baseflow. At the smaller QC scale, the baseflows increased due to further degradation, however, at the larger Secondary catchment scale no changes in the accumulated baseflow with further degradation were evident. However, when considering the impacts on the low, median and high flows only slight increases were evident in the summer months at the Secondary catchment scale (Figure 3.11). Whereas larger increases in low, median and high flows across all months were simulated at the QC scale (Figure 3.11).

The rehabilitation of 50% of the degraded areas present in 2011 resulted in slight declines in the accumulated streamflow and quickflow at the Secondary catchment scale, while no changes were evident in the accumulated baseflow and across all months at the QC scale (Figure 3.10). No changes in the simulated low, median and high flows at both catchment scales were evident (Figure 3.11).

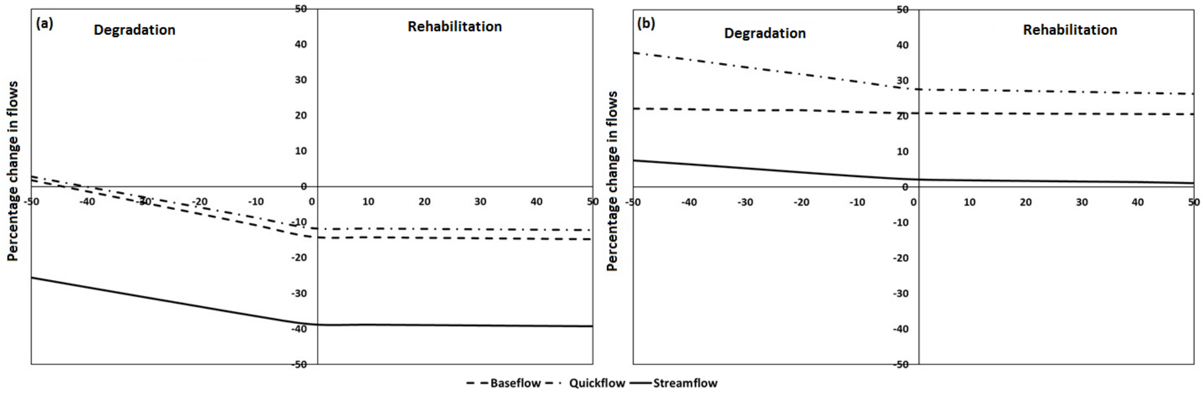

Figure 3.10: The impacts increasing grassland degradation and rehabilitation of degraded grassland (% change) on accumulated baseflow, quickflow and streamflow (1960-1999), relative to baseline vegetation (0 x-axis point is Year 2011 land use) at catchment V31F (a) and V1 (b).

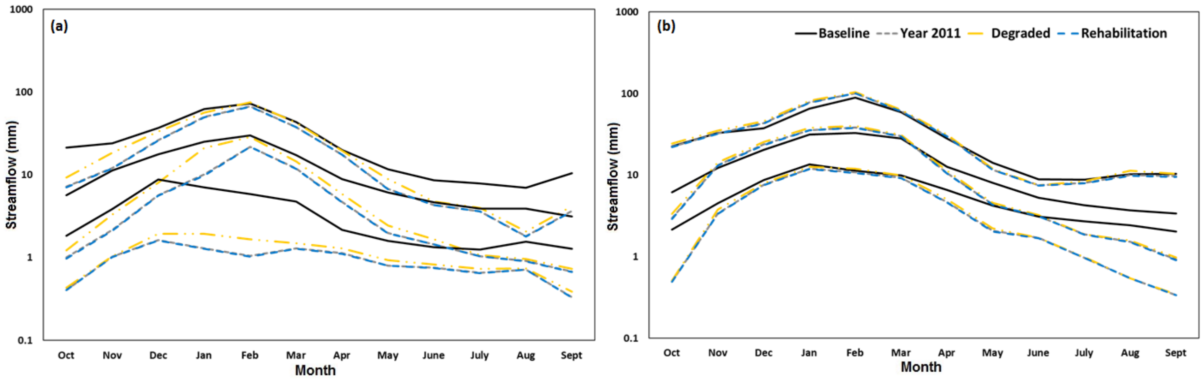

Figure 3.11: The impact of degradation (50% natural vegetation area) and rehabilitation of already-degraded areas on monthly low, median and high flows (mm) for catchment V31F (a) and V1 (b), relative to baseline vegetation, for period 1960-1999.

3.3.5 Burning

For the Year 2011, no burning of the natural vegetation areas was assumed. Thus, the burning scenarios considered burning of these natural vegetation areas in 10% increments up to burning of 50% of the natural vegetation area. Two burning scenarios, namely an annual burn and a biennial severe burn were considered. Increasing the area of natural vegetation burnt, regardless of the burning scenario, resulted in increased accumulated baseflow, quickflow and streamflow at both catchment scales (Figure 3.12). However, the changes were far more pronounced at the QC scale than at the Secondary catchment scale. The biennial severe burn scenario increased accumulated flows more than the annual burn scenario. The lack of response in the accumulated quickflow under the annual burn scenario was not in agreement with what was expected.

At the Secondary catchment scale, the burning of 50% of the natural vegetation area under either of the considered burning scenarios had no impact on the low, median and high flows (Figure 3.13). However, at the QC scale under the biennual severe burn scenario the low, median and high flows were greater than those that occur under the Year 2011 land use.

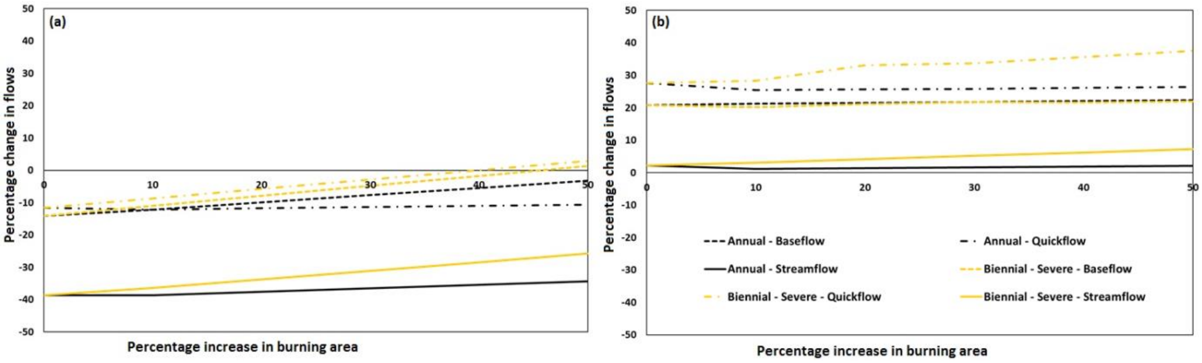

Figure 3.12: Percentage change in accumulated baseflow, quickflow and streamflow (1960-1999) due to increased burning, relative to baseline vegetation (0 x-axis point is Year 2011 land use) at catchment V31F (a) and V1 (b).

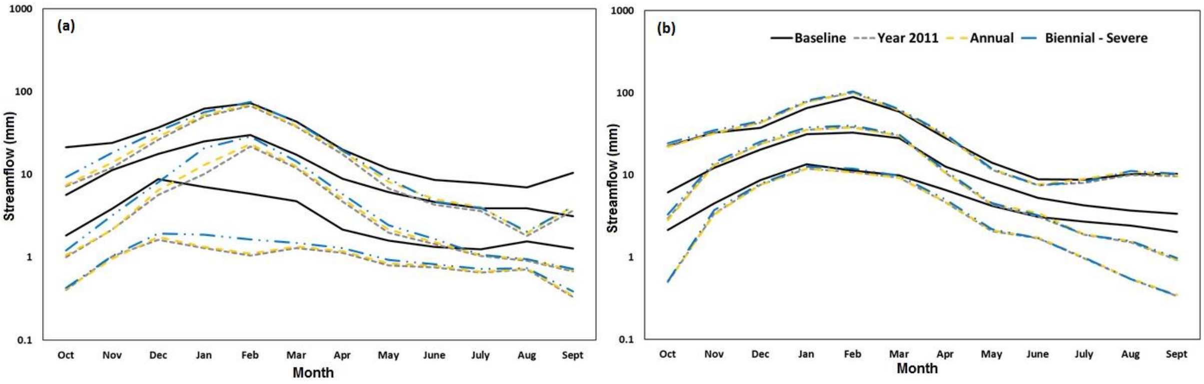

Figure 3.13: The impacts increased burning (50% of natural vegetation area) on monthly low, median and high flows at catchment V31F (a) and V1 (b), relative to baseline vegetation, for period 1960-1999.

3.4 Discussion

This study investigated the potential impacts of changes in agricultural land management practices on water resources in the upper uThukela catchment through quantification of changes in accumulated runoff components, *viz*. baseflow, quickflow and streamflow, using the ACRU model over a 40-year simulation period (1960-1999).

Results show that increasing the proportion of irrigated agriculture poses the greatest threat to water quantity. Thus, the proposed local government plans to intensify agriculture through irrigation is concerning for a catchment already facing water scarcity issues with dams running dry due to prolonged periods of low precipitation and resultant low streamflow generation (Andersson *et al.,* 2009). Community members of the upper uThukela region largely depend on water flowing in rivers and groundwater resources for household water (Andersson *et al*., 2009; Ellebdout, 2012). Therefore, expansion irrigation poses a risk to water availability for downstream communities. Irrigation had the greatest impact on low flows, particularly during the non-rainfall season as crop water requirements are highest during this time (van Oel *et al*., 2008). According to the National Water Act (NWA, 1998), low flows are important for the Ecological Reserve; therefore, increasing these activities poses a threat on the downstream aquatic ecosystems. In addition, increasing irrigated agriculture will raise health concerns to downstream communities as return flows from irrigated fields may carry chemicals such as fertilizer, pesticides and herbicides (Merchán *et al*., 2013). Therefore, careful consideration and planning measures should be taken before further expansion of irrigated areas.

Replacing commercial dryland vegetation with biofuel crops resulted in flow increases, with greater increases experienced under soya beans as opposed to sorghum. This is because soya bean crops use less water than the replaced crops (i.e. sugarcane at V31F and maize at V1). Sugarcane and maize crops can grow up to a height 4.25 m and 2 m, respectively, while the height of a fully-grown soya bean crop ranges between 0.4 and 1 m (DAFF, 2010, 2014; PANNAR, 2017). Both sugarcane and maize crops have deep rooting systems, distributed across the A and B horizons. Soya bean crop roots, on the other hand, are limited to the top 30 cm of the soil (DAFF, 2010). Therefore, replacing sugarcane and maize with soya beans results in increased baseflows as the shorter rooting system of soya bean crops access less soil water.

Increasing land degradation, mainly through overgrazing and burning resulted in increases in streamflow. These land management practices are associated with loss of surface cover and surface crusting, which results in decreased total evaporation and interception storage, increased overland flow and decreased infiltration. The increased overland flow increases the susceptibility to severe erosion (Gifford and Hawkins, 1978; Warren *et al*., 1986; Strauch *et al*., 2009; Sanjari *et al*., 2010; Chaplot *et al*., 2012). Increased streamflow due to increased overland flow alters the natural flow regime of downstream rivers, therefore, impacting on the health of aquatic ecosystems. In addition, water from degraded areas due to poor land management practices such as overgrazing and uncontrolled burning may carry nutrients with a potential to significantly affect the ecological health of downstream rivers.

Rehabilitation of degraded grasslands did not have a significant impact on flows. These results are contrary to findings from other studies. For example, studies by Blignaut *et al*. (2010), van Luijk *et al*. (2013) and Gao *et al*. (2015) suggest that restoration of degraded grasslands decreases runoff, encouraging infiltration and thereby increasing soil moisture storage and baseflow. Results from the study may have been due to the small size of degraded areas compared to natural grassland in the year 2011 land cover for both catchments (see Table 3.1). Degradation is mainly in the upper parts of the catchment, on steep landscapes with shallow soils. Therefore, impacts at the catchment outlet may not be as significant at it would be at a local scale. Thus, further research should investigate the impacts of rehabilitation at a subcatchment scale, focusing on highly degraded subcatchments.

Several studies have shown that the impacts of changes in land management are more significant at a local scale (Ashagrie *et al*., 2006; Blöschl *et al*., 2007; Peel, 2009). Similar findings were observed in this study. The impacts of land use management changes on flow were quantified at the catchment outlet. These impacts were more significant at a smaller scale than at the larger catchment as large catchments have a slower recession than small catchments due to increased attenuation of flow (Bergström and Graham; 1998; Fohrer *et al*., 2001). Siriwardena *et al*. (2006) showed that models developed for small-catchment studies remain applicable to large scale modelling.

Runoff at the catchment outlet is dependent on the size and geographic location of specific land uses within a catchment (Warburton *et al*., 2012; Baker and Miller, 2013; Hu *et al*., Nian *et al*., 2014; Hu *et al*., 2015). This was evident in this study. For example, natural grasslands were the dominant land cover, distributed along the high elevation areas within each subcatchment (cf. Figure 1.1 and Table 3.1); thus, conversion of grassland to other land uses, i.e. burning and degradation, resulted in significant flow changes. In contrast, land uses such as degraded vegetation and subsistence agriculture were small in size, concentrated only in the upper parts of the study catchments, resulting in less significant impacts on runoff components at the outlet.

The results presented in this paper are affected by uncertainties related to model configuration, mainly associated with input information. For example, due to insufficient information, irrigation was based on expert consultation. There was also no information on water movement from the Woodstock Dam (i.e. transfer to the Gauteng Province and power generation) and other inter-basin transfers between farm dams within the catchment. A study by Smithers *et al*. (2007) concluded that application of the ACRU model in an operational catchment where exact figures of irrigation and inter-basin transfers proved a challenge. Therefore, the lack of information may have affected the results. DWS together with the Council for Scientific and Industrial Research, are currently working on a project titled “Verification and Validation of Water Users” which quantifies the water usage by licenced users in the country’s Water Management Areas, specifically focusing on irrigation. Results from this project will be beneficial for hydrological modelling as these would improve the quality of studies when using data intensive models such as ACRU.

This study was completed using rainfall and climate information for period 1960-1999, due to lack of good quality data extending to present day (Shabalala and Toucher, 2018, Chapter 2), while land management scenarios were based on year 2011 land cover. Climate patterns have changed significantly from year 2000 to present day, both at a global and regional scale (IPCC, 2007, 2012), and several extreme events have occurred, which may have shaped the current state of land uses. Therefore, results from this study cannot be used to make concrete decisions for future land management. However, the study can be used as an indication of possible impacts of changes in agricultural land use management practices in the uThukela catchment.

3.5 Conclusion

Increasing irrigated areas had the greatest impact on flows, particularly low flows. Increasing subsistence agriculture and rehabilitation of degraded grassland resulted in little to no change in runoff quantity. Conversion of dryland commercial crops to biofuel crops increased flows, with more impact from soya beans. Severe, widespread burning and degradation increased accumulated quickflow and streamflow, with biennial severe burning having the greatest impact. The study was completed under limited climate and land use information. Therefore, future studies should incorporate high quality climate data, extending to present day, and finer resolution land use data to enable sound decision making.

3.6 References

Acocks, JPH. 1988. Veld Types of southern Africa. Botanical Research Institute, RSA. *Botanical Survey of South Africa Memoirs* 57: 146.

Adams, MA, Cunningham, SC and Taranto, MT. 2013. A critical review of the science underpinning fire management in the high altitude ecosystems of south-eastern Australia. *Forest ecology and management* 294: 225-237.

Andersson, L, Wilk, J, Graham, P and Warburton, M. 2009. Local Assessment of Vulnerability to Climate Change Impacts on Water Resources in the Upper Thukela River Basin, South Africa: Recommendations for Adaptation. Meteorological and Hydrological Institute. S-601 76 Norrköping, Sweden.

Ashagrie, AG, De Laat, PJM, De Wit, MJM, Tu, M and Uhlenbrook, S. 2006. Detecting the influence of land use changes on Floods in the Meuse River Basin? the predictive power of a ninety-year rainfall-runoff relation. *Hydrology and Earth System Sciences Discussions* 3(2): 529-559.

Baker, TJ and Miller, SN. 2013. Using the Soil and Water Assessment Tool (SWAT) to assess land use impact on water resources in an East African watershed. *Journal of Hydrology* 486: 100-111.

Bakker, MM, Govers, G, van Doorn, A, Quetier, F, Chouvardas, D and Rounsevell, M. 2008. The response of soil erosion and sediment export to land-use change in four areas of Europe: the importance of landscape pattern. *Geomorphology* 98(3-4): 213-226.

Bart, R and Hope, A. 2010. Streamflow response to fire in large catchments of a Mediterranean-climate region using paired-catchment experiments. *Journal of hydrology* 388(3-4): 370-378.

Bennett, EM, Carpenter, SR and Caraco, NF. 2001. Human Impact on Erodable Phosphorus and Eutrophication: A Global Perspective: Increasing accumulation of phosphorus in soil threatens rivers, lakes, and coastal oceans with eutrophication. *AIBS Bulletin* 51(3): 227-234.

Bergström, S, and Graham, LP. 1998. On the scale problem in hydrological modelling. *Journal of Hydrology* 211(1-4): 253-265.

Blignaut, J, Mander, M, Schulze, R, Horan, M, Dickens, C, Pringle, C, Mavundla, K, Mahlangu, I, Wilson, A, McKenzie, M and McKean, S. 2010. Restoring and managing natural capital towards fostering economic development: Evidence from the Drakensberg, South Africa. *Ecological Economics* 69(6): 1313-1323.

Blöschl, G, Ardoin-Bardin, S, Bonell, M, Dorninger, M, Goodrich, D, Gutknecht, D, Matamoros, D, Merz, B, Shand, P. and Szolgay, J. 2007. At what scales do climate variability and land cover change impact on flooding and low flows? *Hydrological Process*es 21: 1241-1247.

Bosch, JM, Schulze, RE and Kruger, FJ. 1984. The effect of fire on water yield. In: J de V. Booysen and NM Tainton eds. *Ecological Effects of Fire in South African Ecosystems*, pp. 327-348. Springer, Berlin, Heidelberg.

Bossio, D, Critchley, W, Geheb, K, van Lynden, G, Mati, B, Bhushan, B, Hellin, J, Jacks, G, Kolff, A, Nachtergaele, F, Neely, C, Peden, D, Rubiano, J, Shepherd, G, Valentin, C and Walsh, M. 2007. Conserving land- protecting water. In: ed. Molden, D. *Water for Food, Water for Life: A Comprehensive Assessment of Water Management in Agriculture*. 551-538, Earthscan, London, UK.

Butterworth, JH, Schulze, RE, Simmonds, LP, Moriarty, P and Mugabe, F. 1999. Hydrological processes and water resources management in a dryland environment IV: Long-term groundwater level fluctuations due to variation in rainfall. *Hydrol. Earth Syst. Sc.* 3: 353–361.

Chaplot, V, Dlamini, P, Mchunu, C, Oakes, E, Orchard, C, Jewitt, G and Lorentz, S. 2012. *Water, Sediment, Nutrient and Organic Carbon Fluxes in Small-Scale Agriculture Landscapes*. Water Research Commission Report No. 1904/1/12, Pretoria, RSA.

Chaplot, V, Dlamini, P and Chivenge, P. 2016. Potential of grassland rehabilitation through high density-short duration grazing to sequester atmospheric carbon. *Geoderma* 271: 10-17.

Choi, W and Deal, BM. 2008. Assessing hydrological impact of potential land use change through hydrological and land use change modeling for the Kishwaukee River basin (USA). *Journal of Environmental Management* 88(4): 1119-1130.

De Wiennaar, G and Jewitt, G. 2010. Ecohydrological implications of runoff harvesting in the headwaters of the Thukela River basin, South Africa. *Physics and Chemistry of the Earth, Parts A/B/C* 35(13): 634-642.

Department of Agriculture, Forestry and Fisheries (DAFF). 2010. *Soya beans- Production guideline*. Pretoria, South Africa.

Department of Agriculture, Forestry and Fisheries (DAFF). 2010. *Sugarcane- Production guideline*. Pretoria, South Africa.

Department of Water Affairs and Forestry (DWAF). 2003. *Thukela Water Management Area: Overview of Water Resources Availability and Utilisation*. Report No. P WMA 07/000/00/0203. http://www.dwa.gov.za/projects.aspx

Dlamini, P, Chivenge, P, Manson, A and Chaplot, V. 2014. Land degradation impact on soil organic carbon and nitrogen stocks of sub-tropical humid grasslands in South Africa. *Geoderma* 235: 372-381.

Elleboudt, R. 2012. Are conservation agriculture practices an interesting option for the smallholder farmer communities of the Okhahlamba Local Municipality, KwaZulu-Natal, South Africa? Unpublished Master's dissertation, University of Ghent, Belgium.

Ezemvelo, KZN Wildlife, EKZN. 2011. KwaZulu-Natal Land Cover 2008 V1. 1. *Unpublished GIS Coverage [Clp_KZN_2008_LC_V1_1_grid_w31. zip]*, Biodiversity Conservation Planning Division, Ezemvelo KZN Wildlife, PO Box, 13053.

Fang, CL, Bao, C and Huang, JC. 2007. Management implications to water resources constraint force on socio-economic system in rapid urbanization: a case study of the Hexi Corridor, NW China. *Water Resources Management* 21(9): 1613-1633.

Fohrer, N, Haverkamp, S, Eckhardt, K and Frede, HG. 2001. Hydrologic response to land use changes on the catchment scale. *Physics and Chemistry of the Earth, Part B: Hydrology, Oceans and Atmosphere* 26(7-8): 577-582.

Foley, JA, DeFries, R, Asner, GP, Barford, C, Bonan, G, Carpenter, S. R and Helkowski, JH. 2005. Global consequences of land use. *Science* 309(5734): 570-574.

Forbes, KA, Kienzle, SW, Coburn, CA, Byrne, JM and Rasmussen, J. 2011. Simulating the hydrological response to predicted climate change on a watershed in southern Alberta, Canada. *Climatic Change* 105(3): 555-576.

Gao, JH, Jia, J, Kettner, A.J, Xing, F, Wang, YP, Li, J and Gao, S. 2015. Reservoir-induced changes to fluvial fluxes and their downstream impacts on sedimentary processes: the Changjiang (Yangtze) River, China. *Quaternary International*.

Galloway, JN, Dentener, FJ, Capone, DG, Boyer, EW, Howarth, RW, Seitzinger, SP, Asner, GP, Cleveland, CC, Green, PA, Holland, EA, Karl, DM, Michaels, AF, Porter, JH, Townsend, AR and Vöösmarty, CJ. 2004. Nitrogen cycles: past, present, and future. *Biogeochemistry* 70(2): 153-226.

Gifford, GF and Hawkins, RH. 1978. Hydrologic impact of grazing on infiltration: a critical review. *Water Resources Research* 14(2): 305-313.

Godfray, HCJ, Beddington, JR, Crute, IR, Haddad, L, Lawrence, D, Muir, JF, Pretty, J, Robinson, S, Thomas, SM and Toulmin, C. 2010. Food security: the challenge of feeding 9 billion people. *Science* 327(5967): 812-818.

Gordon, LJ, Finlayson, CM and Falkenmark, M. 2010. Managing water in agriculture for food production and other ecosystem services. *Agricultural Water Management* 97(4): 512-519.

Hargreaves, GH and Samani, ZA. 1985. Reference crop evapotranspiration from temperature. *Applied engineering in agriculture* 1(2): 96-99.

Headey, D and Fan, S. 2008. Anatomy of a crisis: the causes and consequences of surging food prices. *Agricultural economics* 39(s1):375-391.

Herpertz, D. 2001. Schneehydrologische Modellierung im Mittelgebirgsraum. Unpublished PhD thesis, Bonn University, Germany.

Hu, X, Lu, L, Li, X, Wang, J and Guo, M. 2015. Land Use/Cover Change in the Middle Reaches of the Heihe River Basin over 2000-2011 and Its Implications for Sustainable Water Resource Management. *PloS one* 10(6): e0128960.

IPCC, 2007. Climate Change 2007. The Physical Science Basis. Contribution of Working Group I to the Fourth Assessment Report of the Intergovernmental Panel on Climate Change. In: eds. Solomon, S, Quin, D, Manning, M, Chen, Z, Marquis, M, Averyt, KB, Tignor, M and Miller, HL. Cambridge University Press, Cambridge, UK.

IPCC, 2012. Managing the Risks of Extreme Events and Disasters to Advance Climate Change Adaptation. In: eds. Field, CB, Barros, V, Stocker, TF, Qin, D, Dokken, DJ, Ebi, KL, Mastrandrea, MD, Mach, KJ, Plattner, GK, Allen, SK, Tignor, M and Midgley, PM. A Special Report of Working Groups I and II of the Intergovernmental Panel on Climate Change. Cambridge University Press, Cambridge, United Kingdom and New York, NY, USA.

Jewitt, GPW, Lorentz, SA, Gush, MB, Thornton-Dibb, S, Kongo, V, Wiles, L, Blight, J, Stuart-Hill, SI, Versfeld, D and Tomlinson, K. 2009. *Methods and Guidelines for the Licensing of SFRAs with Particular Reference to Low Flows*. Report No. 1428/1/09 Water Research Commission, Pretoria, South Africa.

Kemerink, JS, Méndez, LE, Ahlers, R, Wester, P and Van der Zaag, P. 2013. The question of inclusion and representation in rural South Africa: challenging the concept of water user associations as a vehicle for transformation. *Water Policy* 15(2): 2013; authors version (post-print).

Kienzle, SW, Lorentz, SA and Schulze, RE. 1997. *Hydrology and water quality of the Mgeni Catchment*. Report No. TT87/97, Water Research Commission, Pretoria, South Africa.

Kienzle, SW and Schmidt, J. 2008. Hydrological impacts of irrigated agriculture in the Manuherikia catchment, Otago, New Zealand. *Journal of Hydrology (New Zealand*) 47(2): 67.

Kremen, C, Williams, NM and Thorp, RW. 2002. Crop pollination from native bees at risk from agricultural intensification. *Proceedings of the National Academy of Sciences* 99(26): 16812-16816.

Le Maitre, DC, Kotzee, IM and O'Farrell, PJ. 2014. Impacts of land-cover change on the water flow regulation ecosystem service: Invasive alien plants, fire and their policy implications. *Land Use Policy* 36: 171-181.

Leng C, Chen YN and Li XG. 2011. Evaluation of oasis stability in the lower reaches of the Tarim River. *Journal of Arid Land* 3(2): 123–131.

Lynch, SD. 2004. *Development of a Raster Database of Annual, Monthly and Daily Rainfall for Southern Africa*. Report No. 1156/1/03, Water Research Commission, Pretoria, South Africa.

Martinez, CJ, Campbell, KL, Annable, MD and Kiker, GA. 2008. An object-oriented hydrologic model for humid, shallow water-table environments. *Journal of Hydrology* 351(3): 368-381.

Merchán, D, Causapé, J and Abrahao, R. 2013. Impact of irrigation implementation on hydrology and water quality in a small agricultural basin in Spain. *Hydrological sciences journal* 58(7): 1400-1413.

Moody, JA and Martin, DA. 2001. Post‐ fire, rainfall intensity–peak discharge relations for three mountainous watersheds in the western USA. *Hydrological processes* 15(15): 2981-2993.

National Land Cover (NLC). 2000. Council for Scientific and Industrial Research and Agricultural Research Council Consortium. Pretoria, South Africa.

National Planning Commission (NPC). 2013. *National development plan vision 2030*. Pretoria, South Africa.

National Water Act (NWA). 1998. RSA Government Gazette No. 36 of 1998: 26 August 1998, No. 19182. Cape Town, RSA.

Ndoro, JT, Hitayezu, P, Mudhara, M and Chimonyo, M. 2013, September. Livelihood factors influencing market participation and supply volumes decisions among smallholder cattle farmers in the Okhahlamba Local Municipality, South Africa: Implications for agricultural extension programming. In *4th International Conference of the African Association of Agricultural Economists,* 22-25 September 2013, African Association of Agricultural Economists, Hammamet, Tunisia.

Nian, Y, Li, X, Zhou, J and Hu, X. 2014. Impact of land use change on water resource allocation in the middle reaches of the Heihe River Basin in northwestern China. *Journal of Arid Land* 6(3): 273-286.

Nsuntsha, ANM. 2000. Change and continuity in government institutional arrangements: implications for environmental management in the Upper Tugela area of KwaZulu-Natal. Unpublished Doctoral Dissertation, University of KwaZulu-Natal, Durban, South Africa.

Okhahlamba Local Municipality (OLM). 2016. Okhahlamba Integrated Development Plan Review 2016/2017. Okhahlamba Local Municipality, Bergville, South Africa.

Öztürk, M, Copty, NK and Saysel, AK. 2013. Modeling the impact of land use change on the hydrology of a rural watershed. *Journal of Hydrology* 497: 97-109.

PANNAR. 2017. Know the Maize Plant. PANNAR, Greytown, South Africa.

Parajuli, PB, Jayakody, P, Sassenrath, GF, Ouyang, Y and Pote, JW. 2013. Assessing the impacts of crop-rotation and tillage on crop yields and sediment yield using a modeling approach. *Agricultural water management*, *119*, 32-42.

Peel, MC. 2009. Hydrology: catchment vegetation and runoff. *Progress in Physical Geography* 33(6): 837-844.

Pielke, RA, Marland, G, Betts, RA, Chase, TN, Eastman, JL, Niles, JO and Running, SW. 2002. The influence of land-use change and landscape dynamics on the climate system: relevance to climate-change policy beyond the radiative effect of greenhouse gases. *Philosophical Transactions of the Royal Society of London A: Mathematical, Physical and Engineering Sciences* 360(1797): 1705-1719.

Pommerieux, M, Bourblanc, M and Ducrot, R. 2014. *Monitoring and evaluation of a participative planning process for the integrated management of natural resources in the uThukela District Municipality (South Africa)*. Working paper No. 2014/1, University of Pretoria, South Africa.

Rogers, DH, Aguilar, J, Kisekka, I, Barnes, PL and Lamm, FR. 2015. *Agricultural crop water use*. Kansas State University, Agricultural Experiment Station and Cooperative Extension Service.

Rulli, MC, Saviori, A and D’Odorico, P. 2013. Global land and water grabbing. *Proceedings of the National Academy of Sciences* 110(3): 892-897.

Sanjari, G, Yu, B, Ghadiri, H, Ciesiolka, CA and Rose, CW. 2010. Effects of time-controlled grazing on runoff and sediment loss. *Soil Research* 47(8): 796-808.

Schulze, RE. (Ed.). 1995. *Hydrology and Agrohydrology: A Text to Accompany the ACRU 3.00 Agrohydrological Modelling System*. Water Research Commission, Pretoria, South Africa.

Schulze, RE, Angus, GR and Guy, RM. 1995. Soils. In: ed. Schulze, RE. *Hydrology and Agrohydrology: A Text to Accompany the ACRU 3.00 Agrohydrological Modelling System*, Chapter 5, AT5-1-28. Water Research Commission, Pretoria, South Africa.

Schulze, R, Summerton, M, Meier, K, Pike, A and Lynch, S. 1997. The ACRU*forest* Decision Support System to Assess Hydrological Impacts of Afforestation Practices in South Africa. In: *Proceedings of the Eighth South African National Hydrology Symposium*, Pretoria, South Africa.

Schulze, RE. 2004. Determination of baseline land cover variables for applications in addressing land use impacts on hydrological responses in South Africa. In: eds. Schulze, RE and Pike, A. *Development and evaluation of an installed hydrological modelling system*. Chapter 4, 37-50, Report No. 1155/1/04, Water Research Commission, Pretoria, South Africa.

Schulze, RE and Maharaj, M. 2004. *Development of a Database of Gridded Daily Temperatures for Southern Africa*. Report No. 1156/2/04, Water Research Commission, South Africa.

Schulze, RE. 2007. Soils: Agrohydrological Information Needs, Information Sources and Decision Support. In: Schulze, RE. (Ed). 2007. *South African Atlas of Climatology and Agrohydrology*. Report No. 1489/1/06, Water Research Commission, Pretoria, South Africa, Section 4.1.

Schulze, RE and Horan, MJC. 2007. *Hydrological Modelling as a Tool for Ecosystem Services Trading: Case Studies from the Drakensberg Region of South Africa*. University of KwaZulu-Natal, Pietermaritzburg, School of Bioresources Engineering and Environmental Hydrology, *ACRUcons* Report 56. pp 71.

Schulze RE and Horan MJC. 2011. Methods 1: Delineation of South African Lesotho and Swaziland into quinary catchments. In: eds. Schulze, RE, Hewitson, BC, Barichievy, KR, Tadross, M, Kunz, RP, Horan, MJC and Lumsden, TG. 2010. *Methodological Approaches to Assessing Eco-Hydrological Responses to Climate Change in South Africa*. Report No. 1562/1/10, Chapter 6, 55-62. Water Research Commission WRC, Pretoria, South Africa.

Schmidt, J, Kienzle, SW and Srinivasan, MS. 2009. Estimating increased evapotranspiration losses caused by irrigated agriculture as part of the water balance of the Orari Catchment, Canterbury, New Zealand. *Journal of Hydrology (NZ)* 48: 89-94.

Scott, DF and Schulze, RE. 1992. The hydrological effects of a wildfire in a eucalypt afforested catchment. *South African Forestry Journal* 160(1): 67-74.

Shabalala, MM and Toucher, ML. 2018. The influence of declining hydrometeorological monitoring networks on hydrological modelling: a model confirmation case study from the uThukela catchment. *To be submitted to Physics and Chemistry of the Earth*.

Siriwardena, L, Finlayson, BL and McMahon, TA. 2006. The impact of land use change on catchment hydrology in large catchments: The Comet River, Central Queensland, Australia. *Journal of Hydrology* 326: 199 – 214.

Smakhtin, VU. 2001. Low flow hydrology: a review. *Journal of hydrology* 240(3): 147-186.

Smithers, JC and Schulze, RE. 2004. *ACRU Agrohydrological Modelling System: User Manual Version 4.00.* School of Bioresources Engineering and Environmental Hydrology, University of KwaZulu-Natal, South Africa.

Smithers, JC, Chetty, KT, Frezghi, MS, Knoesen, DM and Tewolde, MH. 2007. *Development and Assessment of a Continuous Simulation Modelling System for Design Flood*

Estimation. Report No. 1318/1/07. Water Research Commission, Pretoria, South Africa.

Strauch, AM, Kapust, AR and Jost, CC. 2009. Impact of livestock management on water quality and streambank structure in a semi-arid, African ecosystem. *Journal of Arid Environments* 73(9): 795-803.

Tang, L, Yang, D, Hu, H and Gao, B. 2011. Detecting the effect of land-use change on streamflow, sediment and nutrient losses by distributed hydrological simulation. *Journal of Hydrology* 409(1-2): 172-182.

Tarboton, KC and Schulze, RE. 1990. Impacts of increased afforestation and farm dams on water resources of the upper Mgeni catchments. *Agricultural Engineering in South Africa* 22: 201–215.

Tarboton, KC and Schulze, RE. 1991. The ACRU modelling system for large catchment water resources management. *Hydrology for the Water Management of Large River Basins* 219-232

van Luijk, G, Cowling, RM, Riksen, MJPM and Glenday, J. 2013. Hydrological implications of desertification: Degradation of South African semi-arid subtropical thicket. *Journal of arid environments* 91: 14-21.

van Oel, PR., Krol, MS, Hoekstra, AY and De Araújo, JC. 2008. The impact of upstream water abstractions on reservoir yield: the case of the Orós Reservoir in Brazil. *Hydrological sciences journal* 53(4): 857-867.

Wagner, PD, Kumar, S and Schneider, K. 2013. An assessment of land use change impacts on the water resources of the Mula and Mutha Rivers catchment upstream of Pune, India. *Hydrology and Earth System Sciences* 17(6): 2233-2246.

Warburton, ML, Schulze, RE and Jewitt, GP. 2012. Hydrological impacts of land use change in three diverse South African catchments. *Journal of Hydrology* 414: 118-135.

Warren, SD, Blackburn, WH and Taylor Jr, CA. 1986. Effects of season and stage of rotation cycle on hydrologic condition of rangeland under intensive rotation grazing. *Journal of Range Management* 486-491.

Watanabe, MD and Ortega, E. 2014. Dynamic emergy accounting of water and carbon ecosystem services: A model to simulate the impacts of land-use change. *Ecological Modelling* 271: 113-131.

Wood, H.2011. *A Brief Overview of Farming Systems and Practices in the uThukela District*. KZN Department of Agriculture, Environment Affairs and Rural Development, Ladysmith.

Yan, B, Fang, NF, Zhang, PC and Shi, ZH. 2013. Impacts of land use change on watershed streamflow and sediment yield: an assessment using hydrologic modelling and partial least squares regression. *Journal of Hydrology* 484: 26-37.

Yokwe, S. 2009. Water productivity in smallholder irrigation schemes in South Africa. *Agricultural water management* 96(8): 1223-1228.

3.7 Appendices

Appendix A: Monthly water use input values for vegetation types used in modelling.

Land use	**Variable**	**Monthly input**											
		Jan	**Feb**	**Mar**	**Apr**	**May**	**Jun**	**Jul**	**Aug**	**Sept**	**Oct**	**Nov**	**Dec**
Commercial agriculture													
-dryland maize	CAY	1.02	0.55	0.2	0.2	0.2	0.2	0.2	0.2	0.2	0.4	0.77	1.05
	COIAM	0.15	0.15	0.2	0.3	0.3	0.3	0.3	0.3	0.3	0.3	0.15	0.15
	VEGINT	1.5	1.4	1.3	1.2	0.5	0.5	0.5	0.5	0	0.6	0.9	1.2
	ROOTA	0.78	0.91	1	1	1	1	1	1	1	0.92	0.79	0.74
-dryland sugarcane	CAY	0.83	0.83	0.83	0.83	0.83	0.83	0.83	0.83	0.83	0.83	0.83	0.83
	COIAM	0.35	0.35	0.35	0.35	0.35	0.35	0.35	0.35	0.35	0.35	0.35	0.35
	VEGINT	1.7	1.7	1.7	1.7	1.7	1.7	1.7	1.7	1.7	1.7	1.7	1.7
	ROOTA	0.75	0.75	0.75	0.75	0.75	0.75	0.75	0.75	0.75	0.75	0.75	0.75
-irrigated maize	CAY	1.02	0.55	0.2	0.2	0.2	0.2	0.2	0.2	0.2	0.4	0.77	1.05
	COIAM	0.15	0.15	0.35	0.2	0.3	0.3	0.3	0.3	0.3	0.3	0.2	0.15
	VEGINT	1.5	1.4	1.3	1.2	0.5	0.5	0.5	0.5	0	0.6	0.9	1.2
	ROOTA	1	1	1	1	1	1	1	1	1	1	1	1
-irrigated wheat	CAY	0.2	0.2	0.2	0.2	0.3	0.79	1	0.52	0.2	0.2	0.2	0.2
	COIAM	0.15	0.15	0.35	0.2	0.3	0.3	0.3	0.3	0.3	0.3	0.2	0.15
	VEGINT	0.5	0.5	0.5	0.3	0.8	1	1.5	1	0.5	0.5	0.5	0.5
	ROOTA	1	1	1	1	1	1	1	1	1	1	1	1
-irrigated pasture	CAY	0.8	0.8	0.8	0.7	0.6	0.5	0.5	0.5	0.6	0.7	0.8	0.8
	COIAM	0.3	0.3	0.3	0.3	0.3	0.3	0.3	0.3	0.3	0.3	0.3	0.3
	VEGINT	1.4	1.4	1.4	1.4	1.2	1	1	1.2	1.3	1.4	1.4	1.4
	ROOTA	1	1	1	1	1	1	1	1	1	1	1	1
-double irrigation (maize, wheat)	CAY	1.1	0.95	0.46	0	0.2	0.3	0.6	0.97	0.94	0.2	0.49	0.98
	COIAM	0.15	0.15	0.35	0.2	0.3	0.3	0.3	0.3	0.3	0.3	0.2	0.15
	VEGINT	1.5	1.4	1.3	0	0.5	1	1.3	1.5	1	0	0.5	1
	ROOTA	1	1	1	1	1	1	1	1	1	1	1	1
-soya beans	CAY	0.73	0.94	0.55	0.2	0.2	0.2	0.2	0.2	0.2	0.2	0.2	0.33
	COIAM	0.2	0.2	0.2	0.2	0.2	0.2	0.2	0.2	0.2	0.2	0.3	0.25
	VEGINT	1	1.3	1.2	1	0.5	0.5	0.5	0.5	0.5	0.5	0	0.6
	ROOTA	0.74	0.74	0.78	0.91	1	1	1	1	1	1	1	0.92
-sorghum	CAY	1.1	0.95	0.46	0.2	0.2	0.2	0.2	0.2	0.2	0.2	0.49	0.98
	COIAM	0.35	0.35	0.35	0.35	0.35	0.35	0.35	0.35	0.35	0.35	0.35	0.35
	VEGINT	0.64	0.64	0.6	0.5	0.5	0.5	0.5	0.5	0.5	0	0.5	0.6
	ROOTA	0.74	0.78	0.91	1	1	1	1	1	1	1	0.92	0.79
Subsistence agriculture													
-maize	CAY	0.89	1.1	0.96	0.46	0.2	0.2	0.2	0.2	0.2	0.2	0.2	0.5
	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
	VEGINT	1	1.5	1.4	1.3	1.2	0.5	0.5	0.5	0.5	0.5	0	0.5
	ROOTA	0.79	0.74	0.78	0.91	1	1	1	1	1	1	1	0.92
-sugarcane	CAY	0.8	0.8	0.8	0.8	0.8	0.8	0.8	0.8	0.8	0.8	0.8	0.8
	COIAM	0.25	0.25	0.25	0.25	0.25	0.25	0.25	0.25	0.25	0.25	0.25	0.25
	VEGINT	1.6	1.6	1.6	1.6	1.6	1.6	1.6	1.6	1.6	1.6	1.6	1.6

	ROOTA	0.8	0.8	0.8	0.8	0.8	0.8	0.8	0.8	0.8	0.8	0.8	0.8
Commercial forestry													
-Pine	CAY	0.85	0.85	0.85	0.85	0.85	0.85	0.85	0.85	0.85	0.85	0.85	0.85
	COIAM	0.35	0.35	0.35	0.35	0.35	0.35	0.35	0.35	0.35	0.35	0.35	0.35
	VEGINT	3.5	3.5	3.5	3.5	3.5	3.5	3.5	3.5	3.5	3.5	3.5	3.5
	ROOTA	0.66	0.66	0.66	0.66	0.66	0.66	0.66	0.66	0.66	0.66	0.66	0.66
Natural vegetation													
-Southern tall grassveld	CAY	0.75	0.75	0.75	0.5	0.4	0.2	0.2	0.2	0.55	0.7	0.75	0.75
	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
	VEGINT	1.6	1.6	1.6	1.6	1.5	1.4	1.4	1.4	1.5	1.6	1.6	1.6
	ROOTA	0.9	0.9	0.9	0.95	0.95	1	1	1	0.95	0.9	0.9	0.9
-Natal sour sandveld	CAY	0.75	0.75	0.7	0.5	0.35	0.2	0.2	0.2	0.5	0.65	0.7	0.75
	COIAM	0.15	0.15	0.2	0.3	0.3	0.3	0.3	0.3	0.3	0.3	0.25	0.15
	VEGINT	1.8	1.8	1.8	1.8	1.6	1.4	1.4	1.4	1.7	1.7	1.8	1.8
	ROOTA	0.9	0.9	0.9	0.95	0.95	1	1	1	0.95	0.9	0.9	0.9
-Indigenous forest	CAY	0.85	0.85	0.85	0.85	0.6	0.6	0.6	0.6	0.85	0.85	0.85	0.85
	COIAM	0.35	0.35	0.35	0.35	0.35	0.35	0.35	0.35	0.35	0.35	0.35	0.35
	VEGINT	3.3	3.3	3.3	3.3	3.3	3.3	3.3	3.3	3.3	3.3	3.3	3.3
	ROOTA	0.66	0.66	0.66	0.66	0.66	0.66	0.66	0.66	0.66	0.66	0.66	0.66
Degraded vegetation	CAY	0.55	0.55	0.55	0.45	0.2	0.2	0.2	0.2	0.2	0.45	0.55	0.55
	COIAM	0.1	0.1	0.1	0.15	0.15	0.2	0.2	0.2	0.2	0.15	0.1	0.1
	VEGINT	0.8	0.8	0.8	0.7	0.6	0.6	0.6	0.6	0.65	0.75	0.8	0.8
	ROOTA	0.9	0.9	0.9	0.94	1	1	1	1	0.95	0.92	0.9	0.9
Burning													
-Annual (June)	CAY	0.65	0.65	0.65	0.5	0.28	0.2	0.2	0.3	0.4	0.55	0.62	0.65
	COIAM	0.15	0.15	0.25	0.3	0.3	0.1	0.1	0.2	0.25	0.3	0.2	0.15
	VEGINT	1.5	1.5	1.5	1.3	1.1	0.7	0.7	0.75	0.8	0.15	0.35	1.5
	ROOTA	0.9	0.9	0.9	0.95	1	1	1	1	0.95	0.9	0.9	0.9
-biennial severe	CAY	0.55	0.55	0.55	0.45	0.25	0.2	0.2	0.2	0.4	0.45	0.55	0.55
	COIAM	0.1	0.1	0.1	0.15	0.15	0.2	0.2	0.2	0.2	0.15	0.1	0.1
	VEGINT	0.8	0.8	0.8	0.7	0.6	0.6	0.6	0.6	0.65	0.75	0.8	0.8
	ROOTA	0.9	0.9	0.9	0.95	0.95	1	1	1	0.95	0.9	0.9	0.9

CAY is the crop coeeficient; COIAM is the coeficient of initial abstraction of water by the plant during rainfall or irrigation; VEGINT is the total amount of intercepted water (mm) and ROOTA is the fraction of roots in the A-horizon.

4. SYNTHESIS

Through adoption of the National Development Plan (National Planning Commission, NPC, 2013), the South African National, KwaZulu-Natal Provincial and Okhahlamba Local Governments aim to develop agriculture in the uThukela catchment to improve the region's economy and assist in meeting the country's food demands. To achieve this, the Government aims to (i) improve commercial agriculture through investment in research towards the development of innovative, efficient technologies (i.e. irrigation systems, seeds, cultivars, etc.); (ii) increase the fraction of irrigated agriculture, where resource allows; (iii) transfer commercial agricultural land to subsistence farmers through the land reform programme, and (iv) provide the necessary financial resources for infrastructural and skills development for the subsistence farmers. Implementation of these changes will impact on water resources and other environmental ecosystems. Thus, the main aim of this study was to investigate the impacts of the proposed land use change/management activities through a scenario-based modelling approach using the soil-sensitive, daily time-step, multi-purpose ACRU model. The specific objectives were, (i) to investigate the impacts of declining hydrometeorological data availability and quality on hydrological modelling, (ii) to confirm the adequacy of the ACRU model to simulate flows in three, relatively small subcatchments in the uThukela Catchment, (iii) to use the ACRU model to simulate the impacts of changing agricultural management practices in the subcatchments selected for the confirmation study and (iv) to investigate the impacts of land use changes with significant impacts at a larger catchment scale.

Due to poor observed streamflow data, model confirmation was only performed in two of the three selected catchments. Poor streamflow and climatic data beyond Year 2000 further limited confirmation of the model to pre-2000 periods with the most consistent, good quality data.

Increasing the proportion of irrigated agriculture resulted in the highest flow reduction, while replacing commercial dryland agriculture with crops with biofuel potential resulted in the highest flow increases. Increased degradation and burning activities corresponded to significant flow increases. Rehabilitation of currently-degraded grasslands and increasing subsistence agriculture resulted in insignificant changes in flow.

The study was completed in the face of several challenges related to data unavailability and modelling uncertainties. These challenges, the lessons learnt from them and suggestions for application of the ACRU model in future water resources management are discussed below. The implication of the results for water resources management in the context of ecosystem services at the uThukela catchment is also discussed below. Furthermore, the potential impacts of the study results in the context of climate change are highlighted.

4.1 The Impacts of Scale and Data Unavailability on Modelling

Many authors argue that the issue of scale depends on the specific hydrological problem to be solved and the scientific approach and perspective of the modeller (Bergström and Graham, 1998; Beven 2000). For example, a 1 km^2 catchment may be considerd large-scale and highly heterogeneous in a lysimeter study, while several thousands of kilometres may be considered small scale in the context of a climate change modeller. In the context of rainfall-runoff modelling, physically-based models attempt to represent all the relationships between the surface and subsurface processes that control runoff generation making these kinds of models data intensive (Bergström and Graham, 1998; Beven, 1996, 2000, 2001; Devia *et al*., 2015). Due to the high data requirements, the application of physically-based models is often limited to small scale modelling. At a larger scale, more conceptual, highly parameterized models are used. At a small scale, hydrological response to change is significant (Devia *et al*., 2015; Kauffeldt *et al*., 2016).

ACRU is a relatively physical model, as it mainly requires measured climate, and physically representative soil and plant variables, rather than parameters. Therefore, the model requires large data inputs. Thus, Schulze (1995) recommends the application of the ACRU model to be for catchments ranging from 10-50 km^2. However, the model can be used in distributed mode for larger catchments, with subdivisions less than 50km^2.

ACRU requires daily rainfall and temperature information to operate. In South Africa, national databases of pre-2000 daily rainfall and temperature information have been developed (Lynch, 2004; Schulze and Maharaj, 2004). Additionally, a database of soil information in ACRU relevant parameters is available at a national scale (Schulze, 2007). This makes it easier to use the ACRU model for pre-2000 conditions in South African catchments. In the study area, there was a limited number of functional climate stations with record extending beyond Year 2000, making it difficult to confirm the ability of the ACRU model to simulate streamflow for current conditions at QCs V14C (156 km^2) and V31F (148 km^2). With the current decline in the number of climate and streamflow gauging stations, model confirmation studies for current conditions will prove difficult in many operational catchments, where imminent water resources management decisions are required. These can only be limited to well-monitored, small size research catchments.

In this study, ACRU was set as a distributed model, where the modelled area was divided into smaller subcatchments which logically flow into each other. This allows for the impacts of changes in land management to be measured at the bottom of any subcatchment. Therefore, the model allows the user to link downstream streamflow response to the land uses within the upstream subcatchment. The subdivisions of the large-scale modelling were based on altitudinal breaks (i.e. quanaries, Schulze and Horan, 2011), rather than catchment hydrological and land use attributes. In many cases, one quinary catchment was composed of different land uses, making it difficult to relate streamflow response to subcatchment land use. In addition, some quinary subcatchments are above the 50 km^2 recommended by Schulze (1995). Future studies should investigate the possibility of using hydrological and land use derived subdivisions such as those used in the model confirmation study (Shabalala and Toucher, 2018; Ch2). This would enable the modeller to easily relate streamflow response to land use change when using ACRU as a distributed model in large scale studies. In addition, such subdivisions would allow for the use of the model in investigating the impacts of land use change-induced water quality issues (i.e. nutrient load, sedimentation, etc).

4.2 Ecosystem Considerations for Improved Water and Land Management Decisions in the upper uThukela Catchment

This study highlights the potential impacts of intensification of current agricultural activities within the uThukela catchment. Successful implementation of the proposed agricultural expansion can only be achieved through careful consideration and incorporation of the impacts of agricultural land management changes on water resources. Water management decisions need to be based on a holistic understanding of catchment biophysical and climatic characteristics. There is a need to link upstream water agricultural management decisions with potential loss of downstream ecosystems benefits, and the potential impacts of the loss of ecosystem services to human livelihood and the agricultural sector itself. Deterioration of ecosystem services due to agricultural production poses a threat to erode efforts to alleviate poverty through agriculture in many rural communities (WRI, 2005). Restoration of these ecosystem services is often difficult and costly (Gordon *et al.*, 2010). Therefore, there is a need to improve awareness of benefits from natural ecosystems other than food production among decision-makers and the general public.

Irrigation expansion will prove a severe challenge for water managers in the uThukela catchment as it poses a significant threat to water availability in the already-stressed Thukela River and its tributaries. Streamflow reduction due to agricultural activities has been documented to have transformed several of the world's largest rivers into highly-stabilized and/or seasonally non-discharging channels (Snaddon *et al.*, 1999). Therefore, careful consideration is required prior expansion of irrigated agriculture in the catchment, to maintain the integrity of the Thukela River, as it supports the livelihood of millions of people within KZN and Gauteng. Further expansion of irrigated agriculture will require adoption of efficient irrigation systems and conservation agricultural practices. Additionally, agricultural expansion within the limited water resources requires investment into water-efficient, high-yielding crop cultivars. Furthermore, increasing irrigated areas will require consideration of the several inter-basin transfers, which were not included in the study, as these pose an additional threat to downstream water availability in the catchment (Meybeck and Ragu, 1997; Walling and Fang, 2003; Scanlon *et al.*, 2007).

Irrigation expansion will pose a threat to the quantity of water required to maintain aquatic ecosystems, particularly during the non-rainfall period. The National Water Act (NWA, 1998) prioritises water required for basic human needs (Human Reserve) and protection of aquatic ecosystems (Ecological Reserve) before any withdrawals for economic activities. Based on results from this study, water availability for the Human and Ecological Reserves is threatened by agricultural expansion.

Beyond the impacts on water availability, agricultural expansion may result in water quality deterioration. High agricultural production to meet increasing demands will require application of chemicals such as fertilizers, herbicides and pesticides. Poor management of agricultural fields will result in transportation of these chemicals into downstream water resources as overland or subsurface flow. This may result in eutrophication of water bodies, which is followed by loss of ecosystem services (Verhoeven *et al.*, 2006). In addition, abundance of agricultural chemicals in water resources poses a threat to human health in downstream communities, particularly in the uThukela catchment, where many communities abstract water from rivers for domestic use.

Apart from being the source of water for the Thukela River, the Maloti-Drakensberg mountain range is well endowed for its biodiversity, especially for its diversity of endemic plant species (van Niekerk, 2007; Wood, 2011; OLM, 2016). Additionally, the scenic beauty and rich cultural heritage in these mountains attracts tourists and hikers from several parts of the world. As a result of these unique characteristics, several efforts have been made to protect this area in the form of parks through the establishment of the uKhahlamba Drakensburg Park and the Royal Natal National Park, with the former being later declared a World Heritage Site. Furthermore, the mountains serve as a source of grazing for subsistence farmers within the upper uThukela (MDTP, 2007). According to Blignaut *et al.* (2010), the Maloti-Drakensburg mountain range can be classified as a fire-prone grassland ecosystem. Therefore, increased degradation through overgrazing and uncontrolled burning activities could impact ecosystem services provided by these mountains, resulting in significant socioeconomic damages.

Agricultural water management decisions should incorporate the potential impacts of climate change on production. Thus, policy-makers, stakeholders and the general public should develop and continuously update climate change adaptation strategies to ensure resilience to the environmental, economic and social impacts of climate change within the region.

4.3 Agricultural Development in the Context of Climate Change

Beyond the potential impacts of agricultural land management changes on current/historical climate conditions, it is important to plan socioeconomic development in the context of changing climate patterns. The southern African region has been argued to be one of the most vulnerable regions to the impacts of climate change (IPCC, 2012; Kusangaya *et al*., 2014). Several studies have predicted an increase in the frequency and intensity of extreme hydrometeorological events in the region (Schulze *et al*., 2011; Ziervogel *et al*., 2014). The magnitude and intensity of rainfall events in expected to increase, with longer dry spells between the events (Christensen *et al*., 2007; Gbetibouo and Ringler, 2009). Agriculture, as the main land use in the uThukela catchment, is highly susceptible to changes in local climate conditions (Turpie and Visser, 2013). Thus, climate change impacts on agriculture will have direct effects on human livelihood as the majority of households in the uThukela catchment depend on agriculture for food and income (Elledboudt, 2012; OLM, 2016).

South Africa recently experienced its worst drought since 1992, recording an annual rainfall amount of 403 mm in 2015, the lowest since 1904 (Agri SA, 2016). This resulted in several impacts on the agricultural sector, including yield losses and livestock death (ARC, 2015; Grain SA, 2015; Agri SA, 2016; Red Meat Producers Organisation, 2016). Thus, if this recent history is anything to go by, the possibility of prolonged drought periods will place more pressure on the already-stressed water resources in the uThukela catchment. Such conditions pose a threat to dryland cropping and livestock ranching, which are a source of food and income for the majority of the uThukela population. Furthermore, long dry spells would result in limited water available for expansion of irrigated agriculture. Additionally, prolonged drought conditions would threaten water availability for the Human and Ecological Reserves, especially if irrigated agriculture is increased. Therefore, increasing irrigated agriculture under the predicted climatic conditions poses a threat to water security and human livelihood in the uThukela catchment.

Following a long period of below-average precipitation in many parts of the country, South Africa has been experiencing heavy rainfall events across the country from October 2017 to April 2018. These rainfall events have resulted in significant environmental and socioeconomic damages. In the rural parts of KZN, the flooding lead to infrastructural damage (destroyed homes and washed away bridges) and human death (Wicks, 2018). In agricultural land, flooding results in soil erosion, crop removal, waterlogging and delayed farming farming operations (Gornall *et al.*, 2010). As a result, flooding leads to yield loss, which may exacerbate poverty in agriculture-dependent communities like the uThukela. The KZN province has also been subjected to some intense hail storms over this period. Hail can destroy crops, vehicles, houses and cause livestock death. These recent events further highlight the importance of the need for careful planning before expansion of agricultural activities to avoid environmental, economic and human losses.

Given the added threats that changing climate patterns pose to water and food security, future studies should investigate the potential impacts of changes in agricultural land management practices on water resources under climate change scenarios, as well as the potential impacts of climate change on the agriculture sector in the uThukela catchment. This would aid the development of adaptation strategies, improving the region’s resilience to climate change.

In South Africa, the monitoring and management of anthropogenic and natural hazards is governed by the Disaster Management Act (DMA, 2002) which emphasizes that policy development needs to incorporate risk reduction strategies into development initiatives. The DMA designates disaster risk management powers to local government. Through its latest development plan, the OLM acknowledges its responsibilities as contemplated in the DMA. However, the municipality is yet to establish the necessary structures required to enforce efficient disaster management. Absence of these structures makes the upper uThukela catchment highly vulnerable to the impacts of climate change.

4.4 Conclusion

The lack of rainfall stations with data extending to present day, and the poor data quality from stations with record, curbed the confirmation of the ACRU model’s ability to simulate streamflow for current conditions. Nevertheless, the model adequately simulated flows for two, relatively small catchments within the uThukela Catchment for periods with the consistent, good quality data.

Irrigation resulted in the highest flow reductions, particularly low flows. Based on these results, there is little room for further expansion of irrigated agriculture in the catchment. Replacing commercial dryland crops with subsistence crops had a relatively small impact on water flows. Converting dryland commercial crops to crops with biofuel potential resulted in increased flows, with plantation of soya beans highly increasing baseflow. Increasing degradation and burning resulted in increased quickflow and streamflow, with the biennial burning having the highest effect. Therefore, intensification of burning and further degradation should be avoided, as this may increase soil erosion and sedimentation of downstream water resources. Improved livestock management and conservation tillage practices should be employed in order to avoid further degradation.

This study was completed under limited hydrometeorological and land use data conditions. Therefore, results from this study cannot be used as a final decision-making tool. However, these results can be used as an indication of the possible impacts of changes in land management practices on water quantity

4.5 Recommendations for Future Research

This study was completed under a number of challenges, mainly related to data unavailability and modelling uncertainties. The key challenges faced, lessons learnt and recommendations for future research are given below:

- It is important to improve the maintanence of hydrometeorological monitoring stations to improve the quality of model input data for sound water resources management decisions. In addition, the potential to incorporate data estimated from techniques outside the ‘traditional’ monitoring methods into modelling studies should be explored (for example, remote sensing and citizen science).
- This study was mainly desktop-based, coupled with a few field visitations and expert consultation. Future studies should incorporate more field-based data in order to improve the accuracy of model input and confidence in the results. In addition, there should more initiatives such as the “Verification and Validation of Water Users” by the Department of Water and Sanitation, in order to create a database of ground-collected water usage records.
- Similar studies should be carried out in other parts of the uThukela Catchment, as it characterized by high climatic variability.
- Future studies should be carried out at small catchment scales as the impacts of land use change have a greater impact at a local scale.
- With climate change models predicting an increase in the intensity and frequency of extreme hydrometeorological events, future studies should investigate the potential impacts of land management change under the projected climate change conditions in order to develop climate change adaptation strategies.
- The current version of the ACRU model, *viz*. ACRU4, requires high computational power for simulation at large catchments with multiple subcatchments and land uses. This was a major limitation on this study when modelling the impacts of land use change on runoff for the Upper uThukela Secondary Catchment. This study forms part of an ongoing project by the Water Research Commission, which aims to model

the impacts of land use change on water quantity and quality for the entire uThukela and three other large catchments in the country (i.e. Mzimvubu, Limpopo, Breede-Gouritz). To complete the project within the allocated timeframe, the possibility of successfully using other versions of the model which perform faster than ACRU4 should be investigated, or necessary modifications and adjustments should be made to improve the speed of current version when handling large datasets.

4.6 References

Agri SA. 2016. *A Raindrop in the Drought. Report to the Multi-Stakeholder Task Team on the Drought*. Agri SA, Pretoria, South Africa.

Agricultural Research Council (ARC). 2015. *Economic Output Report XVII*. Economic Services Unit, ARC, Pretoria, South Africa.

Beven, KJ. 1996. A discussion of distributed hydrological modelling. In: eds. Abbott, MB and Refsgaard, JC, *Distributed hydrological modelling*, Chapter 13A, 255-278. Kluwer Academic Publishers, Dordrecht, Netherlands.

Beven, KJ. 2000. Uniqueness of place and process representations in hydrological modelling. *Hydrology and Earth System Sciences Discussions* 4(2): 203-213.

Beven, KJ. 2001. How far can we go in distributed hydrological modelling? *Hydrology and Earth System Sciences* 5(1): 1-12.

Bergström, S and Graham, LP. 1998. On the scale problem in hydrological modelling. *Journal of Hydrology* 211(1-4): 253-265.

Blignaut, J, Mander, M, Schulze, R, Horan, M, Dickens, C, Pringle, C, Mavundla, K, Mahlangu, I, Wilson, A, McKenzie, M and McKean, S. 2010. Restoring and managing natural capital towards fostering economic development: Evidence from the Drakensberg, South Africa. *Ecological Economics* 69(6): 1313-1323.

Christensen, JH, Hewitson, B, Busuioc, A, Chen, A, Gao, X, Held, I, Jones, R, Kolli, RK, Kwon, WT, Laprise, R, Magaña Rueda, V, Mearns, L, Menéndez, CG, Räisänen, J, Rinke, A, Sarr, A and Whetton, P. 2007. Regional climate projections. In: eds. Solomon, S, Qin, D, Manning, M, Chen, Z, Marquis, M, Averyt, KB, Tignor, M and Miller, HL. *Climate Change 2007: The Physical Science Basis. Contribution of Working Group I to the Fourth Assessment Report of the Intergovernmental Panel on Climate Change*. Cambridge University Press, Cambridge, United Kingdom and New York, NY, USA.

Devia, GK, Ganasri, BP and Dwarakish, GS. 2015. A review on hydrological models. *Aquatic Procedia* 4: 1001-1007.

Disaster Management Act (DMA). 2002. RSA Government Gazatte No. 57 of 2002. Cape Town, South Africa.

Elleboudt, R. 2012. Are conservation agriculture practices an interesting option for the smallholder farmer communities of the Okhahlamba Local Municipality, KwaZulu-Natal, South Africa? Unpublished Master's dissertation, University of Ghent, Belgium.

Gbetibouo, GA and Ringler, C. 2009. *Mapping South African farming sector vulnerability to climate change and variability: A subnational assessment*. International Food Policy Research Institute (IFPRI) and Center for Environmental Economics and Policy in Africa (CEEPA), Washington, USA.

Gordon, LJ, Finlayson, CM and Falkenmark, M. 2010. Managing water in agriculture for food production and other ecosystem services. *Agricultural Water Management* 97(4): 512-519.

Gornall, J, Betts, R, Burke, E, Clark, R, Camp, J, Willett, K and Wiltshire, A. 2010. Implications of climate change for agricultural productivity in the early twenty-first century. *Philosophical Transactions of the Royal Society of London B: Biological Sciences*, 365(1554): 2973-2989.

GrainSA. 2015. *Facing New Realities, The Climate Has Changed*. Grain SA, Pretoria, South Africa.

IPCC, 2012. Managing the Risks of Extreme Events and Disasters to Advance Climate Change Adaptation. In: eds. Field, CB, Barros, V, Stocker, TF, Qin, D, Dokken, DJ, Ebi, KL, Mastrandrea, MD, Mach, KJ, Plattner, GK, Allen, SK, Tignor, M and Midgley, PM. A Special Report of Working Groups I and II of the Intergovernmental Panel on Climate Change. Cambridge University Press, Cambridge, United Kingdom and New York, NY, USA.

Kauffeldt, A, Wetterhall, F, Pappenberger, F, Salamon, P and Thielen, J. 2016. Technical review of large-scale hydrological models for implementation in operational flood forecasting schemes on continental level. *Environmental Modelling & Software* 75: 68-76.

Kusangaya, S, Warburton, ML, Van Garderen, EA and Jewitt, GP. 2014. Impacts of climate change on water resources in southern Africa: A review. *Physics and Chemistry of the Earth, Parts A/B/C* 67: 47-54.

Lynch, SD. 2004. *Development of a Raster Database of Annual, Monthly and Daily Rainfall for Southern Africa*. Report No. 1156/1/03, Water Research Commission, Pretoria, South Africa.

MDTP. 2007. *Payment for ecosystem services: An Ecosystem Services Trading Model for the Mnweni/Cathedral Peak and Eastern Cape Drakensberg Areas*. Development Bank of Southern Africa, Department of Water Affars and Forestry, Department of Environment Affairs and Tourism and Ezemvelo KZN Wildlife, South Africa.

Meybeck, M and Ragu, A. 1997. Presenting the GEMS-GLORI, A compendium of world river discharge to the oceans. In: ed. Webb, B. Freshwater Contamination. *Proceedings of a Symposium Held During the Fifth IAHS Scientific Assembly at Rabat. Morocco, April–May 1997*. Publication 243. International Association of Hydrological Sciences, Wallingford, UK.

National Planning Commission (NPC). 2013. *National development plan vision 2030*. Pretoria, South Africa.

National Water Act (NWA). 1998. RSA Government Gazette No. 36 of 1998. Cape Town, South Africa.

Okhahlamba Local Municipality (OLM). 2016. Okhahlamba Integrated Development Plan Review 2016/2017. Okhahlamba Local Municipality, Bergville, South Africa.

Scanlon, BR, Jolly, I, Sophocleous, M and Zhang, L. 2007. Global impacts of conversions from natural to agricultural ecosystems on water resources: Quantity versus quality. *Water resources research* 43(3).

Schulze, RE. (Ed.). 1995. *Hydrology and Agrohydrology: A Text to Accompany the ACRU 3.00 Agrohydrological Modelling System*. Water Research Commission, Pretoria, South Africa.

Schulze, RE and Maharaj, M. 2004. *Development of a Database of Gridded Daily Temperatures for Southern Africa*. Report No. 1156/2/04, Water Research Commission, South Africa.

Schulze, RE. 2007. Soils: Agrohydrological Information Needs, Information Sources and Decision Support. In: Schulze, RE. (Ed). 2007. *South African Atlas of Climatology and Agrohydrology*. Report No. 1489/1/06, Water Research Commission, Pretoria, South Africa, Section 4.1.

Schulze RE and Horan MJC. 2011. Methods 1: Delineation of South African Lesotho and Swaziland into quinary catchments. In: eds. Schulze, RE, Hewitson, BC, Barichievy, KR, Tadross, M, Kunz, RP, Horan, MJC and Lumsden, TG. 2010. *Methodological*

Approaches to Assessing Eco-Hydrological Responses to Climate Change in South Africa. Report No. 1562/1/10, Chapter 6, 55-62. Water Research Commission WRC, Pretoria, South Africa.

Schulze, RE, Hewitson, BC, Barichievy, KR, Tadross, MA, Kunz, RP, Horan, MJC and Lumsden, TG. 2011. *Methodological approaches to assessing eco-hydrological responses to climate change in South Africa*. Report No. 1562/1/10. Water Research Commission, Pretoria, South Africa.

Shabalala, MM and Toucher, ML. 2018. The influence of declining hydrometeorological monitoring networks on hydrological modelling: a model confirmation case study from the uThukela catchment. *To be submitted to Physics and Chemistry of the Earth*.

Snaddon, CD, Davies, BR and Wishart, MJ. 1999. *A global overview of inter-basin water transfer schemes, with an appraisal of their ecological, socio-economic and socio-political implications, and recommendations for their management*. Water Research Commission Technology Transfer Report TT 120/00. Water Research Commission, Pretoria, South Africa.

Turpie, J and Visser, M. 2013. The Impact of Climate Change on South Africa's Rural Areas. In: Technical Report: Submission for the 2013/14 Division of Revenue - For an Equitable Sharing of National Revenue. Midrand: Financial and Fiscal Comission, pp. 127-220. United Nations Environment Programme. 2006. *GEO Year Book 2006*: *An Overview of Our Changing Environment*, Nairobi.

van Niekerk, K, Everson, T, Turpie, J, Scovronick, N, Mander, M, McKean, S. 2007. Identification of land use practices impacting on water related ecosystem services. In: (Ed), *Payment for Ecosystem Services: Developing an Ecosystem Services Trading Model for the Mnweni/Cathedral Peak and Eastern Cape Drakensberg Areas*. Maloti Drakensberg Transfrontier Project, Development Bank of Southern Africa, Department of Water Affairs and Forestry, Department of Environment Affairs and Tourism, Ezemvelo KZN Wildlife, South Africa.

Verhoeven, JT, Arheimer, B, Yin, C and Hefting, MM. 2006. Regional and global concerns over wetlands and water quality. *Trends in ecology & evolution* 21(2): 96-103.

Walling, DE and Fang, D. 2003. Recent trends in the suspended sediment loads of the world's rivers. *Global and planetary change* 39(1-2): 111-126.

Wicks, J. 2018. Floods in Nothern KZN claim life of a 7-year-old boy. Internet. Times live, South Africa. Available from: https://www.timeslive.co.za/news/south-africa/2018-

02-19-floods-in-northern-kzn-claims-life-of-7-year-old-boy/. Accessed: 20 February 2018.

Wood, H. 2011. *A Brief Overview of Farming Systems and Practices in the uThukela District*. KZN Department of Agriculture, Environment Affairs and Rural Development, Ladysmith.

WRI (World Resources Institute), 2005. *UNDP (United Nations Development Programme), UNEP (United Nations Environment Programme), World Bank, World resources 2005: The wealth of the poor- Managing ecosystems to fight poverty*. World Resources Institute, Washington, DC.

Ziervogel, G, New, M, Archer van Garderen, E, Midgley, G, Taylor, A, Hamann, R, Stuart-Hill, S, Myers, J and Warburton, M. 2014. Climate change impacts and adaptation in South Africa. *Wiley Interdisciplinary Reviews: Climate Change* 5(5): 605-620.