CHALLENGES IN MODELLING HYDROLOGICAL RESPONSES TO IMPACTS AND INTERACTIONS OF LAND USE AND CLIMATE CHANGE

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ABSTRACT

To meet society's needs for water, food, fuel and fibre the natural land cover throughout the world has been extensively altered. These alterations have impacted on hydrological responses and thus on available water resources, as the hydrological responses of a catchment are dependent upon, and sensitive to, changes in the land use. Similarly, changes in the climate through enhanced carbon dioxide (CO_2) levels in the atmosphere have resulted in increased temperature and altered precipitation patterns that alter hydrological responses. In combination, land use change and global climate change form a complex and interactive system, whereby both human influences and climate change manipulate land use patterns, and changes in land uses feed back to influence the climate system, with both impacting on hydrological responses.

Relatively few studies have been undertaken examining the combined impacts of climate change and land use change on water resources, with no consensus emerging as yet as to combined influence of land use change and climate change on hydrological responses and the role of geographical characteristics in determining the overriding influence. There is, however, agreement that the effect on hydrological responses will be amplified. Given that South Africa is currently water stressed and considered to be highly exposed to climate change impacts, an understanding of hydrological responses to the complex interactions between land use and climate change is crucial to allow for improved integration of land use planning in conjunction with climate change adaptation into water resources management.

To determine the sensitivity of land use to changing climate, a sensitivity study assessing the potential impacts of climate change on the areas climatically suitable for key plantation forestry species was undertaken. Under sensitivity scenarios of climate change the climatically optimum areas for specific forest species were shown to shift, with optimum areas changing in extent and location between and within South Africa's provinces. With potential for shifts in land use due to climate change shown, the imperative to improve understanding of the dynamics between land use and climate change as well as the subsequent impacts on hydrological responses was further established.

For the assessment of climate-land use-water interactions, a process-based hydrological model, sensitive to land use and climate, and changes thereof, *viz*. the daily time step *ACRU* model was selected. In order to increase the confidence in results from the model in a study such as this, its representation of reality was confirmed by comparing simulated streamflow output against observations across a range of climatic conditions and land uses. This comparison was undertaken in the three diverse South African catchments chosen for the study, *viz.* the semi-arid, sub-tropical Luvuvhu catchment in the north of the country, which has a large proportion of subsistence agriculture and informal residential areas, the Upper Breede catchment in the winter rainfall regions of the south, where the primary land uses are commercial orchards and vineyards, and the sub-humid Mgeni catchment along the eastern seaboard, where plantation forestry is dominant in the upper reaches, commercial plantation sugarcane and urban areas in the middle reaches, and urban areas dominate the lower reaches. Thus, in effect a space for time study was undertaken, thereby reducing the uncertainty of the model's ability to cope with the projected future climate scenarios. Overall the *ACRU* model was able to represent the high, low and total flows, and thus it was concluded that the model could be used with confidence to simulate the streamflows of the three selected catchments and was able to represent the hydrological responses from the range of climates and diversity of land uses present within the catchments.

With the suitability of the model established for the theme of this research, the understanding of the complex interactions between hydrological responses and land use could be improved. The hydrological responses of the three selected catchments to land use change were varied. Results showed that the location of specific land uses within a catchment plays an important role in the response of the streamflow of the catchment to that land use change. Furthermore, it was shown that the contributions of different land uses to the streamflow generated from a catchment are not proportional to the relative area of those land uses, and the relative contribution of the land use to the catchment streamflow varies with the annual rainfall of the catchment.

With an improved understanding of the dynamics between land uses and hydrological responses, the impacts of climate change on hydrological responses were assessed prior to analysing the combined impacts on land use and climate change. Five plausible climate projections from three

coupled atmosphere-ocean global climate models covering three SRES emissions scenarios which were downscaled with the RCA3 regional climate model and adjusted using the distribution-based scaling (DBS) approach for bias correction were used as climate input to the *ACRU* model, with future projections applied to a baseline land cover scenario compared to historical climate applied to the same baseline land cover scenario. No consistent direction of change in the streamflow responses was evident in the Mgeni and Luvuvhu catchments. However, decreases in streamflow responses were evident for all five scenarios for the Upper Breede.

With an understanding of the separate impacts of land use and climate change on hydrological responses, an analysis of the combined impacts was undertaken to determine which changes were projected to be of greater importance in different geographical locations. Results indicated that the drier the climate becomes, the relatively more significant the role of land use becomes, as its impact becomes relatively greater. The impacts of combined land use and climate change on the catchments' streamflow responses varied across both the temporal and spatial scales, with the nature of the land use and the magnitude of the projected climate change having significant impacts on the streamflow responses.

From the research undertaken, the key results were

- that the climatic variable to which plantation forestry species are most sensitive is rainfall;
- that optimum growth areas for plantation forestry are projected to shift under changing climates, having a potentially significant impact on the landscape and thus on the hydrological responses from the landscape;
- that the daily time-step, physical-conceptual and process-based *ACRU* model is appropriate for use in land use change and climatic change impact studies as shown through a space for time study;
- that the contributions of different land uses to the streamflow generated from a catchment is not proportional to the relative area of that land use and that, as the mean annual precipitation of a subcatchment decreases, so the disparities between the relative areas a land use occupies and its contribution to catchment streamflow increases;

- that specific land use changes have a greater impact on different components of the hydrological response of a catchment;
- that land uses which currently have significant impacts on catchment water resources will place proportionally greater impacts on the catchment's water resources if the climate were to become drier; thus the drier the climate becomes, the more relatively significant the role of land use becomes;
- that when considering any hydrological impacts of land use change, climate change or combined land use and climate change, assessments need to consider the scale where the localized impacts may be evident, the progression of the impacts as the streamflow cascades through the catchment, as well as the impacts at the whole catchment scale where the accumulation of the effects through the catchment are evident; and lastly
- that each catchment is unique with its own complexities, feed forwards and feedbacks, thus each catchment will have a unique threshold as to where land use change or climate change begins to have a significant influence of the hydrological response.

Given these complex interactions between land use, climate and water, there is a growing imperative to improve the understanding of the movement of water within catchments, to be receptive and adaptive to new concepts and information, and to developing resilient and adaptive water management strategies for the future in a way that minimises the risks and maximises the benefits to potential impacts of climate change.

DECLARATION 1 - PLAGIARISM

I, *Michele Lynn Warburton*, declare that

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

(ii) This thesis has not been submitted for any degree or examination at any other university;

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

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Signed:………………………………..	Signed:………………………………..
Prof. Roland E. Schulze	Prof. Graham P. W. Jewitt

DECLARATION 2 - PUBLICATIONS

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

Publication 1 – Chapter 2 of this thesis

Warburton, M.L. and Schulze, R.E. 2008. Potential impacts of climate change on the climatically suitable growth areas of the *Pinus* and *Eucalyptus* families in southern Africa: Results from a sensitivity study. *Southern Forests: Journal of Forest Science,* 70 (1): 27 - 36.

The analysis for this publication was conducted by M.L. Warburton with technical advice from R.E. Schulze. The publication was written in its entirety by M.L. Warburton and all figures, tables and graphs were produced by the same, unless otherwise referenced in the text of the paper. Editing and advice regarding interpretation was provided by R.E. Schulze.

Publication 2 – Chapter 3 of this thesis

Warburton, M.L., Schulze, R.E. and Jewitt, G.P.W. 2010. Confirmation of *ACRU* model results for applications in land use and climate change studies. *Hydrology and Earth Systems Science,* 14: 2399 – 2414.

Data collection, hydrological modelling and analysis for this publication was conducted by M.L. Warburton with technical advice from R.E. Schulze and G.P.W. Jewitt. The publication was written in its entirety by M.L. Warburton and all figures, tables and graphs were produced by the same, unless otherwise referenced in the text of the paper. Editing and advice regarding interpretation was provided by R.E. Schulze and G.P.W. Jewitt.

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Hydrological modelling and analysis for this publication was conducted by M.L. Warburton with technical advice from R.E. Schulze and G.P.W. Jewitt. The publication was written in its entirety by M.L. Warburton and all figures, tables and graphs were produced by the same, unless otherwise referenced in the text of the paper. Editing and advice regarding interpretation was provided by R.E. Schulze and G.P.W. Jewitt.

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Hydrological modelling and analysis for this publication was conducted by M.L. Warburton with technical advice from R.E. Schulze and G.P.W. Jewitt. The publication was written in its entirety by M.L. Warburton and all figures, tables and graphs were produced by the same, unless otherwise referenced in the text of the paper. Editing and advice regarding interpretation was provided by R.E. Schulze and G.P.W.Jewitt.

PREFACE

The work described in this thesis was carried out in the School of Bioresources Engineering and Environmental Hydrology, University of KwaZulu-Natal, Pietermaritzburg under the supervision of Professor Roland Schulze and Professor Graham Jewitt.

These studies represent original work by the author and have not otherwise been submitted in any form for any degree or diploma to any tertiary institution. Where use has been made of the work of others it is duly acknowledged in the text.

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I also should like to acknowledge the following persons and extend my gratitude for their assistance with this thesis:

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1. INTRODUCTION

Relatively few areas of pristine land cover currently remain throughout the world. Through multiple forces of change such as increasing and shifting populations, increasing and changing food demands, as well as international, national and regional policies, climate variability and macro-economic activities, humans have extensively altered the natural land cover (Hobbs, 2000; Legesse *et al.*, 2003; Calder, 2004). These alterations combine to impact upon the hydrological system at different spatial and temporal scales (Falkenmark *et al.*, 1999; Legesse *et al.*, 2003; Schulze *et al.*, 2004). Similarly, changes in the climate through enhanced atmospheric carbon dioxide levels (CO_2), with resultant increasing temperatures and changing precipitation patterns may alter hydrological responses (Kundzewicz *et al.*, 2007). In combination, land use change and global climate change form a complex and interactive system, whereby both human influences and climate change manipulate land use patterns, and changes in land uses feed back to influence the climate system (Turner *et al.*, 1995), with both impacting on hydrological responses. These complex relationships are illustrated in Figure 1.1 and are further analysed and discussed in the Sections 1.1 – 1.3 which follow.

1.1 Land Use Change and Hydrological Responses

The natural landscape has, for centuries, been manipulated both physically and chemically to meet society's needs, and these changes impact on water resources (Legesse *et al.*, 2003; Claussen *et al.*, 2004; De Fries and Eshleman, 2004). For example, Roman civilization, approximately 2 100 years ago, cultivated climatically marginal land and through the damming of rivers, construction of aqueducts and drainage systems modified the environment (Claussen *et al.*, 2004). Following the initial colonisation by settlers of European descent in the late 1600s, land use change in to a previously near-pristine South African landscape occurred relatively slowly (Biggs and Scholes, 2005). However, in the past few decades significant, large-scale land use changes have occurred (Biggs and Scholes, 2005) and these are expected to continue in the future, driven by the increasing population, society's needs for food, shelter and water, as well as macro and regional economic and development policies.

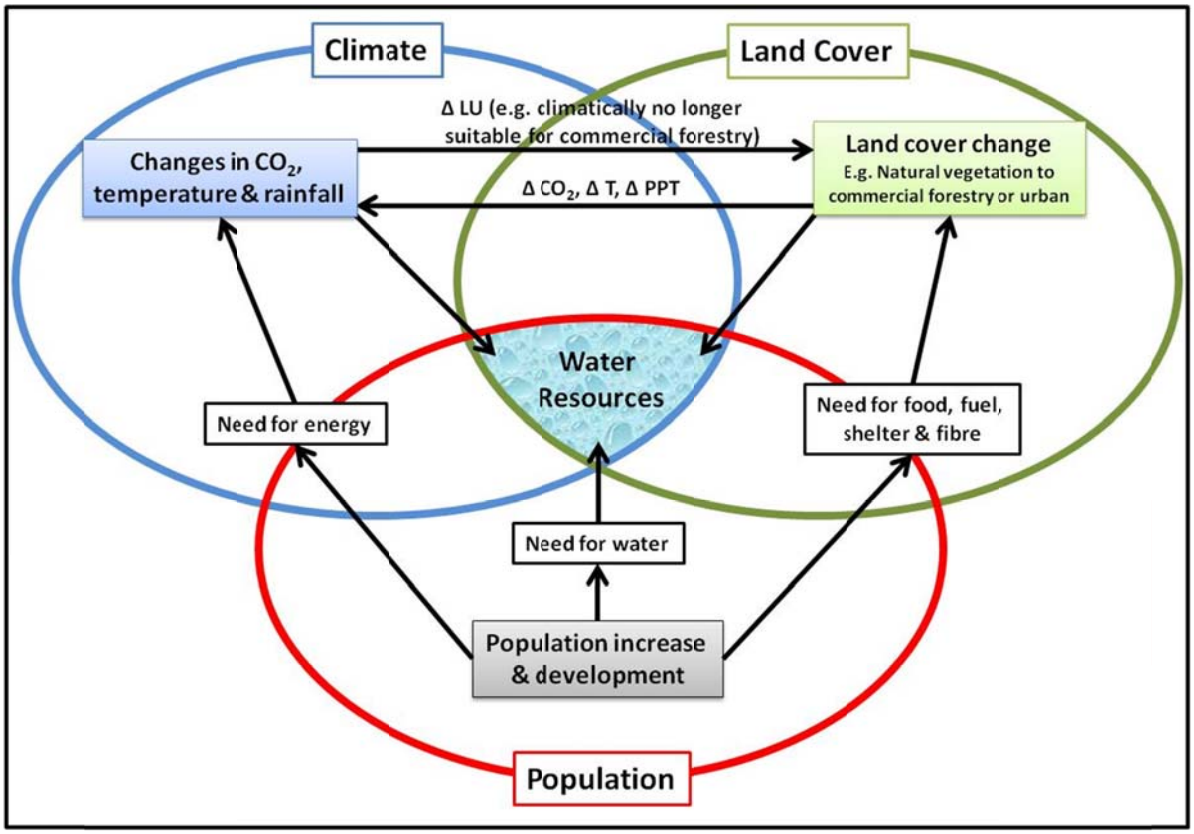

Figure 1.1: Illustration of the interactions and feedbacks of climate, land, and population on water resources (Schulze, 2008; based on ideas taken from Harding and Kabat, 2007)

For the purposes of this document, land cover refers to the biophysical condition of the earth's surface and its immediate subsurface in terms of broad categories such as grassland, cropland, natural or planted forestry and human settlements (Turner *et al*., 1993; Turner *et al*., 1995). These broad land cover categories may be altered by natural forcing such as long-term climate changes or by natural events such as volcanic activity. Most commonly, however, these categories of land cover are exploited by human actions and changed through conversion or modification, to a land use (Turner *et al*., 1995; Lambin *et al*., 2000).

Hydrological responses of a catchment are dependent, *inter alia*, upon the land use of the catchment, and are sensitive to changes in land use (Schulze, 2000; Bewket and Sterk, 2005), as any changes in land use or land cover alter the partitioning of precipitation into its various pathways (Falkenmark *et al*., 1999; Costa *et al.*, 2003) such as infiltration, total evaporation (E), surface/near-surface runoff (Q_s) or groundwater recharge (Q_g). The extent to which land use determines the hydrological responses of a catchment depends on the degree of modification of the natural land cover by human influences, the intensity of the changes, and the location of the land use within a catchment. Modifications in land use are easily measured through hydrological changes at a local scale. However, at a larger catchment scale it becomes difficult to distinguish the effects which individual land use alterations have on hydrological responses. The accumulated effects of land use on the hydrological system are most easily identified at the river basin scale, "as the water has a trace memory of its contact with the land" (Falkenmark *et al*., 1999, pg 33). Certain land use changes do not immediately alter the hydrological response of a catchment as there may be a time lag between the land use change and its effect on the water balance (Schulze, 2003a), an example being the effect of afforestation on low flow responses. Schulze (2003a) argues that often the management of the land may have a greater effect on the hydrological response of a catchment than the land use itself. In this regard, Lumsden *et al*. (2003) showed that the ploughing or the type of tillage practice of an agricultural field may have far greater impacts on the partitioning of rainfall into stormflow and baseflow than a change in crop type, *per se*, may have. Furthermore, the impacts of land use on the catchment are often threshold related, with varying stable states existing for each specific catchment, while within each catchment there are feedbacks between the processes and components of that catchment (Sivapalan, 2005).

Hydrological responses are more sensitive to certain land use changes than to others. Three of the more important land uses in regard to hydrological responses are commercial production afforestation (Jewitt *et al*., 2009), urbanization (Schulze, 2003a; Choi and Deal, 2008) and agricultural intensification through irrigation (Schulze, 2003a). The mechanisms by which these land use changes affect hydrological responses vary. For example, deep rooted and evergreen plantation forests alter streamflows by changing the partitioning of rainfall into increased evapotranspiration and reduced stormflows and baseflows (Jewitt *et al*., 2009), while irrigation not only alters the partitioning of rainfall through the irrigated crop-soil complex, but also affects streamflow through the direct abstractions of water and return flows by deep percolation (Schulze, 2003a). Additionally, the relative influences of these three important land uses on total flows as well as its components of stormflows and baseflows can be very different and the hydrological responses to the land use change may be dependent on the macro-climatic region in which it occurs (Taylor and Schulze, 2003). For example, plantation forestry has been shown to have a greater absolute (i.e. volumetric) impact on total flows in wet catchments while having a greater relative (i.e. percentage) impact in drier catchments (Taylor and Schulze, 2003).

In the South African context, plantation forestry is a particular concern to water resource managers. Evergreen, fast-growing and deep-rooted exotic plantation forestry species of high biomass result in increased evapotranspiration, decreased stormflows, reduced recharge into the groundwater store and thus altered overall streamflow patterns, in particular decreases in flows during dry periods, relative to the land use they replace (Gush *et al*., 2002; Jewitt *et al.,* 2009). It is these impacts that have resulted in plantation forestry in South Africa being classed as the only (at the present time) so-called “stream flow reduction activity” according to the South African National Water Act (1998).

To effectively manage water resources, the interdependence between land use and the hydrological system must be recognised (Comprehensive Assessment of Water Management in Agriculture, 2007) as “any land management decision becomes a water management decision” (Falkenmark *et al*., 1999, pg 58). Thus, a greater understanding of the impacts of land use changes on hydrological responses at different spatial and temporal scales is required. An accepted and appropriate method by which to assess the impacts of land use on catchment the hydrological response is the use of a hydrological model which is structured to adequately conceptualise and represent hydrological processes, and is sensitive to land use changes (Turner *et al*., 1995; Ewen and Parkin, 1996; Lambin *et al*., 2000; Bronstert *et al*., 2002; De Freis and Eshleman, 2004; Samaniego and Bárdossy, 2006; Choi and Deal, 2008). However, trust in the model’s ability meet these requirements is required (*cf.* Chapter 3). Additionally, to assess the magnitude of the impacts of various current and future land uses on water resources, a ‘baseline’, or reference, land cover is required as input to hydrological models, in order to be able to simulate changes in hydrological responses that would occur between baseline land cover and perturbed land use conditions (Schulze, 2007). However, due to a changing global environment, land use change needs to be considered in conjunction with climate change.

1.2 Climate Change and Hydrological Responses

Southern Africa currently experiences a highly variable climate (Schulze, 1997). Of the designated 19 Water Management Areas (WMAs) in South Africa, 10 were by 2000 already considered water stressed (NWRS, 2004). Changes in the climate and in climate variability will be an added stressor, placing further pressures on water availability, water accessibility and water demand (Ashton, 2002; Arnell, 2004).

The fourth IPCC report (IPCC, 2007) states that is "*extremely likely* that human activities have exerted a substantial net warming influence on climate since 1750". For the period 1906 to 2005, globally averaged surface temperatures have risen by approximately 0.74°C; however, for the latter 50 years of that period the global average surface temperature has been rising at approximately 0.13°C per decade, i.e. nearly twice the rate of the warming which occurred over the past 100 years (IPCC, 2007).

For South Africa, a warming of 0.1 to 0.3°C per decade has been observed between 1960 and 2003 (Kruger and Shongwe, 2004). It has also emerged that minimum temperatures have risen slightly faster than maximum or mean temperatures (Kruger and Shongwe, 2004). Additionally, an increasing number of warm spells and a decreasing number of cold spells have been observed over southern Africa in the latter half of the 20th century (Warburton *et al*., 2005; New *et al*., 2006). Although no overall long-term trends in annual precipitation patterns have been found, increased inter-annual variability in precipitation has been observed for southern Africa since the 1970s (Richard *et al*., 2001; Fauchereau *et al*., 2003) and changes in monthly rainfall patterns have been found for South Africa (Hewitson *et al*., 2005).

Any changes in precipitation will be amplified in the hydrological responses as the responses of the hydrological system are non-linear, especially on a heterogeneous landscape (Schulze, 2000). Moreover, between different regions the components of the hydrological system (e.g. evaporation, stormflow and baseflow) may respond differently to climate change depending on the physio-geographical and hydro-geological characteristics of the catchment (Schulze, 2000; Kundzewicz *et al*., 2007). The intensity, timing and magnitude of changes in precipitation resulting from climate change will therefore all influence runoff responses (Chiew, 2007). Changes in rainfall will not be the only influencing factor for runoff, as changes in temperature, solar radiation, atmospheric humidity and wind speed all affect potential evapotranspiration and may either offset or re-inforce the impact of changes in precipitation on runoff (Kundzewicz *et al.*, 2007). Areas where snowmelt contributes to streamflow could experience significant changes in hydrological regimes due to changes in the proportion of precipitation received as rainfall rather than snowfall (Forbes *et al.*, 2011). A further factor which could influence the response of runoff to climate change is the effect of enhanced CO_2 on transpiration. For example, Gedney *et al.* (2006) attributed an observed 3% rise in global river discharges over the 20th century to a 5% CO_2-induced reduction in plant transpiration, which was offset by global warming which, by itself, would have decreased discharge by 2%. In a South African sensitivity study, Schulze (2003b) showed that an effective doubling of CO_2 from 280 to 550 ppmv could enhance mean annual runoff by up to 5% in places.

Furthermore, as regional and local climates are key factors in determining the natural vegetation and land use (e.g. Acocks, 1988) changes in climate may alter the location and extent of natural vegetation (Turner *et al.*, 1995; Wasson, 1996) as well as the climatically optimum locations for agricultural crops and plantation forestry (Wasson, 1996; Warburton and Schulze, 2008; Schulze, 2011). These shifts in land use would, in turn, influence various hydrological responses. As changes in climate not only influence land use, but in turn also influence the climate through alterations in surface roughness, albedo, latent and sensible heat flux, any changes in the distribution of land covers have the potential to alter the regional and possibly the global balance of these fluxes (Turner *et al.*, 1995; Kueppers *et al.*, 2007).

Thus, the impacts of climate change on water resources and the subsequent shifts in water management that will be required are likely to be significant. However, climate change will be an additional stressor on a world community which is already generally struggling with poor water and land management (Falkenmark *et al.*, 1999). According to De Fries and Eshleman (2004), land use change will be a major issue for this century. Thus, consideration needs to be taken of the combined and interacting impacts of land use change and climate change on water resources in order to effectively plan for the future.

1.3 Dynamics between Land Use Change, Climate Change and Hydrological Responses

Separately, both land use change and climate change may influence hydrological responses of a catchment significantly. Combined impacts of simultaneous land use change and climate change on the water resources of a catchment will arise from complex interactions across a range of spatial and temporal scales, where anthropogenic climate and/or land use change may either moderate or exacerbate the effects of the other (Wasson, 1996). For example, De Fries and Eshleman (2004), Schulze *et al*. (2004) and Conway (2005) suggest that the consequences of land use change on water resources may in certain locations and for certain land uses be greater than those of climate change.

Relatively few studies have been undertaken in which the impacts of climate change and land use change on water resources are examined, either separately or jointly (Kundzewicz *et al*., 2007), and of the few studies undertaken most analyse the effects of afforestation or deforestation (Chang, 2003) through scenario analysis. Climate change has been shown to have a dominant effect on runoff in comparison to land use for some studies; in other studies however, the impacts of land use and climate change are similar (Kundzewicz *et al*., 2007). Whether changing climate or changing land use is the dominant influence on water resources depends on the spatial location and dominating processes at the scale of analysis.

To the knowledge of the author, no studies which consider the combined influences of changing land use and changing climate on water resources have been undertaken for the South Africa. Similarly, no studies of land use shifts under climate change at the national or regional scale have been undertaken. To improve the integration of land use and climate change into water resources planning, there is a clear need for a better understanding of the interactions between land use, climate change and hydrological response.

1.4 Research Objectives and Approach to Hydrological Modelling of Land Use and Climate Change Impacts

The overall objective of this thesis is to advance the understanding of the interactions between land use change, climate change and hydrological responses to allow for improved integration of land use planning in conjunction with climate change adaptation into water resources management. To achieve this overall objective the approach shown in Figure 1.2 was adopted.

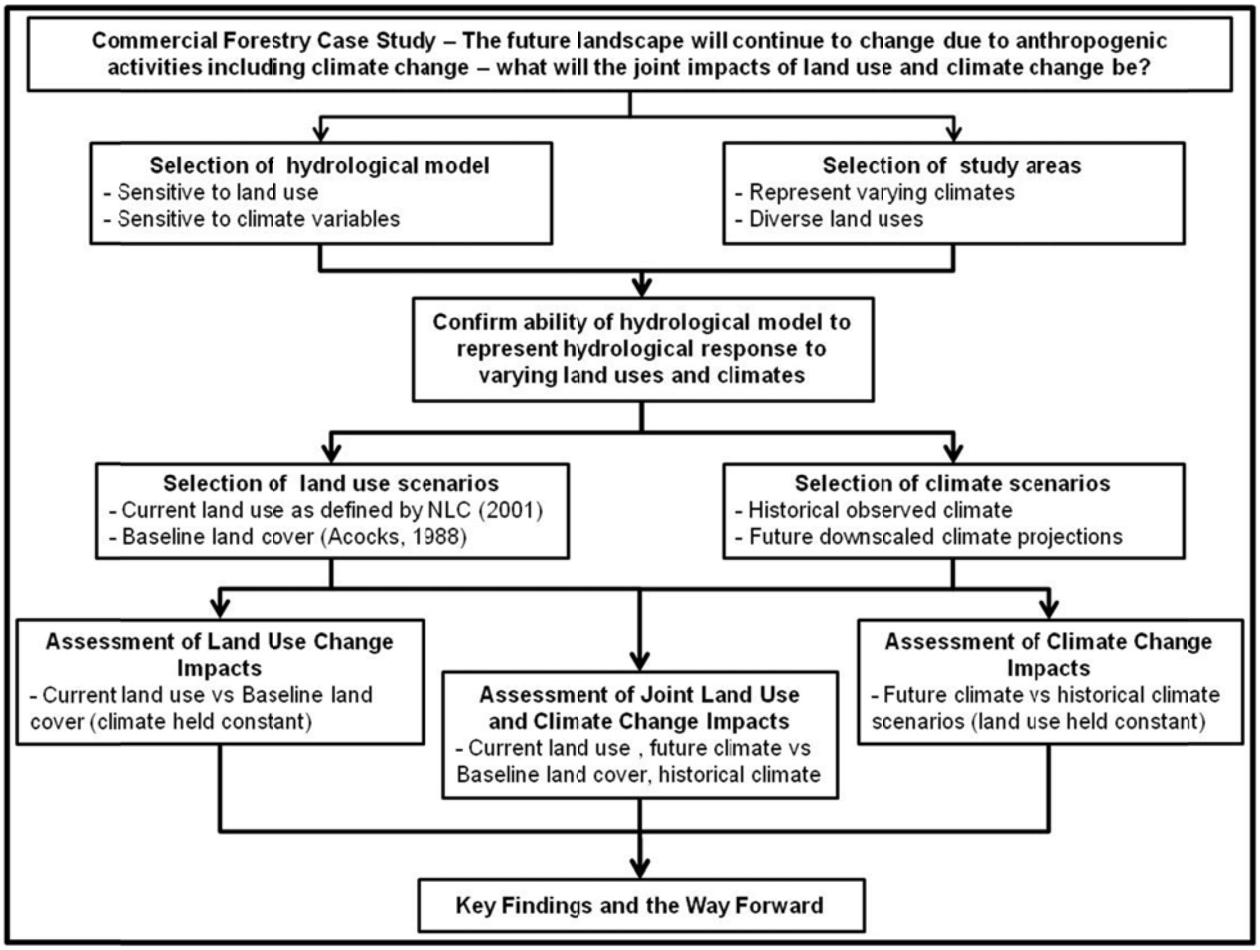

Figure 1.2: Approach taken to achieve the overall objective of this research

Given the potential shifts in land use which may occur due to climate change, an improved understanding of the complex relationships between land use change, climate change and hydrological response was needed. Thus, to determine the sensitivity of land use to changing climate, a sensitivity study assessing the potential impacts of climate change on the areas climatically suitable for key plantation forestry species was undertaken by selecting three species and one hybrid of *Pinus* trees, and of four species and one hybrid of *Eucalyptus* trees (Chapter 2).

To improve the understanding of the impacts of land use and climatic changes on the hydrological responses, a hydrological modelling approach was adopted. Thus, an appropriate hydrological model which is sensitive to land use and climate needed to be selected and study catchments which were representative of a range of land use and climates had to be selected. Following this, a crucial step was to confirm that the selected hydrological model was able to adequately simulate the streamflows under the varying land uses and climate regimes of the study catchments (Chapter 3). With the ability of the hydrological model to represent land uses confirmed, the impacts of land use change (Chapter 4) and climatic changes (Chapter 5) on the hydrological responses of the study catchments could be assessed. To achieve this, appropriate land use scenarios were selected. Additionally, downscaled future climate scenarios were obtained. With an understanding of the separate impacts of land use change and climatic change on the hydrological responses, an assessment of the combined impacts of land use and climate change on the hydrological responses of the study catchments could be undertaken (Chapter 6). Chapter 7 addresses the last step in the adopted methodology by highlighting key findings and discussing the way forward. For clarity and ease of understanding, Figure 1.2 is repeated at the beginning of each Chapter with the relevant parts of the figure that each Chapter addresses being highlighted.

Following the approach now accepted by the University of KwaZulu-Natal, this thesis is structured such that findings of the research which was undertaken are written as a series of research papers for publication in refereed journals. Following this structure implies that some overlap between the Chapters is inevitable. This overlap is, primarily, in the description of the catchments selected for the study and the description of the configuration and parameterization of the hydrological model that was selected. A literature review relevant to the specific step in the methodology being covered is provided in each research paper. As outlined by the University of KwaZulu-Natal's thesis guidelines the referencing style for each of the research papers adheres to the journal in which the paper was published in or has been submitted to.

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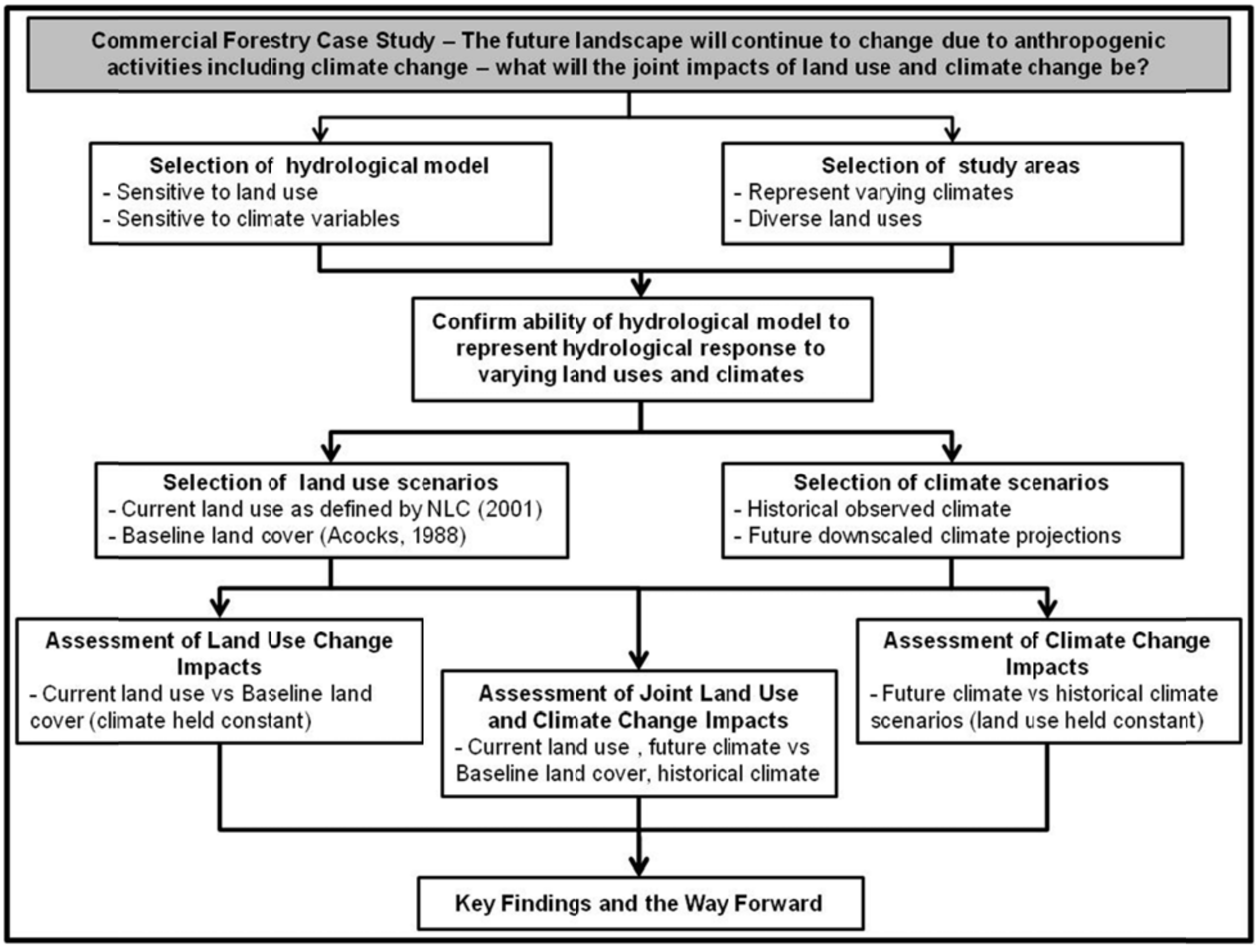
Lead in to Chapter 2

While the overall objective of this thesis is to advance the understanding of the interactions between land use change, climate change and hydrological response to allow for improved integration of land use planning in conjunction with climate change adaptation into water resources management, the specific objective in Chapter 2 is to show that climatically optimal areas for forest species are projected to change as a consequence of climate change, thus indicating that the future landscape is likely to continue to change due to anthropogenic activities including climate change (as highlighted in figure below). Providing evidence for the need to improve the understanding of the complex relationships between land use change, climate change and hydrological response.



2. POTENTIAL IMPACTS OF CLIMATE CHANGE ON THE CLIMATICALLY SUITABLE GROWTH AREAS OF *PINUS* AND *EUCALYPTUS*: RESULTS FROM A SENSITIVITY STUDY IN SOUTH AFRICA[1]

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Abstract

Global average surface temperature has increased by approximately 0.74 °C over the most recent 100-year period. At a regional level in South Africa, detectable changes in both the rainfall and temperature patterns have occurred in the past 50 years. Climate change has become a reality that can no longer be ignored. Given the relatively long timescales of plant to-harvest rotations in the commercial production forestry sector in South Africa, and the significant investment implied, climate change has the potential to have substantial impacts on forestry productivity and profitability. Under climate change conditions the climatically optimum areas for specific forest species are hypothesised to shift, with optimum areas changing in extent and location between and within provinces. This paper focuses on the *Eucalyptus* and *Pinus* genera. From the ICFR Forestry Productivity Toolbox, climate criteria for three *Pinus* species plus one hybrid, and four *Eucalyptus* species plus one hybrid, were used in combination with gridded maps of present mean annual temperature and mean annual rainfall to assess climatically optimum, moderate- and high-risk growth areas, as well as unsuitable growth areas over southern Africa. The temperature and rainfall variables were then perturbed through plausible ranges of projected future climates to determine the potential impacts of climate change on the climatically optimum, moderate and unsuitable growth areas of the *Pinus* and *Eucalyptus* families. For both families,

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[1] Warburton, M.L. and Schulze, R.E. 2008 Potential impacts of climate change on the climatically suitable growth areas of the *Pinus* and *Eucalyptus* families in southern Africa: Results from a sensitivity study. *Southern Forests: Journal of Forest Science, 70 (1): 27 - 36.*

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rising temperatures may slightly increase the optimum growth area in Mpumalanga and the Eastern Cape, whereas in KwaZulu-Natal the area may reduce. The *Pinus* species showed less sensitivity to rising temperatures than eucalypts. The two hybrids exhibited less sensitivity than other species of their genera. The hybrid *Pinus* ExC emerged as least sensitive to increasing temperature. Declining rainfall concomitant with rising temperature will have an especially negative effect on total area of optimal growth. An increase in rainfall will, however, offs*et al*l negative impacts of temperature and increase total optimum growth area for both families.

2.1 Introduction

Over geological timescales, the Earth's climate has changed markedly. Of concern at the present time is not simply a change in climate, but rather the unprecedented rate and magnitude of global warming over the past few decades. The Fourth Assessment of the Intergovernmental Panel on Climate Change (IPCC, 2007a) states that between the periods 1850–1899 and 2001–2005 the mean global air surface temperature increased by 0.74 °C, with a 95% confidence band of 0.57–0.95 °C. Additionally, of the most recent 12 years from 1999 to 2006, 11 rank in the 12 warmest years on record globally since scientific observations of temperature began some 150 years ago (IPCC, 2007a). It is now believed with 'very high confidence' that the warming that has occurred is due to human activities since the industrial revolution, which have increased the concentrations of greenhouse gases in the atmosphere (IPCC, 2007a).

On a regional scale the picture is less clear. Changes in southern Africa's temperature and rainfall regimes, many of them highly statistically significant, have occurred over the period 1950–2000 (Schulze, 2005). These changes are often not consistent in magnitude nor are they spatially uniform within the region. However, hotspots, i.e. clusters of substantial change, have been detected in southern Africa (Schulze, 2005). With regard to temperature, two clear clusters of warming over the period 1950–2000 have emerged, these being a cluster in the Western Cape and a cluster around the KwaZulu-Natal Midlands, along with a band of stations along the KwaZulu-Natal coast (Warburton *et al*., 2005). Some of the changes in precipitation patterns already identified for the 1950–2000 period are notable and of significance to natural ecosystems, as well as to the agricultural and water resource sectors, and hence of consequence to society within the region. Importantly, these precipitation changes are not always apparent in large space-time averages; they are, however, most apparent at subannual scales and in the derivative statistics of precipitation attributes (Hewitson *et al.*, 2005).

Climate change is, therefore, already evident at both a global and regional scale, and these changes are projected to continue occurring as a result of the ongoing and increasing emissions of greenhouse gases into the atmosphere. The impacts of climate change can be shown to be far-reaching and complex, affecting climatic means and climate variability, and thus natural ecosystems and human societies, both directly and indirectly. To date, limited literature exists worldwide on the potential impacts of climate change on forestry and this literature refers primarily to natural forests. Alig *et al.* (2004) hypothesised that climate change may alter forest productivity, shift resource management and alter the economic process of adaptation, thus changing forest production on global, national and regional scales. Increases in atmospheric CO_2 concentration, changes in temperature and rainfall regimes, as well as increases in climate variability expressed by extreme events increasing in both frequency and severity may impact on tree photosynthesis, growth rates, leaf phenology, seed development, root growth and nutrient cycling (van der Meer *et al*., 2002).

Under elevated atmospheric CO_2 concentrations, photosynthesis is enhanced (Curtis, 1996; Eamus and Ceulemans, 2001). For trees, Norby *et al*. (1999) estimated average enhancement of photosynthesis, also known as the ‘fertilisation effect’, to be approximately 60%. This response will, however, vary between species (Naumberg *et al*., 2001) with nitrogen fertility level, season and co-occurring pollutant concentrations (Noormets *et al*., 2001). The effect of elevated atmospheric CO_2 concentrations on long-term growth rates and productivity of trees remains unclear (Körner, 2000) as accurate predictions of growth responses of trees in forest stands are not possible from short-term greenhouse or chamber studies (Karnosky, 2003). Free-air CO_2 enrichment (FACE) experiments have shown increases of 28% in aboveground biomass at elevated CO_2 concentrations of 550 ppm (IPCC, 2001). Decreases of approximately 21% in stomatal conductance of forest trees under elevated CO_2 concentrations have been shown by Medlyn *et al.* (2001). Root growth under elevated atmospheric CO_2 concentrations is hypothesised to increase, with the increase being primarily in the production and mortality of fine roots (Matamala and Schlesinger, 2000; Pregitzer *et al*., 2000; King *et al*., 2001; Pritchard *et al*., 2001). Decreases in nitrogen levels in the foliage of trees growing under elevated atmospheric CO_2 concentrations have been shown to occur (Lindroth *et al*., 2001). This decreasing trend follows through to the litter layer (Norby *et al*., 2001). However, the quantity of litter has been shown to increase by 20–30% under elevated CO_2 concentrations (DeLucia *et al*., 1999). It is believed that the disturbance regimes of a forest will be changed under climate change, these including more frequent insect and disease outbreaks (Simberloff, 2000) and/or a greater frequency of wild fires (Flannigan *et al*., 2000).

From the literature reviewed it is evident that large uncertainty still surrounds the exact nature of the impacts of climate change on forestry. There are three primary reasons for this uncertainty. First, most impact studies have been conducted on small trees, over short durations, inside greenhouses or in field chambers that may modify the environment, but do not allow for interactions with other natural stressors (Karnosky, 2003). Secondly, the 'fertilisation effect' of elevated atmospheric CO_2 concentrations on forest growth has been shown to be offset by interactions with other factors such as soil fertility (Oren *et al*., 2001), atmospheric pollutants (Isebrands *et al*., 2001) and soil moisture (Chaves and Pereira, 1992). Finally, almost all studies on impacts of elevated CO_2 concentrations on trees have either considered a doubling of CO_2 concentrations from pre-industrial revolution levels of 280 ppm or a single large addition of CO_2, and thus little is known about the dose response or the interactive effects of varying doses of greenhouse gases (Karnosky, 2003).

Research into forestry responses needs to move from short-term, small-scale chamber or greenhouse experiments to long-term, large-scale experiments that allow for natural interactions to occur. For southern Africa, defined for the purposes of this study as South Africa plus Lesotho and Swaziland, no detailed assessment has been made of the potential impacts of climate change on the commercial production forestry sector. Given the plant-to-harvest timeframes of one to several decades associated with commercial production forestry, it is crucial to assess the potential impacts of climate change on the commercial production forestry sector and to consider possible adaptation measures.

It is hypothesised that under conditions of climate change the areas climatically optimal for the growth of commercial production forestry may shift (IPCC, 2007b). Thus the objective of this initial sensitivity study is to assess the potential impacts of climate change on the areas climatically suitable for the growth of three species and one hybrid of *Pinus*, and of four species and one hybrid of *Eucalyptus*. To achieve this objective, the areas that are climatically optimal and moderately optimal for the production of pines and eucalypts in present (i.e. baseline) climatic conditions were first compared against the areas currently planted with those species. Thereafter the approach taken on determining plausible future climate scenarios is outlined. Thirdly, the results of a sensitivity analysis on potential impacts of climate change on the above-mentioned species and hybrids grown commercially in southern African are presented and interpreted. The paper is concluded with observations of the general implications of climate change for the commercial production forestry sector and recommendations for future research.

2.2 Materials and Methods

2.2.1 Baseline studies: A point of departure

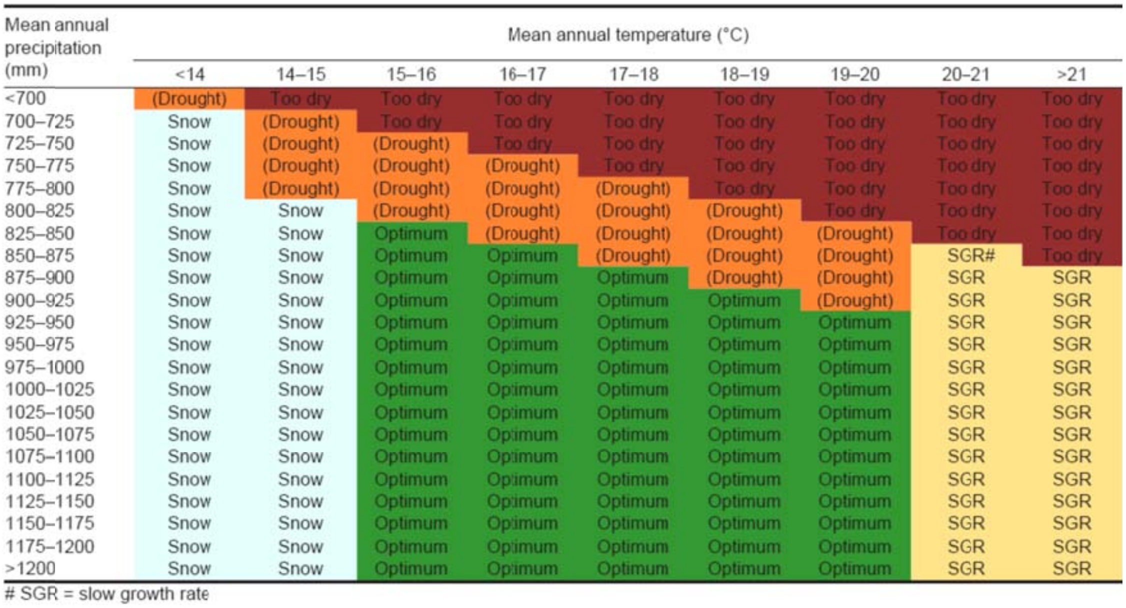
In order to assess potential shifts in climatically suitable areas in the future, it is necessary to determine the present climatically optimal areas and the areas currently planted for commercial production forestry as a baseline against which future areas can be compared. Thus, as a point of departure, maps showing climatically optimal, moderate and high-risk, as well as unsuitable, areas under present climatic conditions were obtained from the South African Atlas of Climatology and Agrohydrology (Schulze, 2006) for the selected species.

These forestry maps were derived by combining the suitable macroclimatic conditions as defined in the Institute for Commercial Forestry Research (ICFR) Forestry Productivity Toolbox (Kunz, 2004) with raster (i.e. grid) surfaces of mean annual precipitation (MAP; Lynch, 2004) and mean annual temperature (MAT; Schulze and Maharaj, 2004). From these, the optimum, suboptimum and high-risk growth areas for each forestry species were mapped at a spatial scale of 1′ latitude by 1′ longitude (i.e. for a raster grid of c. 1.7 km × 1.7 km) within South Africa. Areas that fell below the minimum threshold MAP of 700 mm and outside the MAT bounds of 13 °C and 22 °C were considered climatically unsuitable areas (Kunz, 2004; Schulze, 2006). An example of the matrix of suitable macroclimatic conditions (Table 2.1) and a map derived by this method, whereby the optimum, suboptimum and high-risk growth areas were delineated, is provided in Figure 2.1 using *Pinus taeda* as the species considered.

The mapped forestry suitability areas obtained from Schulze (2006) are based on macroclimatic conditions of MAP and MAT alone, as this was the only level of growth criteria generally available for the range of production forest species and hybrids commercially grown in southern Africa. No cognizance is taken in this study of soil properties, slope, geology, microclimatic conditions, other competing land uses or sociopolitical considerations.

Before performing a sensitivity analysis of the impacts of climate change on optimal growth areas of commercial forestry, a comparison of the mapped baseline areas against areas currently planted for commercial forestry was undertaken to determine the current climatic risk to forestry areas. Areas currently planted with pine and eucalypt were determined from the National Land Cover (NLC) satellite images (NLC, 2000). Although the NLC (2000) distinguishes between pines and eucalypts, no distinction is made between the numerous species and hybrids of each genus. Thus, to compare climatically optimal growth areas to those currently planted, climatically optimal, moderate and high-risk areas for the selected species and hybrids in each genus were grouped together. If a 1′ latitude × 1′ longitude pixel was climatically optimal for any one species within a genus, it was therefore considered generally optimal for that genus. Areas were considered in a hierarchy of optimum growth, then moderate risk and lastly high risk, i.e. if a pixel's climate was high risk for one species, yet optimal for another, it was considered optimal in the lumped coverage. Table 2.2 summarises the distributions of the currently planted areas (according to NLC, 2000) as percentages of the various climatic suitability classes. Of the current area planted with *Eucalyptus* c. 83% is found in climatically optimum areas, with c. 7% grown in climates posing high risks and 6% of the current area under *Eucalyptus* being grown in climatically unsuitable areas. Of the areas currently planted with *Pinus* species and/or hybrids, c.75% are in climatically optimum areas and 17% are in climatically moderate-risk areas (Table 2.2).

Table 2.1: Matrix of climatically suitable areas for the growth of *Pinus taeda* (after Kunz, 2004)



Mean annual precipitation (mm)	Mean annual temperature (°C)								
	<14	14–15	15–16	16–17	17–18	18–19	19–20	20–21	>21
<700	(Drought)	Too dry	Too dry	Too dry	Too dry	Too dry	Too dry	Too dry	Too dry
700–725	Snow	(Drought)	Too dry	Too dry	Too dry	Too dry	Too dry	Too dry	Too dry
725–750	Snow	(Drought)	(Drought)	Too dry	Too dry	Too dry	Too dry	Too dry	Too dry
750–775	Snow	(Drought)	(Drought)	(Drought)	Too dry	Too dry	Too dry	Too dry	Too dry
775–800	Snow	(Drought)	(Drought)	(Drought)	(Drought)	Too dry	Too dry	Too dry	Too dry
800–825	Snow	Snow	(Drought)	(Drought)	(Drought)	(Drought)	Too dry	Too dry	Too dry
825–850	Snow	Snow	Optimum	(Drought)	(Drought)	(Drought)	(Drought)	Too dry	Too dry
850–875	Snow	Snow	Optimum	Optimum	(Drought)	(Drought)	(Drought)	SGR#	Too dry
875–900	Snow	Snow	Optimum	Optimum	Optimum	(Drought)	(Drought)	SGR	SGR
900–925	Snow	Snow	Optimum	Optimum	Optimum	Optimum	(Drought)	SGR	SGR
925–950	Snow	Snow	Optimum	Optimum	Optimum	Optimum	Optimum	SGR	SGR
950–975	Snow	Snow	Optimum	Optimum	Optimum	Optimum	Optimum	SGR	SGR
975–1000	Snow	Snow	Optimum	Optimum	Optimum	Optimum	Optimum	SGR	SGR
1000–1025	Snow	Snow	Optimum	Optimum	Optimum	Optimum	Optimum	SGR	SGR
1025–1050	Snow	Snow	Optimum	Optimum	Optimum	Optimum	Optimum	SGR	SGR
1050–1075	Snow	Snow	Optimum	Optimum	Optimum	Optimum	Optimum	SGR	SGR
1075–1100	Snow	Snow	Optimum	Optimum	Optimum	Optimum	Optimum	SGR	SGR
1100–1125	Snow	Snow	Optimum	Optimum	Optimum	Optimum	Optimum	SGR	SGR
1125–1150	Snow	Snow	Optimum	Optimum	Optimum	Optimum	Optimum	SGR	SGR
1150–1175	Snow	Snow	Optimum	Optimum	Optimum	Optimum	Optimum	SGR	SGR
1175–1200	Snow	Snow	Optimum	Optimum	Optimum	Optimum	Optimum	SGR	SGR
>1200	Snow	Snow	Optimum	Optimum	Optimum	Optimum	Optimum	SGR	SGR

SGR = slow growth rate

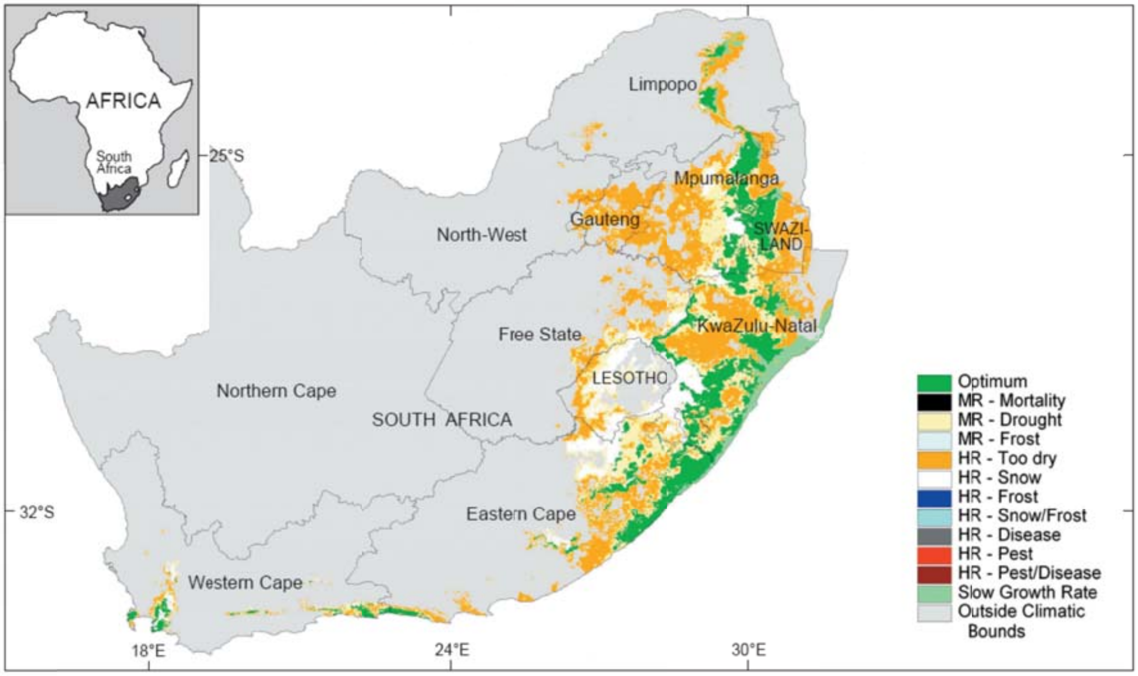


Figure 2.1: Delineation of climatically suitable areas for the growth of *Pinus taeda* (after Schulze, 2006). Suitable macroclimatic conditions were as defined in the Institute for Commercial Forestry Research (ICFR) Forestry Productivity Toolbox (Kunz, 2004). Climate data were taken from Lynch (2004) and Schulze and Maharaj (2004). HR, high risk; MR, moderate risk

Under present climatic conditions, the climatic risk to the planted areas of commercial production forestry is relatively low with approximately 17% of the current *Eucalyptus* and 25% of the current *Pinus* area being at risk (Table 2.2). If the areas currently planted in commercial forestry were to remain constant in the future, a larger proportion of the area may become a moderate- or high-risk climate under conditions of climate change.

Table 2.2: Areas currently (from NLC, 2000) planted with either *Eucalyptus* or *Pinus* species and/or hybrids as percentages of climatic suitability classes

Climatic Suitability Class	**% of Current Areas**	
	***Eucalyptus* species/hybrids**	***Pinus* species/hybrids**
Optimum	82.5	75.5
Moderate Risk	4.4	17.0
High Risk	6.8	1.5
Climatically Unsuitable	6.3	6.0
Total	100.0	100.0

2.2.2 Approaches to defining future climate scenarios used in this study

Across southern Africa the outputs of future climates from the various General Climate Models (GCMs) are now corresponding in the direction of temperature change, in that they are all predicting increases, but they are not yet corresponding perfectly with respect to the magnitude of temperature change at different locations (IPCC, 2007a). With regard to rainfall, the GCMs correspond broadly in the direction of change, viz. a drying in the central and western areas of southern Africa and a possible wetting in the eastern areas, but not yet with the same correspondence on the magnitude of predicted rainfall change in future climates (IPCC, 2007a).

Given the range of GCMs available and the differing GCM results, the approach chosen for this initial study on potential impacts of climate change on commercial forestry in southern Africa was that of a sensitivity analysis. With a sensitivity analysis the selected climatic variables, in this case temperature and rainfall, are perturbed through plausible (i.e. realistic) ranges of future climates. The plausible scenarios used in this study were based on previously reported GCM outputs for future climates in southern Africa from the Third Intergovernmental Panel on Climate Change assessment (IPCC, 2001) and from Engelbrecht (2005)[2], namely:

- temperature increases by either 0.5, 1.0, 1.5 or 2.0 °C from present day climate;
- a temperature increase by 2.0 °C in combination with a rainfall decrease by either 5% or by 10% from present day climate;
- a temperature increase by 2.0 °C in combination with a rainfall increase by either 5% or by 10% from present day climate.

A range of plausible temperature increases is considered, as the magnitudes of future changes remain uncertain across southern Africa (e.g. Engelbrecht, 2005). Both increases and decreases in rainfall are considered as the uncertainty surrounding the nature of precipitation change predicted by various GCMs in the future is still relatively high compared with that of an increase in temperature. The results of the sensitivity analysis for the potential impacts of climate change on the climatically optimum areas of eucalypts and pines are presented in the following section.

2.3 Results

2.3.1 Climate change sensitivity analyses for *Eucalypt*

Four species of *Eucalyptus*, viz. *E. dunnii, E. grandis, E. nitens* and *E. smithii*, and one hybrid, viz. *E. grandis* × *E. urophylla* (*E. G×U*), were selected for the analysis. The species and hybrid chosen cover a range of optimum growing temperatures with, for example, *E. nitens* thriving in colder climates while *E. dunnii* flourishes in warmer areas.

The percentage changes in climatically optimum areas with increasing temperature are shown in Figure 2.2. The results show that the most sensitive *Eucalyptus* species to increasing temperatures is *E. nitens*, with a 2 °C increase in temperature reducing the climatically optimal area over South Africa by 80% from the present area, and a 50% reduction in climatically optimal areas already occurring at a modest 1 °C increase (Figure 2.2). This sensitivity of *E.*

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[2] At the time that this research was undertaken these were the only available scenarios. In comparison to the scenarios currently available, e.g. IPCC 2007, these scenarios are conservative.

nitens to temperature is attributable to the narrow ideal MAT range of 14–15 °C required by this species. By increasing temperature, few areas in southern Africa would remain that meet both the MAT and MAP criteria of this species, with most areas becoming high-risk drought and disease prone areas for this species.

As the increase in temperature from current levels becomes greater, E. smithii becomes relatively more sensitive to changes (Figure 2.2). For a 1 °C increase in temperature the area over South Africa that is climatically optimal for *E. smithii* is reduced by 25%; however, with a 2 °C increase in temperature the reduction is approximately 60%. *Eucalyptus dunnii* and *E. grandis* are both relatively robust to changes in temperature. For a 2 °C increase in temperature the areas climatically optimal for the growth of *E. dunnii* and *E. grandis* reduce by approximately 25% and 30%, respectively (Figure 2.2). The *Eucalyptus* hybrid included in the analysis, *E. G×U*, is particularly robust to changes in temperature. Even for a 2 °C increase in temperature the percentage climatically optimum area over South Africa does not alter from the present for *E. G×U* (Figure 2.2).

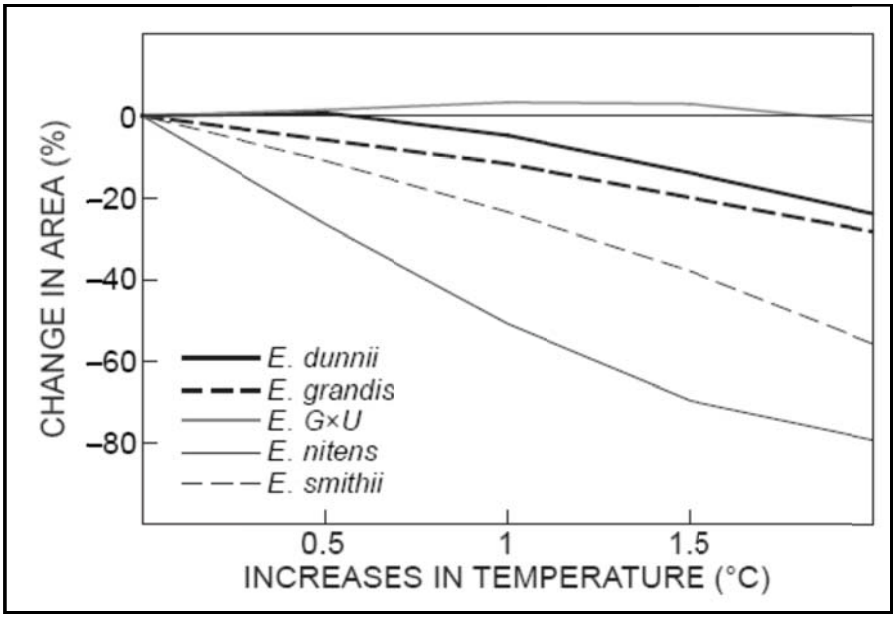

Figure 2.2: Percentage changes in the climatically optimum areas for *Eucalyptus* species and hybrids with increase in temperature

Shown in Figure 2.3 are percentage changes in the climatically optimal areas of the selected four *Eucalyptus* species and one hybrid for a 2 °C increase in temperature combined with a range of modest projected increases and decreases of rainfall. Of the selected *Eucalyptus* species and hybrids, *E. dunnii* is the most robust to changes in rainfall. For this species, a 10% increase in rainfall increases potential optimum growth area by 50% over South Africa; however, a 10% decrease in rainfall in association with a 2 °C increase in temperature results in a 50% reduction in optimum growth area. *Eucalyptus grandis, E. smithii* and *E. G×U* respond similarly to, and are highly sensitive to, changing rainfall combined with a 2 °C increase in temperature. A 10% decrease in rainfall is projected to reduce the areas climatically optimal for the growth of *E. grandis, E. smithii* and *E. G×U* by approximately 60%. However, a 10% increase in rainfall from current levels would result in an increase of 85% in the climatically optimum growth areas over South Africa. *Eucalyptus nitens* is also highly sensitive to changes in rainfall, with a similar 60% reduction in climatically optimum areas projected to occur with a 10% reduction in rainfall. On the other hand, a 100% increase in climatically optimal areas is projected for a 10% increase in rainfall in combination with a 2 °C increase in temperature. This is the highest percentage increase in climatically optimum area of all of the *Eucalyptus* species and hybrid when increases in rainfall are assumed to occur in a warmer climate. However, as the changes in rainfall assume a 2 °C increase in temperature, the area suitable for its growth is small already and thus the changes are negligible.

With climate change, it is hypothesised that shifts in other land uses and their optimum growing conditions will occur simultaneously with those of tree plantation species, thereby changing land use patterns also because of competition from other crops and for a limited resource use. As mentioned above, nearly 83% of the area currently planted with *Eucalyptus* species or hybrids falls within the mapped climatically optimum areas. In the future, these areas currently planted with *Eucalyptus* species or hybrids may no longer fall within climatically optimum areas. Table 2.3 summarises the possible impacts of climate change on areas currently planted with *Eucalyptus* species or hybrids.

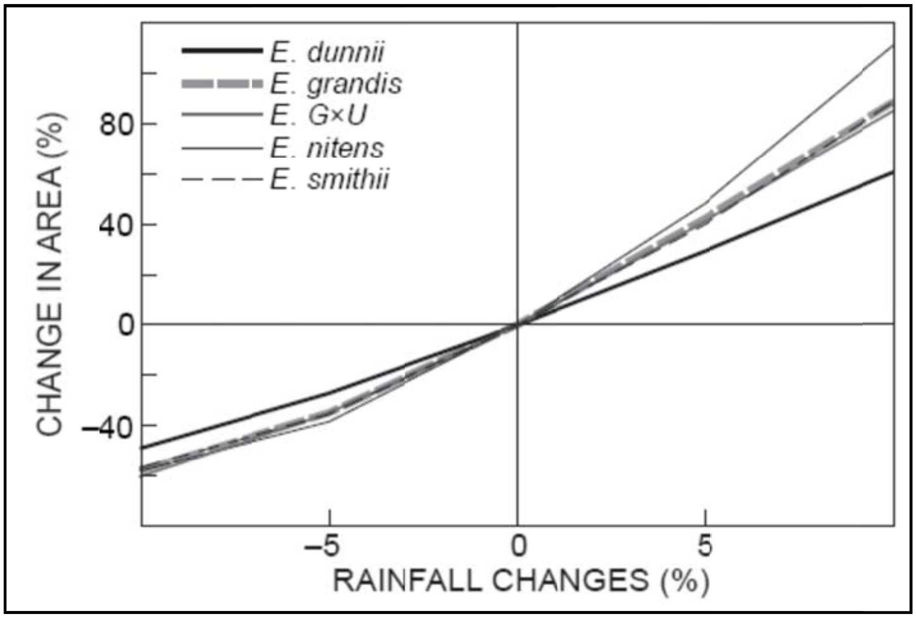

Figure 2.3: Percentage changes in the climatically optimum areas for four *Eucalyptus* species and one hybrid for a 2 °C increase in temperature in combination with a range of negative and positive changes in rainfall

Table 2.3: Distribution in South Africa of areas currently planted with *Eucalyptus* species and hybrids in different climatic suitability classes, and the distributions for a range of climate scenarios relative to the present climate assuming that plantations would remain at their current locations

Climate Suitability Class	**% of Areas Currently Planted to *Eucalyptus* Species**				
	Present	**T + 1°C**	**T + 2°C**	**T + 2°C, PPT - 10%**	**T + 2°C, PPT + 10%**
Optimum	82.4	75.9	66.7	36.7	79.6
Moderate Risk	4.4	2.7	5.3	4.8	4.0
High Risk	6.9	10.6	15.4	42.9	4.4
Climatically Unsuitable	6.3	10.8	12.6	15.6	12.0
Total	100.0	100.0	100.0	100.0	100.0

T = Temperature; PPT = Precipitation

With a 2 °C increase in temperature, approximately 67% of the areas currently planted with *Eucalyptus* species or hybrids would fall within climatically optimal areas. Therefore, although the specific species and hybrids of *Eucalyptus* may need to be changed from where they are grown at present, the majority of the areas where eucalypts are currently grown would remain suitable with a 2 °C rise in temperature. However, *Eucalyptus* species and hybrids are highly sensitive to changes in rainfall, in particular to decreases in rainfall. If the temperature were to increase by 2 °C and the rainfall were at the same time to decrease by 10%, only approximately 40% of the areas currently under *Eucalyptus* would fall within either a climatically optimum or moderate risk area, and nearly 43% of the currently grown *Eucalyptus* would be in high-risk areas (Table 2.3).

A further analysis performed was a determination of the absolute changes (i.e. in km2) in the climatically optimum areas per province in South Africa and for neighbouring Swaziland for the climate scenarios considered in the study. The locations of the provinces within South Africa are shown in Figure 2.1. The results revealed potential opportunities for shifts in commercial forestry areas between provinces (Figure 2.4). The climatically optimal area for *Eucalyptus* species and hybrids in KwaZulu-Natal decreases markedly with increasing temperatures, for example, as well as with increased temperatures combined with decreased rainfall. The climatically optimal areas within the Eastern Cape are slightly less sensitive to increases in temperature in comparison to areas within KwaZulu-Natal; however, they are relatively more susceptible to decreasing rainfall (Figure 2.4). If an increase in rainfall, combined with an increase in temperature, were to occur, a greater area in the Eastern Cape would become climatically optimal for the growth of eucalypts in comparison with the area suitable under the present climate. In Mpumalanga, the area that is climatically optimal for the growth of eucalypts increases slightly with a 1 °C increase in temperature and remains relatively stable for a 2 °C increase in temperature when compared with the area under present climatic conditions. An increase in temperature of 2 °C together with an increase in rainfall of 10% would, however, result in a far larger proportion of Mpumalanga meeting the climatic requirements for optimum growth of eucalypts (Figure 2.4). Potentially, if temperature and rainfall were to increase in the future, new areas for the growth of *Eucalyptus* species and hybrids could therefore be sourced in the Eastern Cape and Mpumalanga. However, if rainfall were to decrease by approximately 10% in a warmer climate, the consequences on commercially grown eucalypts could be significant.

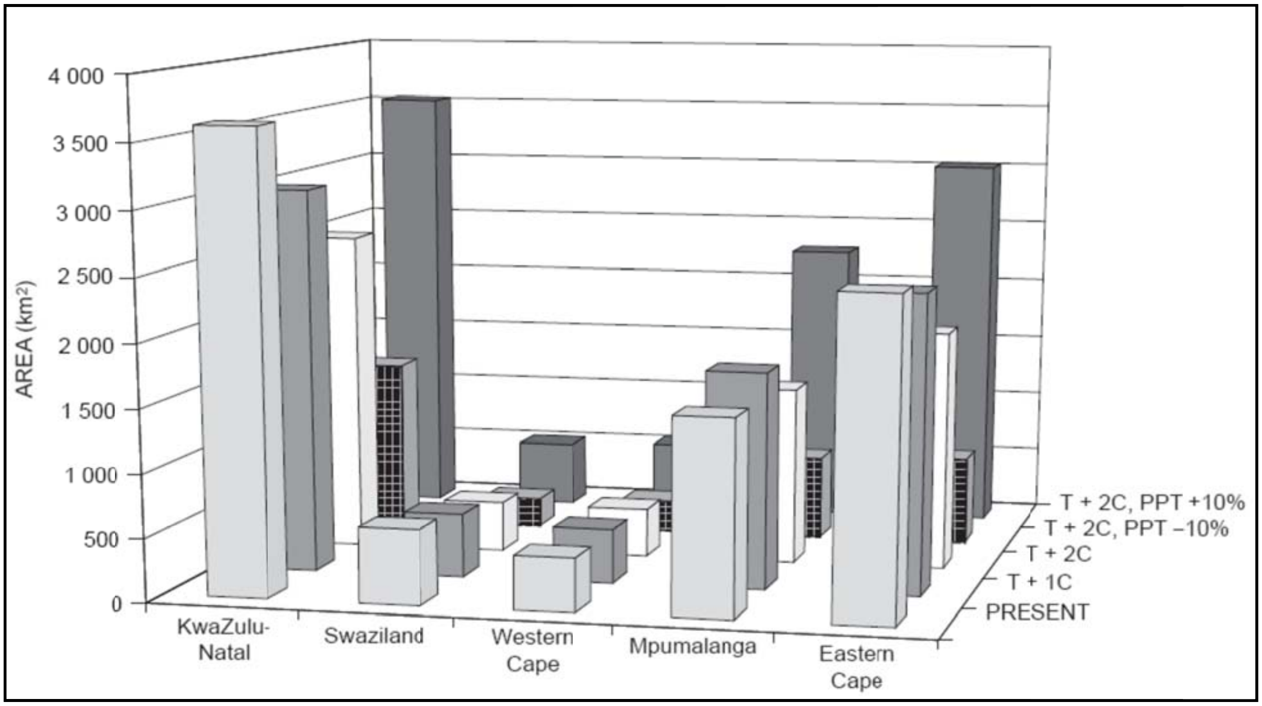

Figure 2.4: Percentage changes in the climatically optimum areas for *Eucalyptus* species and hybrids with increase in temperature

2.3.2 Climate change sensitivity analyses for *Pinus*

For the analysis of the potential impacts of climate change on the *Pinus* genus, three species of *Pinus*, namely *P. elliottii*, *P. taeda* and *P. patula*, and one hybrid, *P. elliottii* × *P. caribaea* (*P. E×C*), were chosen. The reasoning for the selection of these particular species and hybrids was that they are the main varieties grown and that their optimum climates cover a range of temperatures. In Figure 2.5 percentage changes in the climatically optimum areas of the three *Pinus* species and the hybrid are illustrated for increases in temperature from the present climate.

Pinus patula is highly sensitive to temperature changes, with the climatically optimum areas of *P. patula* simulated to decrease by 50% with an increase of 2 °C, while a 1 °C increase in temperature would result in a 25% reduction in area (Figure 2.5). *Pinus patula* thus displays an apparently linear decreasing response to increasing temperatures, certainly up to a 2 °C threshold. From Figure 2.5 it can be seen that the responses of *P. taeda* mimic those of *P. elliottii* to increases in temperature. Both species are relatively robust to changes in temperature. A 1 °C increase in temperature would reduce their climatically optimum areas by 15% while a 2 °C increase in temperature would result in a 30% decrease in climatically optimum areas. As *P. E×C* is a warm-climate hybrid, it is shown to be highly robust to changes in temperature, with slight increases in the climatically optimum areas even projected to occur when temperature is increased (Figure 2.5).

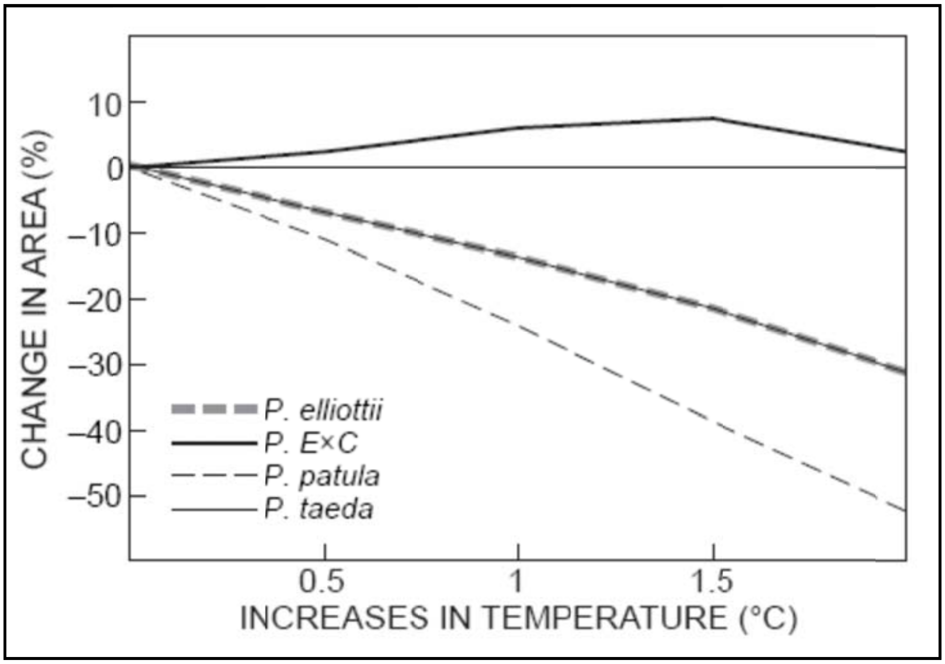

Figure 2.5: Percentage changes in the climatically optimum areas for three *Pinus* species and one hybrid for a 2 °C increase in temperature in combination with a range of negative and positive changes in rainfall

From Figure 2.6, which illustrates percentage changes in the optimum areas for varying changes in rainfall in combination with a 2 °C temperature increase, it can be seen that the projected responses of *P. patula, P. elliottii* and *P. taeda* to changes in rainfall are similar. These three species are highly sensitive to changes in rainfall. However, climatically optimum areas would be significantly reduced if MAP were to decrease simultaneously with a temperature increase. The percentage decrease in climatically optimum areas for *P. patula, P. elliottii* and *P. taeda* for a 10% reduction in MAP in combination with a 2 °C increase in temperature is 60%. A 10% increase in rainfall is simulated to result in an increase of c. 90% of the climatically optimum areas of the three *Pinus* species. *Pinus E×C* proves to be relatively more robust to decreases in rainfall than the three previously mentioned *Pinus* species. For a 10% decrease in rainfall in combination with a 2 °C temperature increase, a 50% reduction in the climatically optimum area is simulated (Figure 2.6). A 10% increase in rainfall in a warmer climate is simulated to result in an increase of 60% in climatically optimum areas for *P. E×C.* This increase is less than that experienced by the other *Pinus* species for the same climate scenario. From the analyses conducted above, the *Pinus* hybrid appears to be the most robust to changes in temperature and rainfall, with *P. patula* being the most sensitive of the three *Pinus* species.

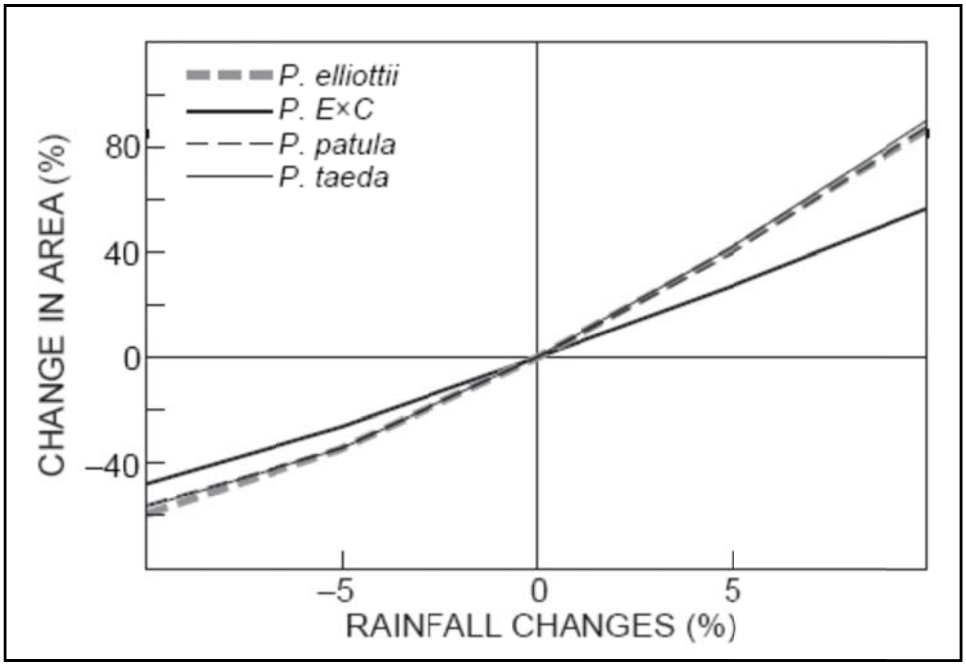

Figure 2.6: Areas (km^2) that are climatically optimal for *Pinus* species and hybrids for various plausible scenarios of climate

With the high overall sensitivity of the *Pinus* species to changes in climate, an analysis was performed to determine how the current areas under *Pinus* species (according to the NLC, 2000) would be distributed between the climatically optimum, moderate- and high-risk areas for the five plausible climate scenarios used in this analysis. Although not all *Pinus* species grown commercially in southern Africa were included in the study, the combined climatically optimum areas of the three *Pinus* species and the hybrid that were included do cover a wide range of temperature and rainfall regimes.

Percentage distributions of the areas currently planted with *Pinus* species between climatically optimum, moderate- and high-risk areas are given in Table 2.4. Currently, 76% of the *Pinus* species and hybrids cultivated in southern Africa fall within the combined climatically optimum area as defined from the ICFR Toolbox (Kunz, 2004). If the temperature were to increase, the *Pinus* species or hybrid planted in a particular location may need to be changed, but of the total area that is currently planted, over three-quarters would remain climatically optimum for at least one of the *Pinus* species and hybrids (Table 2.4). With a 2 °C increase in temperature in combination with a 10% decrease in rainfall, 54% of the current area under *Pinus* would remain in climatically optimum areas, with 30% falling within moderate climate risk areas. Thus, even with an increase in temperature plus a decrease in rainfall *Pinus* will, in general, remain a robust genus to plant.

Table 2.4: Distribution of areas currently planted to three *Pinus* species and one hybrid in different climate suitability classes, for a range of climate scenarios

Climate Suitability Class	**% of Areas Currently Planted to *Pinus* Species/Hybrid**				
	Present	**T + 1°C**	**T + 2°C**	**T + 2°C, PPT -10%**	**T + 2°C, PPT +10%**
Optimum	75.5	78.4	77.1	53.9	85.3
Moderate Risk	17.0	13.9	15.3	30.7	10.2
High Risk	1.5	0.3	0.0	0.0	0.0
Climatically Unsuitable	6.0	7.4	7.6	15.4	4.5
Total	100.0	100.0	100.0	100.0	100.0

T = Temperature; PPT = Precipitation

The final analysis undertaken for *Pinus* species and hybrids was a determination of absolute changes (i.e. in km^2) in climatically optimum, moderate- and high-risk areas per province for the various plausible climate scenarios (Figure 2.7). Climatically suitable areas for *Pinus* species and hybrids in KwaZulu-Natal are simulated to decrease markedly with increasing temperatures, as well as with increased temperatures in combination with decreased rainfall (Figure 2.7). Within the Eastern Cape, climatically optimal areas are robust to increasing temperatures, with even slight increases in optimal growth areas occurring in that province for a 1 °C increase and no discernible changes occurring for a 2 °C increase in temperature. With increases in temperature and rainfall, a larger proportion of the Eastern Cape than at present is projected to become climatically suitable for the growth of *Pinus* species and hybrids. In Mpumalanga, the climatically optimal area for the production of *Pinus* species and hybrids increases slightly for both a 1 °C and a 2 °C increase in temperature, in comparison to the area suitable under present climatic conditions. An increase in temperature of 2 °C in association with an increase in rainfall of 10% would result in a considerably larger proportion of Mpumalanga meeting the climatic requirements for optimum growth of *Pinus* species and hybrids than at present. Thus, with anticipated changes in climate in the future, and if an increase in rainfall were to occur, there would potentially be more areas in Mpumalanga and the Eastern Cape that could become climatically suitable for the growth of *Pinus* species and hybrids.

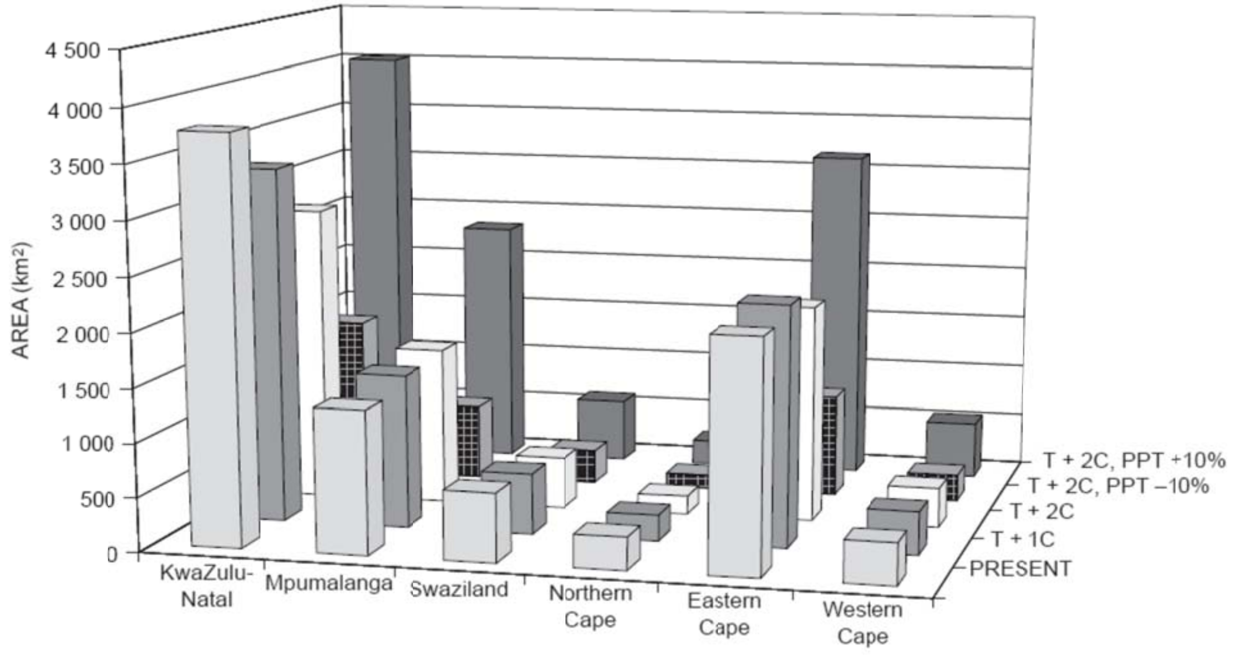

Figure 2.7: Areas (km^2) that are climatically optimal for *Pinus* species and hybrids for various plausible scenarios of climate

2.4 Discussion and Conclusions

Prior to drawing conclusions, a reminder needs to be sounded that the scenarios considered in this paper are plausible climate change scenarios, with only changes in climatically suitable areas considered, and not any other physiographic or economic factors. It furthermore needs reiteration that the climatic requirements for optimum and suboptimum growth are expressed by very broad indices only, viz. MAP and MAT. No cognisance has therefore been taken of possible effects of slope, soils, geology, market forces, competing agricultural land uses, 'committed' other land-cover categories that cannot be afforested (e.g. dams, wetlands, roads, national parks and urban areas), management or local-scale climates.

In assessing the sensitivity of commercial forestry to climate change the following emerged:

- the one climatic driver to which the forest species are most sensitive is rainfall;
- the selected hybrids of both eucalypts and pines are relatively more robust than the commonly grown species to potential increases in temperature (in particular) and, to a certain degree, to decreases in rainfall;
- areas currently under plantations where the climate is only moderately suitable will, under conditions of increasing temperature and decreasing rainfall, most likely become high-risk areas;
- on a provincial basis the climatically optimal areas for plantation forestry within KwaZulu-Natal are likely to decrease with climate change, while it appears that areas within the Eastern Cape and Mpumalanga may offer opportunities for expansion with increasing temperature;
- of the two genera included in this study, *Pinus* is relatively more robust to climate change than *Eucalyptus*.

In conclusion, the forestry models used in this study were simple and took no cognisance of, for example, numbers of frost days, soil properties, slope or competing land uses. As one way forward, a recommendation of the study is for a follow-up to the initial study to examine the impacts of climate change on the commercial forestry sector at a more complex and in-depth level.

2.5 Acknowledgements

Our thanks go to Forestry SA who financially supported this research, to the Water Research Commission for funding the *Development of a Database of Gridded Daily Temperatures for Southern Africa* (Schulze and Maharaj, 2004), the *Development of a Database of Annual, Monthly and Daily Rainfall for South Africa* (Lynch, 2004) as well as the *South African Atlas of Climatology and Agrohydrology* (Schulze, 2006), and to Manju Maharaj for her assistance with computer programming.

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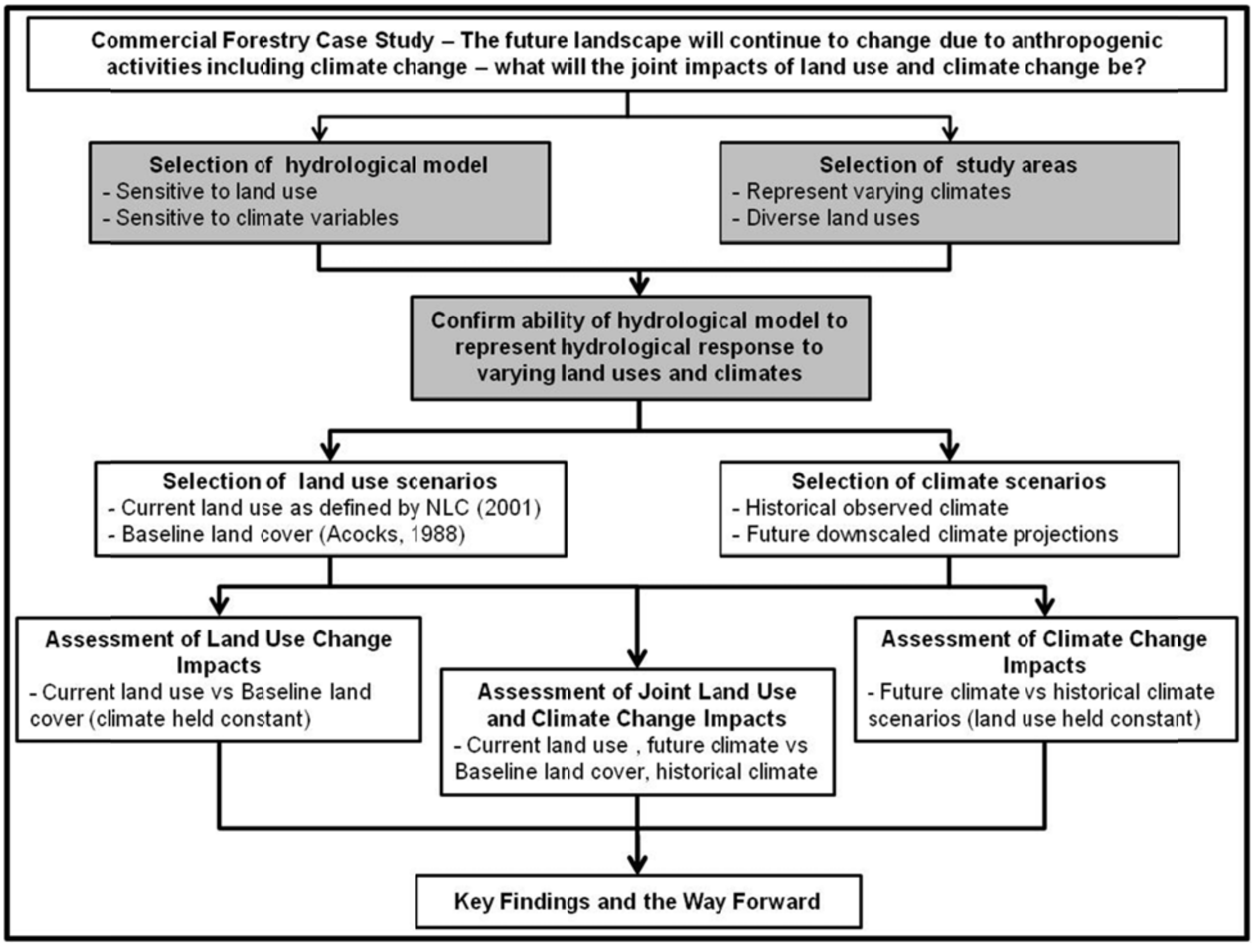
Lead in to Chapter 3

Given the potential shifts in land use which may occur due to climate change, an improved understanding of the complex relationship between land use change, climate change and hydrological response is required. To improve this understanding an appropriate hydrological model needs to be selected, study areas selected, and the ability of the hydrological model to represent hydrological responses to varying climates and land uses needs to be confirmed. Thus the objective of Chapter 3 was select a hydrological model and study areas as well as to demonstrate that the model would be suitable to use in extrapolation situations such as climate and land use change impact studies where data beyond the readily obtainable would not be available (as highlighted in the figure below).



3. CONFIRMATION OF ACRU MODEL RESULTS FOR USE IN LAND USE AND CLIMATE CHANGE IMPACT STUDIES[3]

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Abstract

The hydrological responses of a catchment are sensitive to, and strongly coupled to, land use and climate, and changes thereof. The hydrological responses to the impacts of changing land use and climate will be the result of complex interactions, where the change in one may moderate or exacerbate the effects of the other. Further difficulties in assessing these interactions are that dominant drivers of the hydrological system may vary at different spatial and temporal scales.
To assess these interactions, a process-based hydrological model, sensitive to land use and climate, and changes thereof, needs to be used. For this purpose the daily time step *ACRU* model was selected. However, to be able to use a hydrological model such as *ACRU* with confidence its representation of reality must be confirmed by comparing simulated output against observations across a range of climatic conditions. Comparison of simulated against observed streamflow was undertaken in three climatically diverse South African catchments, ranging from the semi-arid, sub-tropical Luvuvhu catchment, to the winter rainfall Upper Breede catchment and the sub-humid Mgeni catchment. Not only do the climates of the catchments differ, but their primary land uses also vary. In the upper areas of the Mgeni catchment commercial plantation forestry is dominant, while in the middle reaches there are significant areas of commercial plantation sugarcane and urban areas, while the lower reaches are dominated by urban areas. The Luvuvhu catchment has a large proportion of subsistence agriculture and informal residential areas. In the

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[3] Warburton, M.L., Schulze, R.E. and Jewitt, G.P.W. 2010. Confirmation of *ACRU* model results for applications in land use and climate change studies. *Hydrology and Earth Systems Science, 14: 2399–2414.*

* Referencing adheres to format of *Hydrology and Earth Systems Science.*

Upper Breede catchment in the Western Cape, commercial orchards and vineyards are the primary land uses.

Overall the *ACRU* model was able to represent the high, low and total flows, with satisfactory Nash-Sutcliffe efficiency indexes obtained for the selected catchments. The study concluded that the *ACRU* model can be used with confidence to simulate the streamflows of the three selected catchments and was able to represent the hydrological responses from the range of climates and diversity of land uses present within the catchments.

3.1 Introduction

South Africa's land cover and land use have been extensively altered by human activities, such as increasing and shifting populations, increasing and changing food demands, national and regional policies, and other macro-economic activities. These alterations combine to impact upon the hydrological system at different temporal and spatial scales (Falkenmark *et al*., 1999; Legesse *et al*., 2003; Schulze *et al*., 2004; Calder, 2005).

The hydrological response of a catchment is dependent, *inter alia*, upon the land use of the catchment, and is sensitive to changes thereof (Schulze, 2000; Bewket and Sterk, 2005), as any changes in land use or land cover alters the partitioning of precipitation between the various pathways of the hydrological cycle (Falkenmark *et al*., 1999; Costa *et al*., 2003), such as infiltration, total evaporation (E), surface runoff (Q_s) or groundwater recharge (Q_g). Thus, to effectively manage water resources, the interdependence between land use and the hydrological system must be recognized (Comprehensive Assessment of Water Management in Agriculture, 2007) as ultimately, "any land management decision becomes a water management decision" (Falkenmark *et al*., 1999, pg 58).

When considering climate change, an additional level of complexity is introduced into the relationship between land use and the hydrological system. Together, land use change and climate change form a complex and interactive system, whereby both human influences and climate changes can perturb land use patterns, and changes in land use, in turn, can feed back to influence the climate system (Turner *et al*., 1995), with both impacting on hydrological responses. Thus, effective water resources management now needs to take account of, and understand, the interactions between land use change, climate change and hydrological responses. It has been suggested that the use of a hydrological model which is conceptualized to accurately represent hydrological processes, sensitive to land use and adequately accounts for climate change drivers provides a means of assessing these complex interactions (Turner *et al*., 1995; Ewen and Parkin, 1996; Bronstert *et al*., 2002; Herron *et al*., 2002; Chang, 2003; Pfister *et al*., 2004; Hu *et al*., 2005; Samaniego and Bárdossy, 2006; Lin *et al*., 2007; Choi and Deal, 2008; Guo *et al*., 2008; Quilbé *et al*., 2008).

The *ACRU* agrohydrological model (Schulze, 1995; Smithers and Schulze, 2004) is one such model that has been suggested to be suitable for such studies as it is a daily time step process-based model with a multi-soil-layer water budget which is sensitive to land management and changes thereof, as well as to climate input and changes thereof (Schulze, 2005). However, to be able to use the *ACRU* model, and indeed any similar model, with confidence in assessing the interactions between land use change, climate change and hydrological responses, its suitability must be confirmed by assessing its ability to predict output when compared against observed data sets. The objective of this study, therefore, is to confirm the ability of the model through comparisons of its output with observed data sets in three climatically diverse catchments, *viz.* the Mgeni, Luvuvhu and Upper Breede catchments in South Africa, and thus assess the degree of confidence with which the *ACRU* model can be used to assess the hydrological responses to land use change and climate change. Using daily data, the study provides an assessment of the model's ability to simulate total and mean flows as well as the variability of these.

For the purposes of this study, the authors have ascribed to the terminology suggested by Oreskes *et al*. (1994) and Refgaard and Henriksen (2004) that a model's results may be confirmed rather than verified or validated. By confirming the results it produces, the adequacy of the model to produce results of an acceptable level is demonstrated (Refgaard and Henriksen, 2004). Confirmation of model results does not necessarily imply that the model is a truthful representation of reality; rather it supports the probability that the model is a correct representation of reality. The greater the range and number of confirmation studies the greater the probability that the model is not flawed (Oreskes *et al*., 1994).

The *ACRU* model has been conceptualized and structured as an operational model to be applied on catchments where streamflow data are not available, and using national databases of climate, soils, and land use as sources of information, in order to give acceptable results across a range of hydroclimatic regimes. Calibration is a refinement which can be undertaken on catchments with high quality streamflow data, however, few such catchments exist in the developing world or where decisions need to be taken. For these reasons no calibration was undertaken as this would distort the applicability of the model. The purpose of this study was to demonstrate the ability of the *ACRU* model to simulate under a wide range of climatic regimes and land uses using a robust method of configuration where national level datasets as well as experience-based default parameters were used, with the objective to demonstrate that the model would be suitable to use in extrapolation situations such as climate and land use change impact studies where data beyond the readily obtainable would not be available.

3.2 The *ACRU* Agrohydrological Model

The *ACRU* model is a physical-conceptual, daily time-step, multi-level, multi-purpose model which has been developed over approximately 30 years in the School of Bioresources Engineering and Environmental Hydrology at the University of KwaZulu-Natal in South Africa. The *ACRU* model has been applied extensively in South Africa for both land use impact studies (e.g. Schulze and George, 1987; Tarboton and Schulze, 1990; Kienzle and Schulze, 1995; Kienzle *et al*., 1997; Schulze *et al*., 1997; Schulze *et al*., 1997; Jewitt and Schulze, 1999; Schulze, 2000; Jewitt *et al*., 2004) and climate change impact studies (Perks and Schulze, 1999; Perks, 2001; Schulze *et al*., 2005). Additionally, the ACRU model has been applied in Zimbabwe (Butterworth *et al*., 1999; Makoni, 2001), Eritrea (Ghile, 2004), the USA (Martinez *et al*., 2008), Germany (Herpertz, 1994; Herpertz, 2001) and more recently in New Zealand (Kienzle and Schmidt, 2008; Schmidt *et al*., 2009) and Canada (Forbes *et al*., 2010). Figure 3.1 illustrates the conceptualization of the water budget in the *ACRU* model. The conceptualizations of the land use processes within the *ACRU* model are crucial to this study and are described in some detail below.

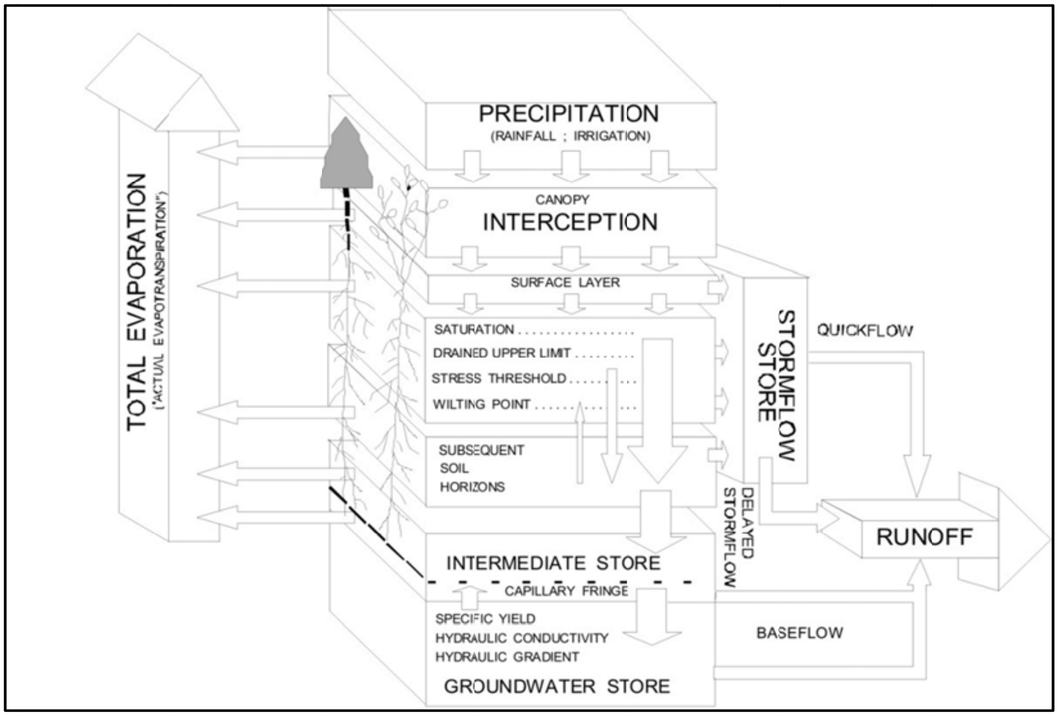

Figure 3.1: Representation of the water budget in the *ACRU* model (Schulze, 1995; Schulze and Smithers, 2004)

The *ACRU* model considers three processes when modelling the land use component, *viz.* canopy interception loss, evaporation from vegetated surfaces and soil water extraction by plant roots (Schulze, 1995). According to Schulze (1995), *ACRU* has several options for estimating the canopy interception component. In this study canopy interception losses per rainday were set using the interception loss parameter (*ACRU* variable name VEGINT) for each month of the year for each land use considered. These values (Table 1), taken from Schulze (2004), range from 3.5 mm per rainday for mature trees grown for commercial timber production to zero for freshly ploughed land, and they account for intra-annual differences in interception loss with growth stage and dormancy. Intercepted water stored in forest canopies has been found to evaporate at faster rates than the available energy from reference potential evaporation because of the higher advection and lower aerodynamic resistances of a wet forest canopy (Calder, 1992). Thus, within *ACRU* there is an option to enhance evaporation from forest canopies (Schulze, 1995). This option was used for the commercial forestry and alien vegetation land use units of the selected catchments.

Within the *ACRU* model, total evaporation from a vegetated surface consists of both evaporation of water from the soil surface (E_s) and transpiration (E_t), which is governed by rooting patterns. These can be modelled either jointly or separately. In this study E_s and E_t were modelled separately. The water use coefficient (K_{cm}) is used to estimate vegetation water use within the *ACRU* model. The water use coefficient is expressed as the ratio of maximum evaporation from the plant at a given stage of plant growth to a reference potential evaporation (Schulze, 1995). During periods of sustained plant stress, when the soil water content of both the upper and lower soil horizons falls below 40% of plant available water, transpiration losses are reduced in proportion to the level of plant stress. When plant available water increases to above 40% in either soil horizon the plant stress is relieved and the evaporative losses recover to the optimum value at a rate dependent on the ambient temperature (Schulze, 1995). Monthly values of K_{cm} for each land use are required as input to the model, and from the monthly values, daily values are computed internally in the model using Fourier Analysis (Schulze, 1995). The monthly input parameter values for the land uses considered in this study are given in Table 3.1.

Extraction of soil water from both soil horizons takes place simultaneously in the *ACRU* model, and is distributed according to the proportion of active roots within each horizon (Schulze, 1995). Thus, an input requirement is monthly values of the fraction of active roots in the topsoil horizon (ROOTA), from which the fraction in the lower soil horizon is computed internally. These monthly values account for genetic and environmental factors affecting transpiration, for example spring regrowth, winter dormancy, senescence, planting date and growth rates (Schulze, 1995). With regard to soil water extraction under stressed conditions, if the subsoil horizon is not below the stress threshold, but the topsoil horizon is, then the subsoil's contribution to total evaporation will be enhanced beyond that computed for its root mass fraction; similarly, the reverse is true (Schulze, 1995). Evaporation of soil water under wet conditions is suppressed by a surface cover, for example a litter layer (Lumsden *et al*., 2003). The assumption is made that

Table 3.1: Monthly values of water use coefficients, canopy interception per rainday, root mass distribution in the topsoil, coefficient of initial abstractions and index of suppression of soil water evaporation by a litter/mulch layer, for the land uses occurring in the Mgeni, Luvuvhu and Upper Breede catchment (Schulze, 2004)

Land Use		**Monthly values**											
	Variable	**Jan**	**Feb**	**Mar**	**Apr**	**May**	**Jun**	**Jul**	**Aug**	**Sep**	**Oct**	**Nov**	**Dec**
Commercial Forestry													
- *Acacia*	CAY	0.90	0.90	0.90	0.88	0.85	0.86	0.89	0.90	0.92	0.92	0.90	0.90
	VEGINT	2.00	2.00	2.00	2.00	1.90	1.85	1.85	1.85	1.90	1.95	2.00	2.00
	ROOTA	0.83	0.83	0.83	0.83	0.83	0.83	0.83	0.83	0.83	0.83	0.83	0.83
	COAIM	0.25	0.25	0.25	0.30	0.30	0.30	0.30	0.30	0.30	0.30	0.25	0.25
- *Eucalyptus*	CAY	0.95	0.95	0.95	0.95	0.95	0.95	0.95	0.95	0.95	0.95	0.95	0.95
	VEGINT	2.50	2.50	2.50	2.50	2.50	2.50	2.50	2.50	2.50	2.50	2.50	2.50
	ROOTA	0.65	0.65	0.65	0.65	0.65	0.65	0.65	0.65	0.65	0.65	0.65	0.65
	COAIM	0.35	0.35	0.35	0.35	0.35	0.35	0.35	0.35	0.35	0.35	0.35	0.35
- *Pinus*	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
	VEGINT	3.50	3.50	3.50	3.50	3.50	3.50	3.50	3.50	3.50	3.50	3.50	3.50
	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
	COAIM	0.35	0.35	0.35	0.35	0.35	0.35	0.35	0.35	0.35	0.35	0.35	0.35
Agriculture													
- Dryland temporary commercial agriculture	CAY	0.99	0.84	0.30	0.30	0.30	0.30	0.30	0.30	0.30	0.30	0.48	0.78
	VEGINT	1.40	1.40	1.40	1.20	1.00	1.00	1.00	0.80	0.00	0.00	0.80	1.40
	ROOTA	0.78	0.91	1.00	1.00	1.00	1.00	1.00	1.00	1.00	0.92	0.79	0.74
	COAIM	0.20	0.20	0.25	0.30	0.30	0.30	0.30	0.30	0.30	0.35	0.30	0.25
- Irrigated temporary commercial agriculture	CAY	0.7	0.7	0.7	0.7	0.7	0.7	0.7	0.7	0.7	0.7	0.7	0.7
	VEGINT	1.40	1.40	1.40	1.20	1.00	1.00	1.00	0.80	0.00	0.00	0.80	1.40
	ROOTA	0.78	0.91	1.00	1.00	1.00	1.00	1.00	1.00	1.00	0.92	0.79	0.74
	COAIM	0.20	0.20	0.25	0.30	0.30	0.30	0.30	0.30	0.30	0.35	0.30	0.25
- Irrigated temporary commercial agriculture	CAY	0.80	0.80	0.8	0.70	0.60	0.50	0.50	0.50	0.60	0.70	0.80	0.80
	VEGINT	1.40	1.40	1.40	1.40	1.20	1.00	1.00	1.20	1.30	1.40	1.40	1.40
	ROOTA	0.80	0.80	0.80	0.90	1.00	1.00	1.00	1.00	0.90	0.90	0.80	0.80
	COAIM	0.30	0.30	0.30	0.30	0.30	0.30	0.30	0.30	0.30	0.30	0.30	0.30
- Commercial Sugarcane	CAY (inland)	0.83	0.83	0.83	0.83	0.83	0.83	0.83	0.83	0.83	0.83	0.83	0.83
	CAY (coastal)	0.86	0.86	0.86	0.86	0.86	0.86	0.86	0.86	0.86	0.86	0.86	0.86
	VEGINT (inland)	1.70	1.70	1.70	1.70	1.70	1.70	1.70	1.70	1.70	1.70	1.70	1.70
	VEGINT (coastal)	1.90	1.90	1.90	1.90	1.90	1.90	1.90	1.90	1.90	1.90	1.90	1.90
	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
	COAIM	0.35	0.35	0.35	0.35	0.35	0.35	0.35	0.35	0.35	0.35	0.35	0.35
- Pasture grass	CAY	0.55	0.55	0.55	0.55	0.35	0.20	0.20	0.20	0.35	0.45	0.55	0.55
	VEGINT	0.70	0.70	0.70	0.70	0.70	0.70	0.70	0.70	0.70	0.70	0.70	0.70
	ROOTA	0.95	0.95	0.95	0.95	0.95	1.00	1.00	1.00	0.95	0.95	0.95	0.95
	COAIM	0.15	0.15	0.15	0.25	0.30	0.30	0.30	0.30	0.30	0.30	0.20	0.15

- Subsistence agriculture	CAY	0.80	0.70	0.30	0.30	0.30	0.30	0.30	0.30	0.30	0.30	0.35	0.60
	VEGINT	1.00	1.00	0.60	0.50	0.50	0.50	0.50	0.50	0.50	0.00	0.50	0.80
	ROOTA	0.74	0.78	0.91	1.00	1.00	1.00	1.00	1.00	1.00	1.00	0.92	0.79
	COAIM	0.20	0.20	0.25	0.30	0.30	0.30	0.20	0.20	0.20	0.35	0.30	0.25
Urbanised Areas													
- Built-up (CBD, industrial areas)	CAY (inland)	0.70	0.70	0.70	0.60	0.30	0.30	0.30	0.30	0.45	0.65	0.70	0.70
	CAY (coastal)	0.80	0.80	0.80	0.70	0.50	0.50	0.50	0.50	0.55	0.75	0.80	0.80
	VEGINT (inland)	1.40	1.40	1.40	1.40	1.20	1.20	1.20	1.20	1.30	1.40	1.40	1.40
	VEGINT (coastal)	1.6	1.6	1.6	1.6	1.4	1.4	1.4	1.4	1.5	1.6	1.6	1.6
	ROOTA	0.80	0.80	0.80	0.90	1.00	1.00	1.00	1.00	0.95	0.80	0.80	0.80
	COAIM	0.15	0.15	0.20	0.25	0.30	0.30	0.30	0.30	0.30	0.25	0.20	0.15
- Formal Residential (Suburbs, flats, includes educational areas)	CAY (inland)	0.80	0.80	0.70	0.60	0.40	0.40	0.40	0.40	0.60	0.70	0.80	0.80
	CAY (coastal)	0.80	0.80	0.80	0.70	0.60	0.50	0.50	0.50	0.50	0.60	0.80	0.80
	VEGINT (inland)	1.40	1.40	1.30	1.20	1.10	1.00	1.00	1.00	1.00	1.30	1.40	1.40
	VEGINT (coastal)	1.5	1.5	1.5	1.5	1.3	1.2	1.2	1.2	1.2	1.3	1.5	1.5
	ROOTA	0.85	0.85	0.85	0.90	0.95	0.95	0.95	0.95	0.90	0.85	0.85	0.85
	COAIM	0.20	0.20	0.20	0.30	0.30	0.30	0.30	0.30	0.30	0.30	0.25	0.20
- Informal Residential													
- Urban & Rural Informal (differentiation in impervious areas)	CAY	0.65	0.65	0.65	0.55	0.30	0.20	0.20	0.20	0.30	0.50	0.55	0.65
	VEGINT	1.50	1.50	1.50	1.50	1.50	1.50	1.50	1.50	1.50	1.50	1.50	1.50
	ROOTA	0.90	0.90	0.90	0.94	0.98	1.00	1.00	1.00	1.00	0.95	0.90	0.90
	COAIM	0.15	0.15	0.15	0.20	0.30	0.30	0.30	0.30	0.30	0.30	0.20	0.15
Degraded Natural Vegetation	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
	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
	COAIM	0.1	0.1	0.1	0.15	0.15	0.2	0.2	0.2	0.2	0.15	0.1	0.1
Alien Vegetation	CAY	0.90	0.90	0.90	0.90	0.90	0.90	0.90	0.90	0.90	0.90	0.90	0.90
	VEGINT	1.70	1.70	1.70	1.70	1.70	1.70	1.70	1.70	1.70	1.70	1.70	1.70
	ROOTA	0.70	0.70	0.70	0.70	0.70	0.70	0.70	0.70	0.70	0.70	0.70	0.70
	COAIM	0.35	0.35	0.35	0.35	0.35	0.35	0.35	0.35	0.35	0.35	0.35	0.35

the relationship between surface cover and soil water evaporation is linear, and that complete surface cover still allows 20% of maximum evaporation from the soil water to occur. Actual soil water evaporation is calculated by accounting for the wetness of the soil after the suppressed maximum soil water evaporation for a day has been calculated (Lumsden *et al*., 2003).

The *ACRU* agrohydrological model is not a model in which parameters are calibrated to produce a good fit; rather, values of input variables are estimated from the physically characteristics of the catchment (Schulze and Smithers, 2004) using available information. Thus, a confirmation study to assess the performance of the model in simulating observed data was required, rather than calibration of the model parameters. The catchments which were selected for the confirmation study cover a range of climatic regimes found in South Africa and contain varied land uses. A description of the study areas follows, after which the results of the confirmation study are presented.

3.3 The Research Catchments

The Mgeni, Luvuvhu and Upper Breede catchments were selected for this study as they vary in both climate and land use. These South African catchments range in climates from the dry sub-tropical regions of the country in the north-east, to the winter rainfall areas of the Western Cape and the wetter eastern seaboard areas of the country with summer rainfall (Figure 3.2). The Mgeni catchment is a complex catchment, both in terms of its land use and water engineered system. Although the Mgeni catchment only occupies 0.33% of South Africa’s land surface, it is economically and strategically important as it provides water resources to ~ 15% of South Africa’s population and supplies the Durban-Pietermaritzburg economic corridor in KwaZulu-Natal, which produces *ca*. 20% of the country’s gross domestic product (Schulze *et al*., 2004). The Luvuvhu catchment has large areas of subsistence agriculture, but is also important in terms of conservation as it includes parts of the Kruger National Park. The Upper Breede catchment forms part of the headwaters of the Breede River Catchment in the Western Cape, where commercial orchards and vineyards, mostly under irrigation, are the primary activity. A more detailed description of the catchments follows.

3.3.1 Mgeni catchment

The Mgeni catchment (4 349 km^2) is located in the KwaZulu-Natal province of South Africa (Figure 2). The altitude in the catchment ranges from 1913 m a.s.l in the western escarpment of the catchment to sea level at the catchment's outlet into the Indian Ocean (Figure 3.3).

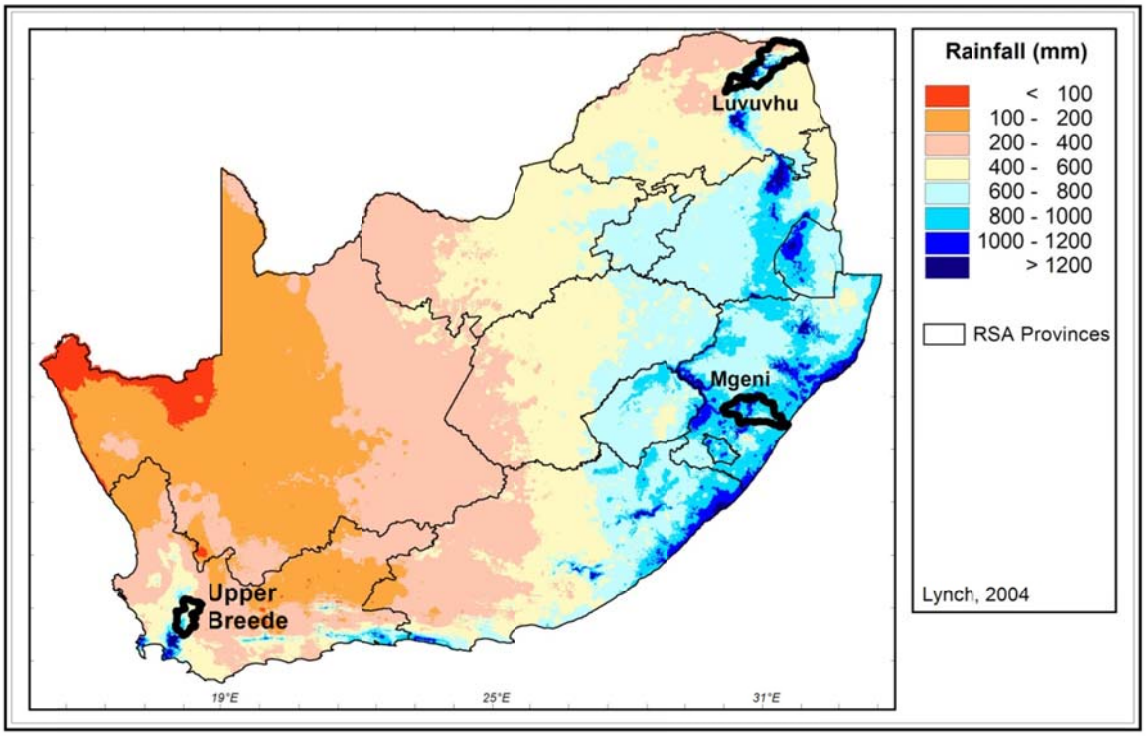

Figure 3.2: Location of the study catchments superimposed on a map of the mean annual precipitation (MAP) of South Africa (MAP after Lynch, 2004)

The Mgeni catchment falls within the summer rainfall region of South Africa and generally experiences a warm subtropical climate. The mean annual precipitation (MAP) of the catchment varies from 1 550 mm p.a in the main water source areas in the west of the catchment to 700 mm p.a in the drier middle reaches of the catchment. The rainfall throughout the catchment, is however, highly variable, both inter- and intra-annually. The mean annual potential evaporation ranges from 1 567 mm p.a to 1 737 mm p.a. The mean annual temperature ranges from 12°C in the escarpment areas to 20°C towards the coastal areas of the catchment.

The water engineered system within the Mgeni currently consists of four main dams (Figure 3.3), namely Midmar (full supply capacity of 237 million m^3) supplying Pietermaritzburg and parts of Durban, as well as Albert Falls (289 million m^3), Nagle (23 million m^3) and Inanda (242 million m^3) dams supplying Durban (Summerton, 2008). Additionally, there are 300 farm dams within the middle to upper reaches of the catchment supplying water for 18 500 ha of irrigation. According to Summerton (2008) the Mgeni is a stressed system which is closed to new streamflow reduction activities for the foreseeable future.

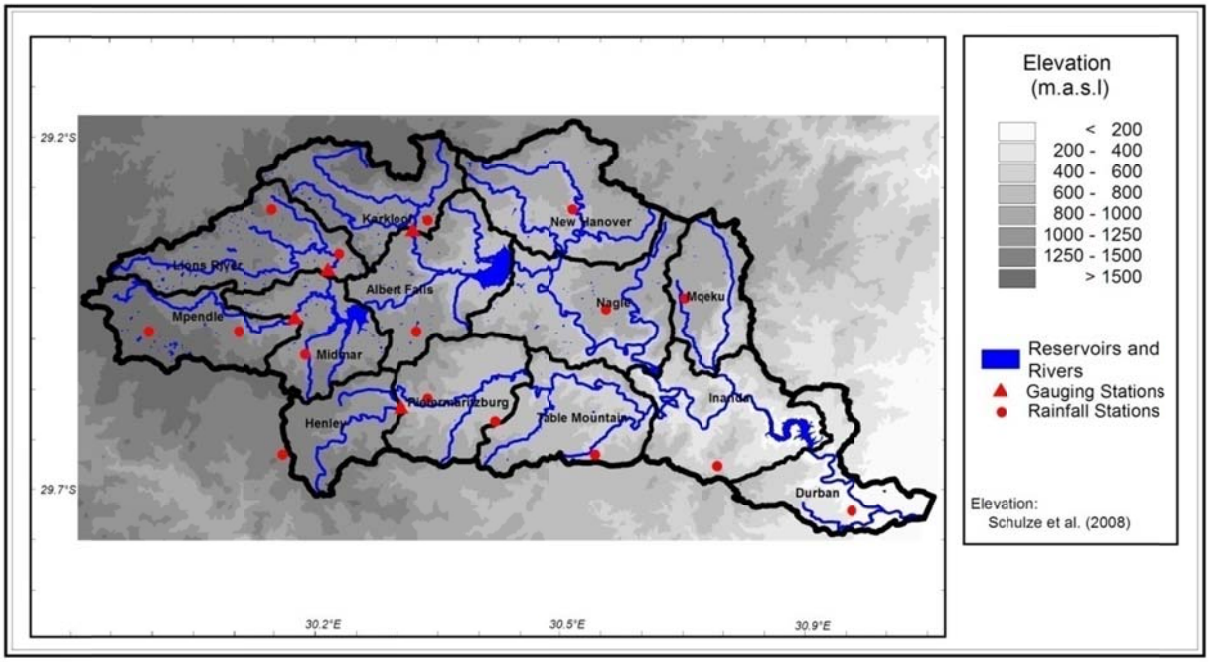

Figure 3.3: Water Management Units of the Mgeni catchment

The Mgeni catchment consists of 13 water management units (WMUs) as shown in Figure 3.3. These WMUs were initially delineated as Quaternary Catchments by the Department of Water Affairs and Forestry according to altitude, topography, soils properties, land cover, water management (water inputs and abstractions), inter-basin transfers, water quality sampling points and streamflow gauging stations and have been used in major studies by Tarboton and Schulze (1992), and later by Kienzle *et al*. (1997) and Summerton (2008). For the purposes of this study, comparison of model output against observed data was undertaken at the gauged outlets of the

Mpendle, Lions River and Karkloof WMUs and at a gauge point within the Henley WMU (Figure 3.3). These WMUs were selected as there are no major dams upstream of the streamflow gauging weirs for which off-takes are not known. The WMUs differ in land use, and observed streamflow data of good quality and reasonable length was available for the time period that corresponds to the available land use data. A summary of the areas, MAPs and land uses in the Mgeni catchment as a whole, as well as the Mpendle, Lions River, Karkloof and Henley WMUs is given in Table 3.2.

Table 3.2: Summary of selected features and land uses of the Mgeni Catchment and the WMUs selected for the confirmation studies

	Mgeni Catchment	**Mpendle WMU**	**Lions River WMU**	**Karkloof WMU**	**Henley WMU**
Area (km^2)	4 349.42	295.69	362.02	334.29	219.98
MAP (mm p.a)	918.18	963.48	963.72	1044.96	947.77
Average Altitude (m.a.s.l)	923.30	1556.00	1387.29	1302.54	1280.05
Gauging station	-	U2H013	U2H007	U2H006	U2H011
Land use (% of area)					
Natural vegetation	57.1	68.2	54.4	50.3	50.9
Water bodies	1.9	1.5	1.8	0.7	0.1
Alien vegetation	0.7	2.7	2.0	1.0	1.7
Degraded areas	2.4	4.1	2.1	0.5	2.7
Commercial forestry	16.0	15.4	15.8	33.6	5.2
Commercial agriculture					
- Sugarcane	5.8	0.0	0.0	0.0	0.0
- Irrigated	4.4	6.2	16.5	11.1	1.8
- Dryland	1.0	1.1	7.1	2.6	0.4
Subsistence agriculture	2.1	0.7	0.0	0.0	12.7
Urban areas					
- Commercial	0.7	0.0	0.0	0.0	0.0
- Formal residential	2.9	0.1	0.3	0.0	0.0
- Informal residential	4.9	0.0	0.0	0.0	24.4

3.3.2 Luvuvhu catchment

The Luvuvhu catchment (5940 km^2), situated in the north-east of the Limpopo province of South Africa (Figure 3.2), is drained by the Luvuvhu and Mutale Rivers, which flow in an easterly direction up to the confluence with the Limpopo River, on the South Africa and Mozambique border. The climate of the Luvuvhu catchment is variable, both spatially and temporally. The

MAP varies from 1 870 mm p.a in the mountainous regions (1 360 m.a.s.l) in the upper reaches of the catchment to 300 mm p.a in the drier, lower (200 m.a.s.l) regions of the catchment. The mean annual potential evaporation ranges from 1 905 mm p.a to 2 254 mm p.a. Mean annual temperatures range from 17°C in the mountainous regions to 24°C towards the catchment outlet. The lower reaches of the Luvuvhu catchment fall within the boundaries of Kruger National Park, an important conservation and ecotourism area. A large proportion of the catchment is under subsistence agriculture (Table 3.3). The Luvuvhu catchment consists of 14 WMUs (Figure 3.4) which were delineated according to the Quaternary Catchments and adjusted to accommodate streamflow gauging stations. Available and good quality observed streamflow data were a constraint for the confirmation study in the Luvuvhu catchment. However, based on a previous study by Jewitt *et al*. (2004), the Upper Mutale WMU (Figure 3.4) presented an ideal opportunity for a confirmation study as high quality streamflow data were available and additionally the land use and climate was representative of the larger Luvuvhu catchment (Table 3.3).

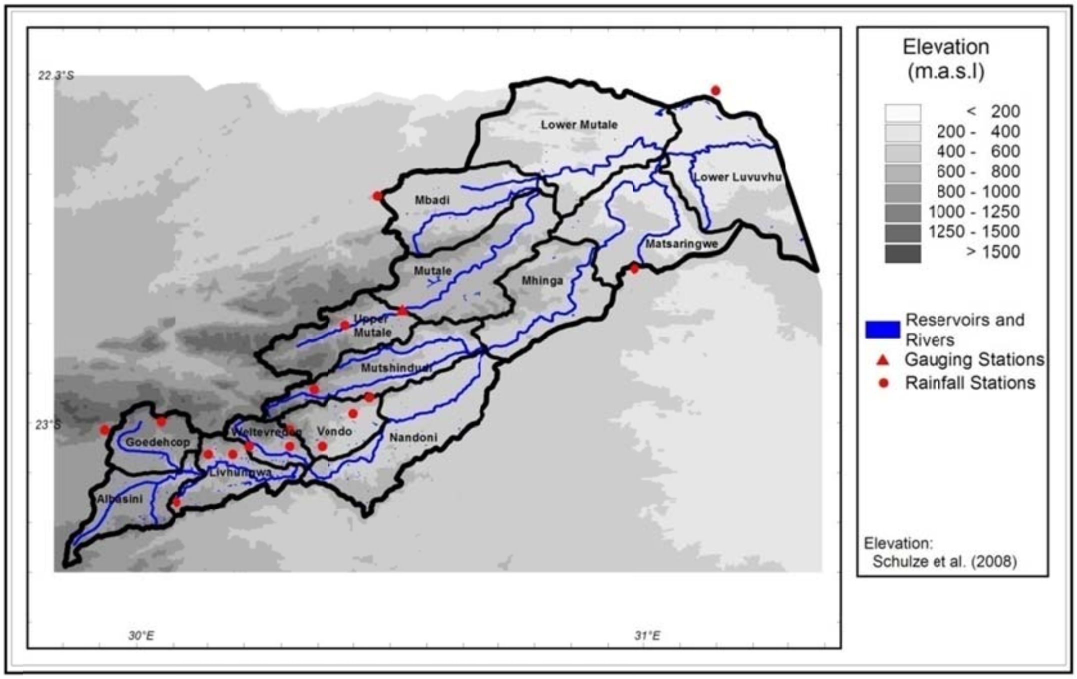

Figure 3.4: Luvuvhu Water Management Units

3.3.3 Upper Breede catchment

The Upper Breede catchment (2046 km^2) is located in the mountainous region of the Western Cape province of South Africa (Figure 3.2). The topography of the catchment is fairly rugged, and altitude ranges from of over 1 990 m a.s.l to 200 m a.s.l. The Upper Breede catchment falls within the winter rainfall region of South Africa. The rainfall of the catchment is highly variable due to the topography, with the MAP varying between 1 190 mm in the higher areas of the catchment to 350 mm p.a in the lower areas of the catchment.

Table 3.3: Summary of selected features and land uses of the Luvuvhu Catchment and the Upper Mutale WMU

	Luvuvhu Catchment	**Upper Mutale WMU**
Area (km^2)	5940.35	328.91
MAP (mm p.a)	684.49	961.02
Average Altitude (m.a.s.l)	589.45	932.92
Gauging Station	-	A9H004
Land use (% of area)		
Natural vegetation	62.5%	60.8%
Water bodies	0.2%	0.0%
Degraded areas	8.1%	4.3%
Commercial forestry	6.0%	12.7%
Commercial agriculture (Irrigated)	3.0%	2.6%
Subsistence agriculture	15.8%	13.4%
Informal residential areas	4.4%	6.2%

Irrigated commercial agriculture is the primary economic activity in the catchment, with the main crop being high value vineyards for wine production. Other farming products include deciduous fruit, dairy and grain. The catchment is also rich in biodiversity, which has led to conflicts between clearing of land for farming and conserving biodiversity (DWAF, 2004). In the lower reaches of the catchment there are two inter-basin transfer schemes which transfer water from the Upper Breede catchment into the neighboring Berg catchment for irrigation purposes (DWAF, 2004). The Upper Breede catchment consists of 11 WMUs, which were delineated according to the Quaternary Catchments, taking into account altitude, topography, land cover and streamflow gauging stations.

For the confirmation study the Koekedou and Upper Breë WMUs were chosen (Figure 3.5). These WMUs have good quality observed streamflow data available of reasonable length and the land use of the WMUs is representative of that of the catchment as a whole (Table 3.4). In addition, these two WMUs are not affected by the interbasin transfer schemes.

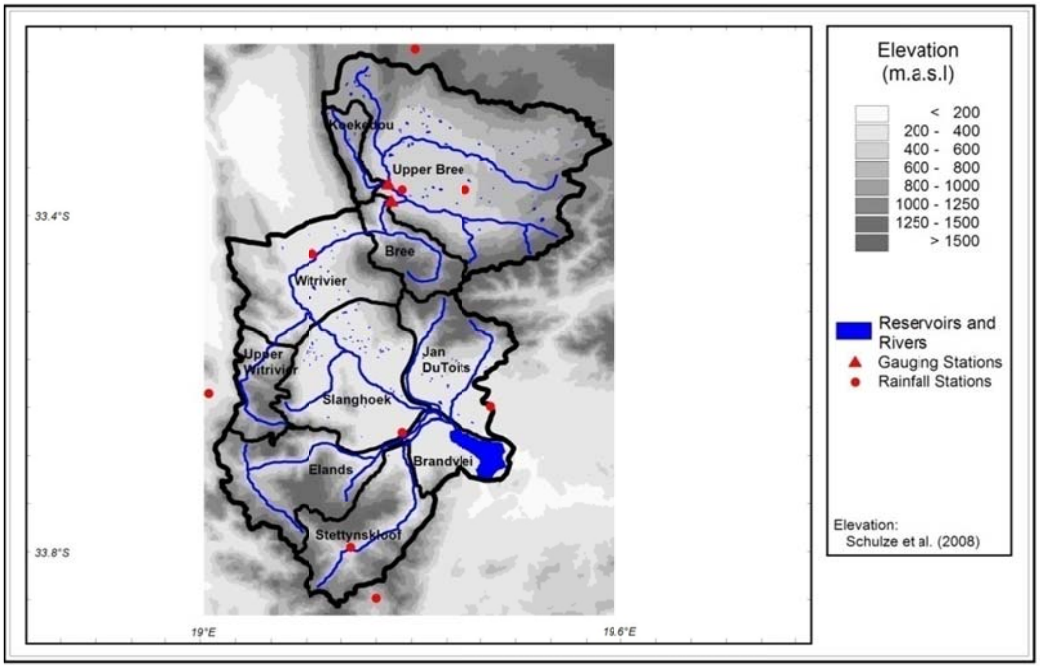

Figure 3.5: Upper Breede Water Management Units

Table 3.4: Summary of selected features and land uses of the Upper Breede Catchment and the WMUs selected for verification

	Upper Breede Catchment	Koekedou WMU	Upper Breë WMU
Area (km^2)	2046.44	48.17	655.74
MAP (mm p.a)	619.66	788.28	573.54
Average Altitude (m.a.s.l)	716.96	934.00	810.07
Gauging Station	-	H1H013	H1H003
Land use (% of area)			
Natural vegetation	75.8%	78.8%	66.4%
Water bodies	2.2%	2.5%	2.5%
Commercial forestry	0.5%	0.2%	0.4%
Commercial agriculture (Irrigated)			
- Permanent	12.7%	18.5%	16.2%
- Temporary	7.9%	0.0%	12.9%
Residential & Urban areas	0.8%	0.0%	1.5%

3.4 Data Sources and Model Configuration

3.4.1 Subcatchment delineation and configuration

For each of the study areas, the WMUs were delineated into subcatchments which reflect the altitude, topography, soils properties, land cover, water management (water input and abstractions), and location of gauging stations. Through the delineation process the Mgeni catchment was subdivided into 145 subcatchments, the Luvuvhu catchment into 52 subcatchments and the Upper Breede into 31 subcatchments. These subcatchments can be considered relatively homogeneous in terms of climate and soils; however, the land use within each subcatchment varies. For this reason each subcatchment was further divided into major land use units for modelling purposes. The modelling units were configured such that their streamflows cascade (route) into each other in a logical sequence representative of river flow, and an example of the flow sequence of a subcatchment in the Mgeni is shown in Figure 3.6.

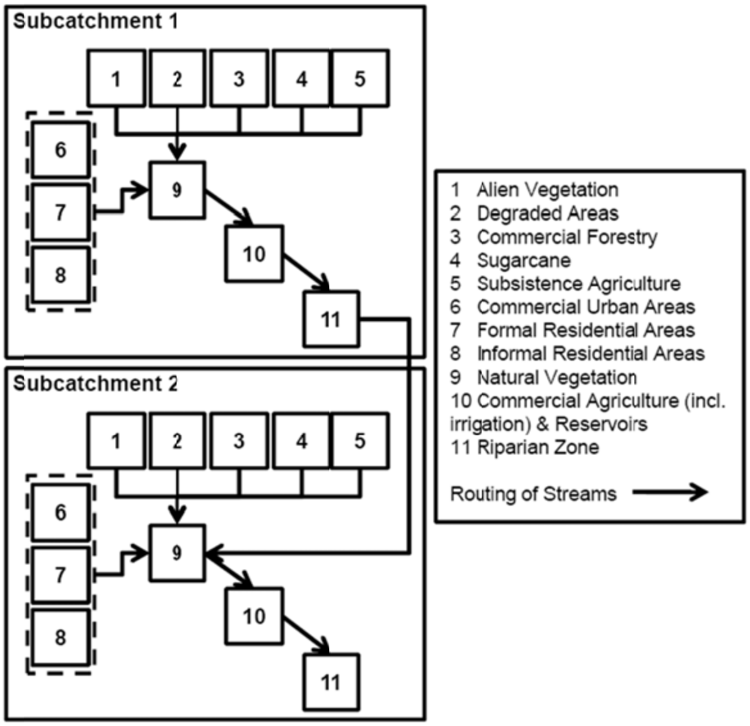

Figure 3.6: An example from the Mgeni catchment of cascading (i.e. routing) of flows between subcatchment and land use units within each subcatchment

3.4.2 Historical climatological data

The hydroclimatological requirements of the *ACRU* model are daily rainfall and daily reference evaporation (A-pan equivalent), with the latter computed from daily minimum and maximum temperature if not provided explicitly. Representative rainfall stations with daily records were chosen for each of the catchments. For the Mgeni catchment 15 rainfall stations were selected, while 16 rainfall stations were selected for the Luvuvhu catchment and nine to represent the rainfall of the Upper Breede catchment. The stations were chosen on the basis of the reliability of the record, the altitude of the rainfall station in relation to that of the streamflow gauge, and the rainfall station's location in respect of the catchment. For each of the chosen stations a 40-year record (1960 – 1999) of daily rainfall was extracted from a comprehensive daily rainfall database for South Africa compiled by Lynch (2004). Although every effort was taken by Lynch (2004) to remove, or correct for, various identified errors and anomalies, a rainfall database of this magnitude can never be rendered totally error free. To improve the rainfall stations' representation of the catchments' areal rainfall, the option in the *ACRU* model to adjust the daily rainfall record by a month-by-month adjustment (multiplication) factor was invoked. 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.

As daily A-pan records were not available for the catchment, the Hargreaves and Samani (1985) daily A-pan equivalent reference evaporation equation, which is an option in the *ACRU* model and only requires daily maximum and minimum temperatures as inputs, was used to estimate daily values. Bezuidenhout (2005) found that the Hargreaves and Samani (1985) equation mimicked the daily values of reference evaporation well for South Africa. The daily minimum and maximum temperatures for the same 40-year period as the rainfall were extracted from a 1' by 1' latitude/longitude raster database of daily temperatures for South Africa (Schulze and Maharaj, 2004) for a point closest to the centroid of each subcatchment which represented the median altitude of the subcatchment.

3.4.3 Soils

The *ACRU* model revolves around a daily multi-layer soil water budget, and operates with surface layer characteristics and two active soil layers, *viz*. a topsoil and subsoil, into which infiltration of rainfall occurs and in which rooting development and soil water extraction take place through the evaporation and transpiration processes, as well as capillary movement and saturated drainage (Schulze, 1995). Thus, information is required on the thickness of the topsoil and subsoil, as well as on soil water content at the soil's lower limit (i.e. permanent wilting point), its drained upper limit (i.e. field capacity) and saturation for both the topsoil and subsoil, and furthermore also on the fraction of 'saturated' soil water (above drained upper limit) to be redistributed daily from the topsoil to the subsoil, and from the subsoil into the intermediate/groundwater store (Schulze, 1995). Values for these variables were obtained for the three study areas from the electronic data accompanying the "South African Atlas of Climatology and Agrohydrology" (Schulze *et al*., 2008).

3.4.4 Streamflow response variables

In the *ACRU* model, streamflow response variables are used to govern the portion of generated stormflow exiting a catchment on a particular day, as well as the portion of baseflow originating from the groundwater store, which contributes to streamflow. For the Mgeni and Luvuvhu catchments it was assumed that 30% of the total stormflow generated in a subcatchment would exit the same day as the rainfall event which generated the stormflow, this being a typical value for South African subcatchments of the size in this study (Schulze *et al*., 2004). However, given the steepness of the Upper Breede catchment it was assumed that 60% of the total stormflow generated in a subcatchment would exit on the same day (Schulze *et al.,* 2004). On any particular day it is assumed that 0.9 % of the groundwater store will become baseflow. This value has been found to be representative of large parts of southern Africa (Schulze *et al*., 2004). The thickness of the soil profile from which stormflow generation occurs is set to the thickness of the topsoil, except in the sugarcane and commercial forestry land use units where is was set to 0.35 in accordance with the various studies reviewed in Schulze (1995). The above streamflow response variables have been based largely on experiences in simulations on small and large, research and operational catchments in climatic regimes ranging from semi-arid to sub-humid[4].

The coefficient of initial abstraction is a variable in *ACRU* which is used to estimate the rainfall abstracted by soil surface interception, detention surface storage and initial infiltration before stormflow commences (Schulze, 1995). This value varies from month-to-month and differs, *inter alia*, according to land use, soil surface conditions and typical seasonal rainfall intensity characteristics (Schulze, 2004; Table 3.1). Impervious areas are hydrologically important and are represented in the urbanized land use units by inputting the fraction of the subcatchment that is impervious according to typical South African values developed by Schulze and Tarboton (1995). In regard to impervious areas the model distinguishes between adjunct impervious areas which are connected directly to rivers or stormwater systems and disjunct impervious areas, i.e. those not connected directly to rivers or stormwater systems, with values used in this study shown in Table 3.5. The fraction of the subcatchment which is specified as an adjunct impervious area contributes directly to the streamflow at the outlet of the subcatchment under consideration on the same day as the rainfall event occurred. On the other hand, the runoff generated from the fraction of the subcatchment specified as disjunct impervious contributes directly to the soil water budget and runoff responses of the pervious portion of the subcatchment under consideration.

Table 3.5: Percentages of adjunct and disjunct impervious areas for different urbanized land uses (after Schulze and Tarboton, 1995)

Urbanized Land Use	**Adjacent Impervious Areas (%)**	**Disjunct Impervious Areas (%)**
Built-up (CBD, Industrial)	30	15
Formal Residential	20	10
Informal Rural Residential Areas	10	5

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[4] The experience is built-up through, for example, Kienzle *et al*. (1997) and Royappen *et al*. (2002).

3.4.5 Water bodies and irrigation

Surface areas of the reservoirs in the Mgeni, Luvuvhu and Upper Breede catchments were obtained from 1:50 000 topographic map sheets dating from 1996 to 2002. Using the algorithm developed by Tarboton and Schulze (1992) the capacity of the reservoirs was calculated from these surface areas. Reservoir seepage was assumed to be equal to 1/1500 of the dam's capacity. Although environmental flow schedules exist for large dams, no environmental flow estimates were available for farm dams in the headwaters of the catchments thus, as suggested in Schulze (1995), environmental flows were assumed to be equal to seepage.

Irrigation areas were identified from the NLC (2000). The irrigation schedule was set at 20 mm applied in a fixed 7 day cycle, with the cycle interrupted only after 20 mm of rain on a given day. Spray evaporation and wind drift losses were input at 12% and conveyance losses at 10 % following typical values summarized by Smithers and Schulze (2004).

3.5 Results of Confirmation Studies

The model was run for the full rainfall record, but the period for the confirmation exercises was governed by availability of gauged data for the respective WMUs. Given the objective of the study to be an assessment of the confidence with which the *ACRU* model can be used when determining hydrological responses to changes in land use and climate, the ability of the model to simulate the variability of streamflows as well as accumulated flows was considered. For this study, the objectives for an adequate simulation were set as a percentage difference between the sum of simulated flows ($\sum Q_s$) and sum of observed flows ($\sum Q_o$) of less than 15% of $\sum Q_o$, a percentage difference between the standard deviation of simulated daily flows (σ_s) and standard deviation of observed flows (σ_o) of less than 15% of σ_o, and an R^2 value in excess of 0.7 for daily simulated flows. These objectives are those suggested for daily simulations by Smithers and Schulze (2004) given the high spatial variability of rainfall in the catchments. To evaluate the goodness-of-fit further, the Nash-Sutcliffe efficiency index (E_f) (Nash and Sutcliffe, 1970) was used. Values of E_f that are similar in magnitude to the coefficient of determination indicate a satisfactory simulation, and thus fulfil the objective for this study.

3.5.1 Mgeni catchment results

Statistics of the performance of the *ACRU* model on the four WMUs included in the confirmation study for the Mgeni catchment are shown in Table 3.6, graphs of observed and simulated streamflow, with the daily values accumulated to monthly totals, are shown in Figure 3.7, and comparision of daily simulated and observed streamflows are shown in Figure 3.8. Gauged data were available for 1987 – 1998. For the Mpendle WMU the low flows and the high flows were marginally undersimulated (Figure 3.7 and Figure 3.8), with the simulated stormflows not being responsive to actual events. The unresponsiveness of the stormflows could be attributed to the portion of degraded land in the WMU, which totals 4%. However, this degraded land is unevenly distributed through the WMU, making the simulation of its combined effects difficult. As the total flows are adequately simulated, the percentage difference between the observed and simulated standard deviation is less than 15%, the R^2 of daily values is 0.836 and the Nash-Sutcliffe E_f is 0.802 (Table 3.6), the simulation of streamflow in the Mpendle WMU can be considered highly acceptable.

Table 3.6: Statistics of performance of the *ACRU* model Mgeni Catchment: Comparison of Daily Observed and Simulated Values

WMU (1987 – 1998)	Mpendle	Lions River	Karkloof	Henley
Total observed flows (mm)	3444.068	2507.196	3456.985	2635.724
Total simulated flows (mm)	3171.486	2257.643	3005.969	2533.988
Ave. error in flow (mm/day)	-0.063	-0.058	-0.105	-0.024
Mean observed flows (mm/day)	0.796	0.582	0.803	0.629
Mean simulated flows (mm/day)	0.733	0.524	0.698	0.605
% Difference between means	7.91%	9.95%	13.05%	3.86%
Std. Deviation of observed flows (mm)	1.823	1.734	1.228	1.246
Std. Deviation of simulated flows (mm)	2.011	1.947	1.305	1.541
% Difference between Std. Deviations	-10.34%	-12.31%	-6.26%	-23.67%
Correlation Coefficient : Pearson's R	0.915	0.939	0.844	0.886
Regression Coefficient (slope)	1.009	1.055	0.897	1.095
Regression Intercept	-0.070	-0.090	-0.022	-0.084
Coefficient of Determination: R^2	0.836	0.882	0.713	0.785
Nash—Sutcliffe Efficiency Index (E_f)	0.802	0.847	0.655	0.654

The Lions River WMU similarly produced acceptable results with an R^2 of 0.882 (Table 3.6). Total values of streamflow were, however, undersimulated, with the rates of baseflow (Figure 3.8) and, consequently, the hydrograph recessions providing the reason for the undersimulation (Figure 3.7).

Both high flows and low flows were undersimulated in the Karkloof WMU (Figure 3.7 and Figure 3.8), resulting in a difference of 13.05% between the daily means of the simulated and observed streamflows. However, the simulation was considered reasonable given that the Nash-Sutcliffe E_f is 0.655 and the other statistics (Table 3.6) fell within the objectives outlined for this confirmation study. The large portion of the Henley WMU under informal residential areas made this WMU a problematic catchment to model. Informal residential areas in South Africa are unstructured and diverse in their nature. In modelling these areas, it is not possible to fully capture the diversity of land uses and soil compaction within these areas. Thus, due to this difficulty the results of the confirmation study for the Henley WMU can be considered reasonable as all statistics, except for the percentage difference between the standard deviations were within the objectives set for the confirmation study, and comparison of daily simulated and observed streamflows(Figure 3.8) indicates that the variability of streamflow was adequately simulated.

The range of land uses represented in the catchment as a whole, and within the individual WMUs, made it difficult to achieve satisfactory simulations. This difficulty was reflected in the statistics produced by the confirmation study. Overall, however, the *ACRU* model performed well on each of the four WMUs included in the confirmation study. The above results show that the *ACRU* model can be used to simulate streamflows of the Mgeni catchment, with its highly diverse land uses, with reasonable confidence.

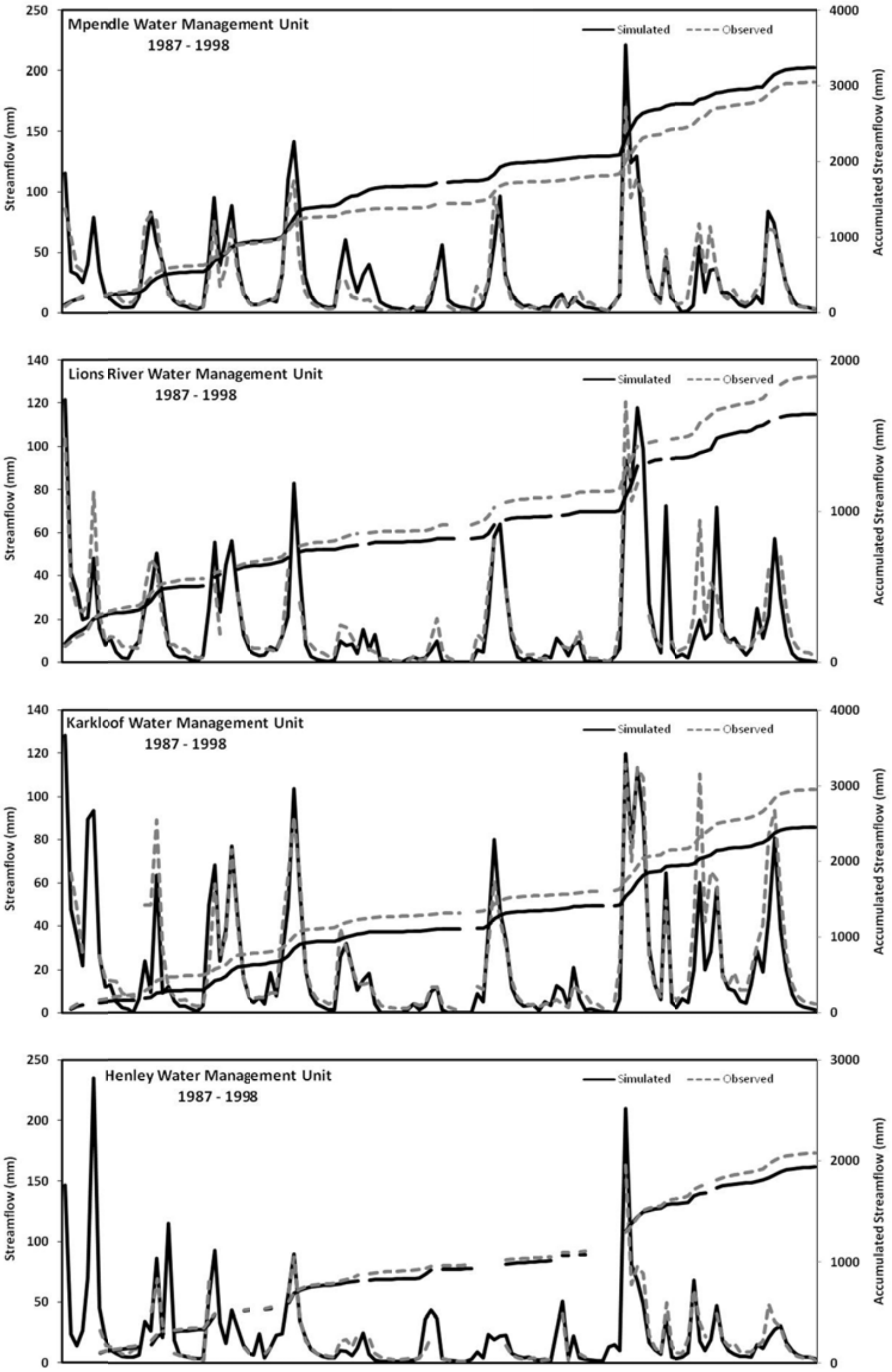

Figure 3.7: Comparison of monthly totals of daily simulated and observed streamflows for (from top to bottom) the Mpendle WMU, Lions River WMU, Karkloof WMU and the Henley WMU of the Mgeni Catchment

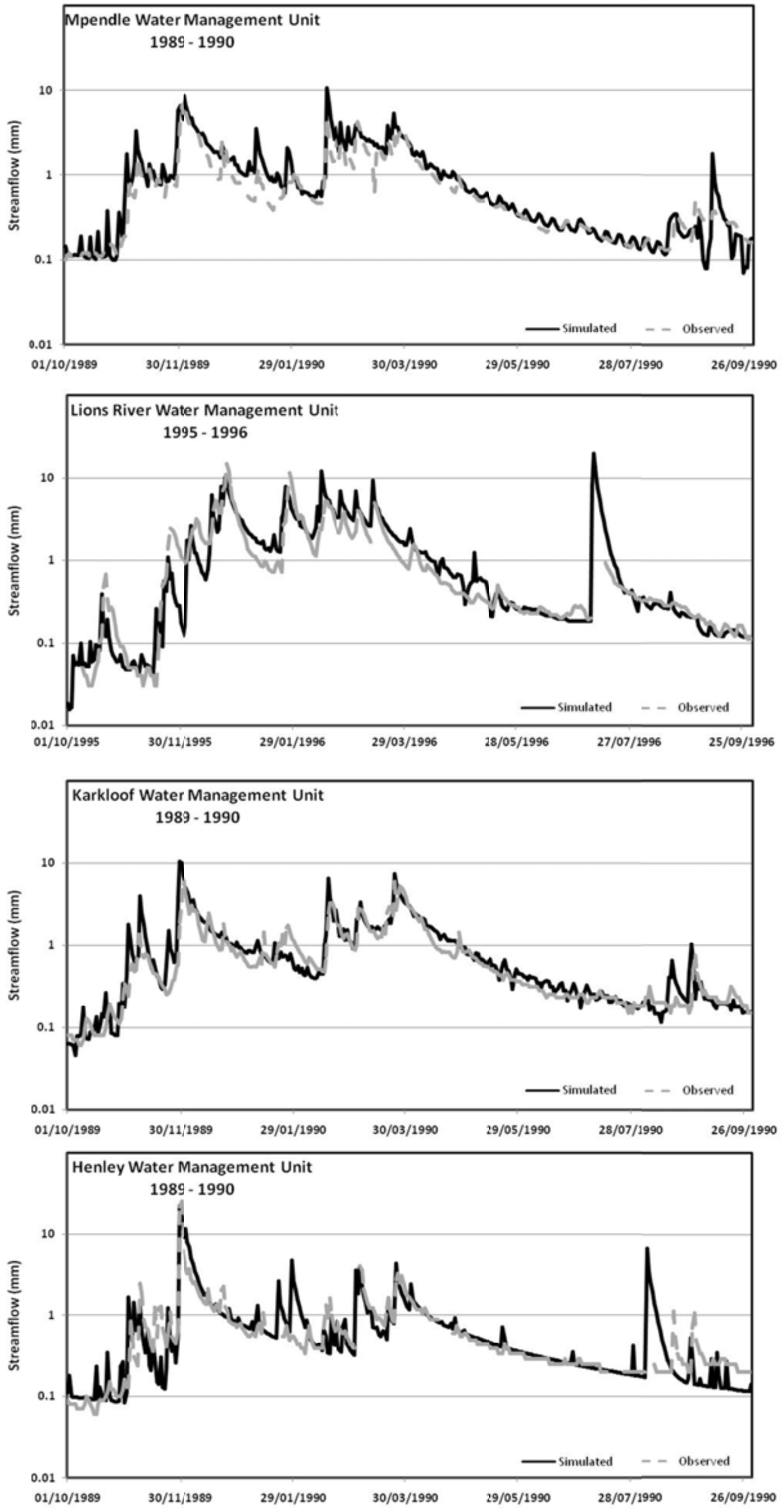

Figure 3.8: Comparison of daily simulated and observed streamflows for (from top to bottom) the Mpendle WMU, Lions River WMU, Karkloof WMU and the Henley WMU of the Mgeni Catchment

3.5.2 Luvuvhu catchment results

Observed streamflow data of appropriate quality in the Luvuvhu Catchment were only available for one gauging station, *viz*. A9H004, which is located at the outlet of the Upper Mutale WMU. The period of acceptable data is 1970 to 1990. The statistics of goodness-of-fit (Table 3.7) for the Upper Mutale WMU are highly acceptable. Total values of streamflow are simulated well, with accumulated totals of observed and simulated streamflows following similar patterns (Figure 3.9). The high flows are slightly undersimulated, the median flows slightly oversimulated and the low flows are well simulated (Figure 3.10), this is further indicated by the regression coefficient of 0.859 and intercept of 0.177. The Nash-Sutcliffe E_f of 0.715 supported the acceptability of the results (Table 3.7). The satisfactory goodness-of-fit statistics produced for the Upper Mutale WMU imply that it may be suggested that streamflows of the larger Luvuvhu Catchment can also be simulated with confidence using the *ACRU* model.

Table 3.7: Statistics of performance of the *ACRU* model Luvuvhu Catchment: Comparison of Daily Observed and Simulated Values

WMU (1970 – 1990)	**Upper Mutale**
Total observed flows (mm)	6689.166
Total simulated flows (mm)	7056.196
Ave. error in flow (mm/day)	0.050
Mean observed flows (mm/day)	0.904
Mean simulated flows (mm/day)	0.954
% Difference between means	-5.49%
Std. Deviation of observed flows (mm)	2.631
Std. Deviation of simulated flows (mm)	2.635
% Difference between Std. Deviations	0.16%
Correlation Coefficient : Pearson's R	0.858
Regression Coefficient (slope)	0.859
Regression Intercept	0.177
Coefficient of Determination: R^2	0.736
Nash—Sutcliffe Efficiency Index (E_f)	0.715

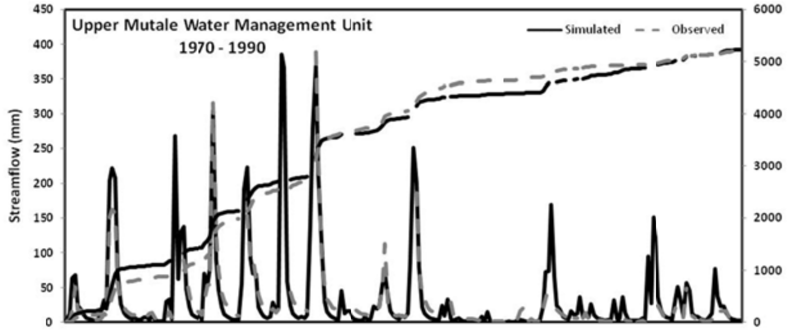

Figure 3.9: Comparison of monthly totals of daily simulated and observed streamflows for the Upper Mutale WMU of the Luvuvhu Catchment

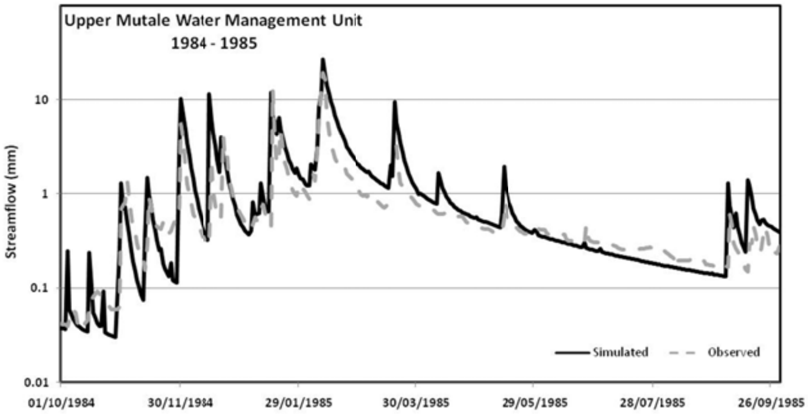

Figure 3.10: Comparison of daily simulated and observed streamflows for the Upper Mutale WMU of the Luvuvhu Catchment

3.5.3 Upper Breede catchment results

The verification study in the Upper Breede Catchment was carried out on two WMUs for the period 1987 – 1998 for which observed streamflow data were available. The goodness-of-fit statistics produced for the Koekedou WMU are highly acceptable (Table 3.8). The Nash-Sutcliffe E_f of 0.785 was attained. Total accumulated flows (Figure 3.11, top) were well simulated, with the simulated pattern closely matching that of the observed. However, the regression intercept, regression coefficient (Table 3.8) and comparison of daily observed and simulated streamflows (Figure 3.12, top) indicate an oversimulation of the baseflows and a slight undersimulation of the high flows.

Table 3.8: Statistics of performance of the *ACRU* model Upper Breede Catchment: Comparison of Daily Observed and Simulated Values

WMU (1987 – 1999)	**Koekedou**	**Upper Breë**
Total observed flows (mm)	4209.394	1663.064
Total simulated flows (mm)	4496.732	1642.908
Ave. error in flow (mm/day)	0.070	-0.005
Mean observed flows (mm/day)	1.021	0.376
Mean simulated flows (mm/day)	1.091	0.372
% Difference between means	-6.83%	-1.21%
Std. Deviation of observed flows (mm)	5.323	0.812
Std. Deviation of simulated flows (mm)	5.639	0.768
% Difference between Std. Deviations	-5.94%	5.39%
Correlation Coefficient : Pearson's R	0.929	0.844
Regression Coefficient (slope)	0.956	0.798
Regression Intercept	0.114	0.071
Coefficient of Determination: R^2	0.864	0.712
Nash—Sutcliffe Efficiency Index (E_f)	0.785	0.516

The statistics of performance for the Upper Breë show that the R^2 value of 0.712, the percentage difference of the means and the percentage difference of the standard deviations between simulated and observed flows fall within the acceptable limits outlined for the confirmation study (Table 3.8). However, the total accumulated flows for the Upper Breë WMU were oversimulated (Figure 3.11, bottom), the high flows were undersimulated and the low flows oversimulated (Figure 3.12, bottom). One reason for this is that the Upper Breë WMU contains steep topography which makes capturing the responsiveness of high flows difficult. However, since statistics of performance were within the acceptable limits outlined for the study, the simulation for the Upper Breë WMU can be considered acceptable. As the *ACRU* model performed well on the Koekedou and satisfactorily on the Upper Breë WMU, it is concluded that streamflows for the Upper Breede Catchment can be simulated with reasonable confidence.

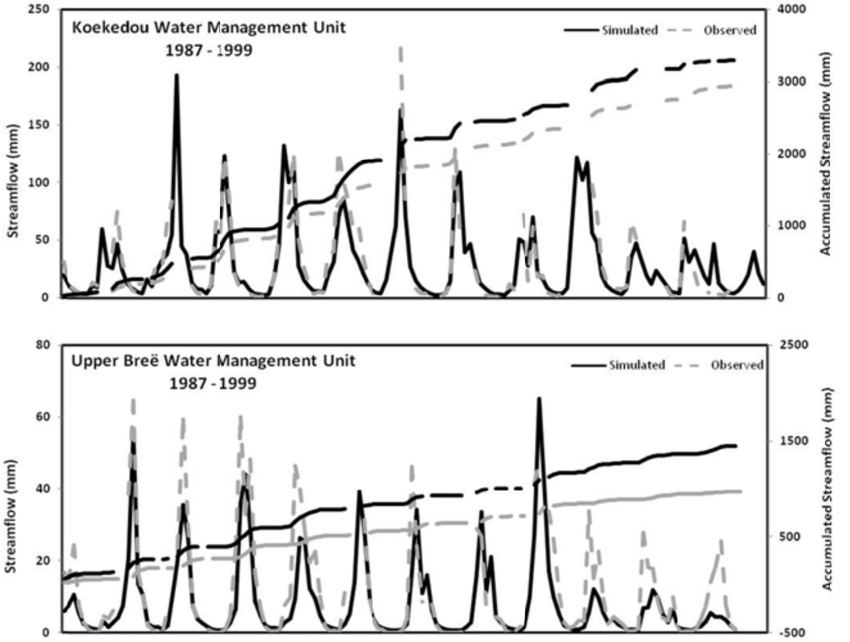

Figure 3.11: Comparison of monthly totals of daily simulated and observed streamflows for (from top to bottom) the Koekedou WMU and the Upper Breë WMU of the Upper Breede Catchment

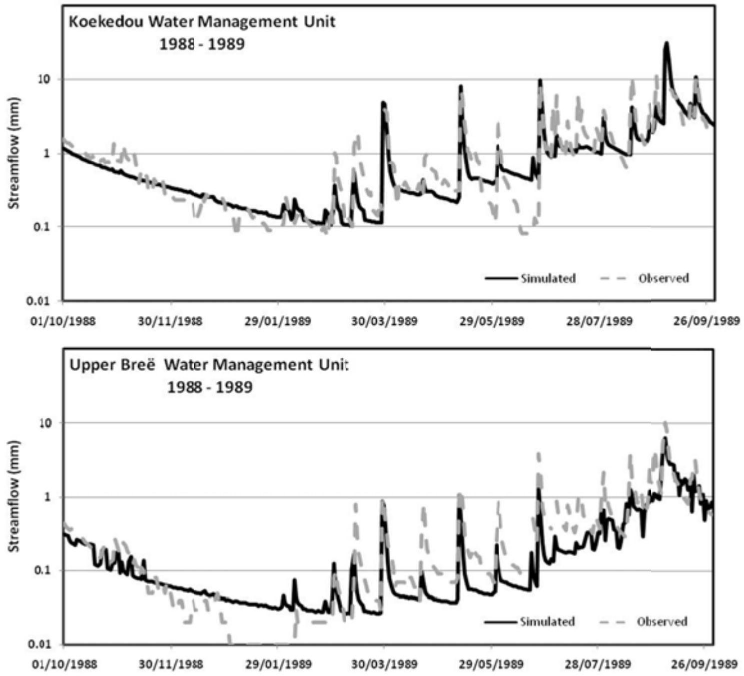

Figure 3.12: Comparison of daily simulated and observed streamflows for (from top to bottom) the Koekedou WMU and the Upper Breë WMU of the Upper Breede Catchment

3.6 Discussion

No fieldwork was carried out in the Mgeni, Luvuvhu and Upper Breede Catchments to determine values of input variables. Thus the simulation results produced in this confirmation study were based on national land use and soils information, together with default input values obtained from the *ACRU* User Manual where no better information was available. Based on the simulation results presented above and that the E_f ranged between 0.847 and 0.597, it is suggested that the *ACRU* model can be used with confidence to simulate the streamflows of the Mgeni, Luvuvhu and Upper Breede Catchments. The *ACRU* model has been used to aid decision-making in South Africa, and applied in numerous hydrological designs, water resource assessments and research projects both in South Africa and internationally (e.g. Schulze, and George, 1987; Schulze, 1988; Smithers, 1991; Tarboton, and Schulze, 1991; Smithers, and Caldecott, 1993; New and Schulze, 1996; Butterworth *et al*., 1999; Jewitt and Schulze, 1999; Smithers *et al*., 2001; Schulze and Smithers, 2004; Jewitt *et al*., 2004; Kiker *et al*., 2006). To demonstrate the model's ability and acceptance, confirmation studies, and in particular confirmation studies at a daily time interval, need to be undertaken. This study, beyond gaining confidence in the *ACRU* model's ability to be used in assessments of impacts of land use and climate changes on hydrological responses, adds to the available literature confirming that the model's process representation is a relatively accurate reflection of reality at a daily time step and over a range of climatic regions.

Although confidence in the *ACRU* model's ability to simulate hydrological responses with past and present observational data has been demonstrated under widely ranging climatic and land use conditions, this is no guarantee that the model will necessarily continue to perform at a satisfactory level when used to predict the future (Oreskes *et al*., 1994). The hydrological system is dynamic (Nordstrom *et al.,* 2005) and, under future climate scenarios, may change in unanticipated ways and may exceed the range under which the model's process representations have been tested. Determination of model input variables such as the streamflow response variables, and the question as to whether the conceptualizations of the processes within the model will be the same under future changes, remain major sources of uncertainty in hydrological modelling. However, to aid future water resource planning, simulations of hydrological responses to plausible scenarios land use and climate change are required. The uncertainties in this regard should be, therefore, recognized and, where possible, be constrained (Beven, 2006), rather than being seen as a reason not to proceed with studies projecting future changes.

By covering a wide range of climates, from the dry sub-tropical Luvuvhu catchment, to the wetter and sub-humid Mgeni catchment in a summer rainfall region and the Upper Breede catchment with winter frontal rainfall, the confidence in the model's ability to represent hydrological responses under a range of climates has increased. Thus, in effect by using a space for time study, the uncertainty of the model's ability to cope with the projected future climate scenarios is reduced. Furthermore, as the model was shown to be sensitive to diverse land uses, including commercial forestry, natural vegetation, urban areas and subsistence agriculture, uncertainties regarding the model's ability to be sensitive to land use change are also seen to be constrained. However, it is noted that the representation of informal residential areas could be a shortcoming of the model, as the unstructured nature of these areas is difficult to capture with the model's input variables. An advantage of the *ACRU* model over many others, in regard to land use and climate change studies, is that it explicitly simulates the stormflow and baseflow components of streamflow, and this is important as the partitioning of rainfall into different flow components may change under future climatic conditions. Through this confirmation study, the model's ability to represent high flows and low flows was assessed. Although either the low flows or high flows in some WMUs (for example the Lions River WMU) were either slightly over- or undersimulated, overall the representation of low flows and high flows was considered to be good.

3.7 Conclusion

The *ACRU* model has successfully accounted for a diverse range of land uses within the three catchments used in this study, which provides confidence in the model's ability to assess hydrological responses of land use change. Furthermore, the three catchments selected for the study experience diverse climates, and based on the results produced, the *ACRU* model performs satisfactorily across the range of climates. It is, therefore, suggested that the model is appropriate as a tool to assess hydrological responses of catchments to land use and climate changes.

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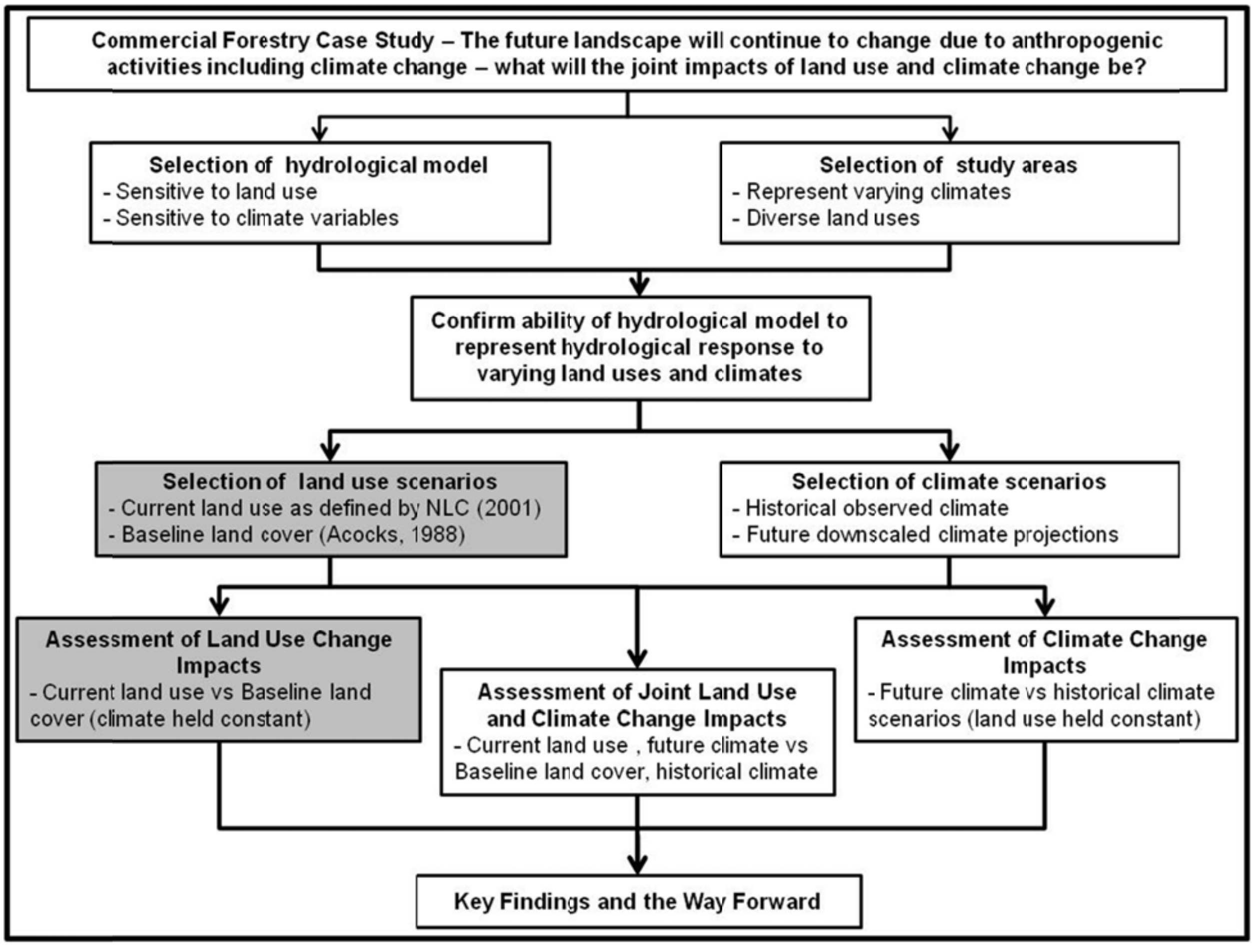
Lead in to Chapter 4

With the ability of the hydrological model to represent hydrological responses under varying land uses and climates confirmed (Chapter 3), the objective of Chapter 4 was to improve understanding of the complex interactions between hydrological responses and land use to aid in water resources planning 9as highlighted in the figure below).



4. HYDROLOGICAL IMPACTS OF LAND USE CHANGE IN THREE DIVERSE SOUTH AFRICAN CATCHMENTS[5]

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Abstract

In order to meet society's needs for water, food, fuel and fibre, the earth's natural land cover and land use have been significantly changed. These changes have impacted on the hydrological responses and thus available water resources, as the hydrological responses of a catchment are dependent upon, and sensitive to, changes in the land use. The degree of anthropogenic modification of the land cover, the intensity of the land use changes and location of land uses within a catchment determines the extent to which land uses influences hydrological response of a catchment.

The objective of the study was to demonstrate and improve understanding of the complex interactions between hydrological response and land use to aid in water resources planning. To achieve this, a hydrological model, *viz.* the *ACRU* agrohydrological model, which adequately represents hydrological processes and is sensitive to land use changes, was used to generate hydrological responses from three diverse, complex and operational South African catchments under both current land use and a baseline land cover. The selected catchments vary with respect to both land use and climate. The semi-arid sub-tropical Luvuvhu catchment has a large proportion of subsistence agriculture and informal residential areas, whereas in the winter rainfall Upper Breede catchment the primary land uses are commercial orchards and vineyards. The sub-humid Mgeni catchment is dominated by commercial plantation forestry in the upper

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reaches, commercial sugarcane and urban areas in the middle reaches , with the lower reaches dominated by urban areas.

The hydrological responses of the selected catchments to land use change were complex. Results showed that the contributions of different land uses to the streamflow generated from a catchment is not proportional to the relative area of that land use, and the disparity between the area under a specific land use and its relative contribution to the catchment's streamflow decreases as the mean annual rainfall of the catchment increases. Furthermore, it was shown that the location of specific land uses within a catchment has a role in the response of the streamflow of the catchment to that land use change. From the Mgeni catchment, the significant role of the water engineered system on catchment streamflow was evident. Hydrological models have drawbacks associated with them due to inherent uncertainties. However, in this study the *ACRU* model proved to be a useful tool to assess the impacts of land use change on the hydrological response as impacts from the local scale to catchment scale could be assessed as well as the progression of impacts of land use changes as the streamflow cascades downstream through the catchment.

4.1 Introduction

The natural landscape has for centuries and even millennia been manipulated, both physically and chemically, to meet society's needs for water, food and security, and these changes both to land cover and land use have impacted on hydrological responses and thus on the water resources (e.g. Legesse *et al.*, 2003; Claussen *et al.*, 2004; De Fries and Eshleman, 2004; Calder, 2005). In this context, and for the purposes of this document, land cover refers to the biophysical condition of the earth's surface and immediate subsurface in terms of broad categories such as grassland, cropland, natural or planted forestry and human settlements (Turner *et al.*, 1993; Turner *et al.*, 1995). These broad land cover categories may be altered by natural forcing such as long-term climate changes or by natural events such as volcanic activity. Most commonly, however, these categories of land cover are exploited by human actions and changed through conversion or modification, to a land use (Turner *et al.*, 1995; Lambin *et al.*, 2000). Changes in land use alter the partitioning of rainwater through the vegetation and soil into the critical hydrological components of interception, infiltration, total evaporation, surface runoff and groundwater recharge (Falkenmark *et al.*, 1999; Costa *et al.*, 2003). Thus, the hydrological responses of a catchment are dependent, *inter alia*, upon the land use of the catchment, and are sensitive to changes in land use (Falkenmark *et al.*, 1999; Schulze, 2000; Bewket and Sterk, 2005).

The extent to which the land use determines the hydrological response of a catchment depends on the degree of modification of the natural land cover by human influences, the intensity of the changes, and the location of the land use within a catchment. Modifications in land use are easily measured at a local scale. However, at a larger catchment scale it becomes difficult to distinguish the effects which individual land use alterations have on hydrological responses. The accumulated effects of land use on the hydrological system are most easily identified at the river basin scale, "as the water has a trace memory of its contact with the land" (Falkenmark *et al.*, 1999, pg 33). Certain land use changes do not immediately alter the hydrological response of a catchment as there may be a time lag between the land use change and its effect on the water balance (Schulze, 2003), for example the effect of afforestation on low flow responses. Schulze (2003) argues that often the management of the land may have a greater effect on the hydrological response of a catchment than the land use itself. In this regard, Lumsden *et al.* (2003) showed that the ploughing or the type of tillage practice of an agricultural field may have far greater impacts on the partitioning of rainfall into stormflow and baseflow than a change in crop type, *per se*, may have.

The interaction of land use and water resources varies greatly in time and in space, as fluxes of water within a catchment move both vertically (e.g. evapotranspiration) and laterally (through soils, hillslopes, aquifers and rivers). Thus, as water moves through the catchment any impacts of the land use can be transmitted through the catchment (Falkenmark, 2003). The impacts of land use on the catchment are often threshold related, with varying stable states existing for each specific catchment, while within each catchment there are feedbacks between the processes and components of that catchment. It has been accepted that use of a hydrological model which is conceptualized to adequately represent hydrological processes, and is sensitive to land use changes, is an appropriate method to assess the impacts of land use on catchment hydrological response (Turner *et al*., 1995; Ewen and Parkin, 1996; Lambin *et al*., 2000; Bronstert *et al*., 2002; De Freis and Eshleman, 2004; Samaniego and Bárdossy, 2006; Choi and Deal, 2008). The *ACRU* agrohydrological model (Schulze, 1995; Smithers and Schulze, 2004) has been shown to be one such model that is suitable for land use impact studies (Warburton *et al.*, 2010). This study builds on the confirmation study by Warburton *et al.* (2010) which showed that the *ACRU* model was able to successfully accommodate a diverse range of land uses and simulate the streamflow and its components of stormflow and baseflow with acceptable confidence in three climatically divergent South African catchments , *viz.* the Mgeni, Luvuvhu and Upper Breede catchments.

To be able to determine the impacts of land use on hydrological responses a baseline land cover, i.e. a reference condition, against which to assess changes is required. The magnitude of the assessed impact of land use change on hydrological responses may also vary according to which baseline or reference land cover was used, and this adds a further layer of complexity to the assessment of the hydrological impacts of land use change. For example, Schulze (2003) and Costa *et al.* (2003) determined impacts of land use change against a natural land cover, while Choi and Deal (2008) and Bewket and Sterk (2005) assessed the impacts of land use change between two points in time. Niehoff *et al*. (2002), on the other hand, assessed scenarios of land use change against the present land use. If these studies had used a different reference land use or cover, their results may have differed. In South Africa, the need for a baseline land cover against which to assess land use change impacts became more important with the implementation of the South African Water Act (NWA, 1998), as reference flows are required for both the determination of the ecological reserve and the assessment of the impact that specific land uses may have on low flows. As the determination of the impact of the land use on the streamflow is completely dependent on the water yield under baseline conditions, it becomes imperative for a relatively accurate baseline to be established (Jewitt *et al.*, 2009). The South African Department of Water Affairs (DWA) support and accepts the use of natural vegetation as a reasonable standard against which to assess land use impacts (Schulze, 2004; Jewitt *et al.*, 2009). To date, the maps produced by Acocks (1953, 1975 and 1988) remain the scientifically most respected and generally accepted maps of natural vegetation from a perspective of South African hydrological impact studies (Schulze, 2004). Thus, for the purposes of this study the

Acocks (1988) Veld Types were used as a baseline land cover against which current land use changes will be assessed to determine the hydrological impacts of these changes.

Given the above background, the objective of this study was to improve the understanding of the dynamics between land use and hydrological response to assist in the integration of land use into water resources planning. This was achieved by modelling the hydrological responses to land use change of three selected South African catchments and assessing the following aspects, *viz*.

- the degree to which the contributions to streamflow from a specific land use are in any way proportional to the relative areas of that land use,
- whether the locations of specific land uses within a catchment are important to the streamflow response and its components of baseflow and stormflow on the premise that the impacts of the land use on streamflow may be attenuated downstream or amplified,
- whether specific land uses have relatively greater impacts on different components (e.g. stormflows) of the streamflow response of a catchment, and
- whether the water engineered system is relatively more important than land use change in influencing the streamflow response of a catchment in terms of total flows, stormflows or baseflows.

4.2 Study Catchments

The South African catchments chosen for this study are described in detail by Warburton *et al*. (2010), with only a brief overview provided here.

The sub-humid Mgeni catchment (4 349 km^2) along the eastern seaboard in the province of KwaZulu-Natal (Figure 4.1), is a complex catchment, both in terms of its land use and its water engineered systems (Schulze *et al*., 2004). It has been sub-delineated into 13 Water Management Units (WMUs), six in the upper reaches, five in the middle reaches and two in the lower reaches. In the upper reaches of the catchment where the rainfall is generally greater than 700 mm p.a, commercial production forestry is a dominant land use (Table 4.1). In the middle reaches there are significant areas of commercial sugarcane plantations and urban areas, while the lower reaches contain substantial urban areas (Table 4.1) associated with the port city of Durban. The water engineered system in the Mgeni catchment plays an important role with four large dams, *viz.* Midmar Dam (237 million m^3 at full supply capacity) supplying Pietermaritzburg and parts of Durban, Albert Falls Dam (289 million m^3), Nagle Dam (23 million m^3) and Inanda Dam (242 million m^3), with the latter supplying the Durban metropolitan area (Summerton, 2008). Additionally, there are approximately 300 farm dams within the middle and upper reaches of the catchment supplying water for 18 500 ha of irrigation.

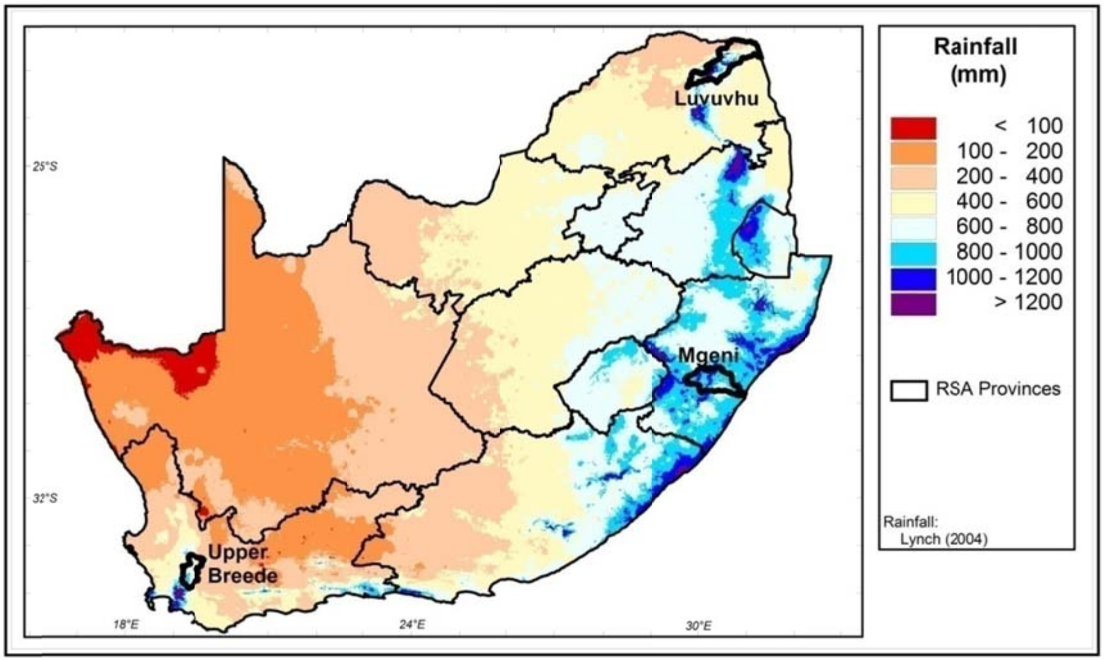

Figure 4.1: The location of the three study catchments in relation to mean annual precipitation (MAP) of South Africa (after Lynch, 2004)

The semi-arid sub-tropical Luvuvhu catchment (5 940 km^2) situated in the northeast of the country in the Limpopo province (Figure 4.1) has a large proportion of its area under subsistence agriculture and informal residential areas. It has been sub-delineated into three reaches with 14 WMUs (Table 4.2). In the upper reaches of the Luvuvhu, there is a substantial area of commercial forestry (Table 4.2). The middle reaches of this catchment are dominated by subsistence agriculture and residential urban areas with the Vondo, Nandoni and Mutshindudi WMUs containing significant areas of degraded land (i.e. denuded of vegetation mainly through overgrazing; Table 4.2). The lower reaches of the Luvuvhu catchment are mainly under natural vegetation.

Table 4.1: Land use distributions in the Water Management Units (WMUs) of the Mgeni Catchment (adapted from NLC, 2000)

	Upper reaches						Middle reaches					Lower reaches	
Present Land Use (%)	Mpendle	Lions River	Karkloof	Midmar	Albert Falls	New Hanover	Nagle	Henley	PMB	Table Mount	Mqeka	Inanda	Durban
Natural Vegetation	60.6	49.7	48.4	43.5	43.0	35.3	53.9	49.2	46.0	82.4	53.7	76.4	51.0
Agriculture													
- Commercial Irrigated	2.0	7.7	4.8	6.4	5.1	3.1	4.4	0.0	0.0	0.8	0.3	0.0	0.0
- Commercial Dryland	12.2	16.5	10.0	13.5	5.9	0.0	3.0	2.0	6.5	3.2	0.1	1.8	3.4
- Commercial Sugar	0.0	0.0	0.0	0.0	2.3	17.4	18.4	0.0	0.8	4.9	20.2	0.0	2.4
- Subsistence	0.6	0.0	0.0	0.3	0.0	1.1	4.4	12.2	0.3	0.0	12.5	0.4	0.2
Commercial Forestry	15.2	15.7	33.3	17.9	31.7	39.9	11.4	6.6	6.9	0.1	7.6	0.2	0.6
Urban/Residential	0.1	0.3	0.0	2.9	3.3	0.2	0.5	24.7	35.8	2.4	2.4	11.6	36.9
Degraded Areas	4.0	2.1	0.5	1.7	0.7	1.2	2.1	2.3	1.8	4.4	1.9	4.5	3.3
Alien Vegetation	2.7	2.0	0.9	1.3	0.1	0.3	0.0	1.5	1.0	0.2	0.0	0.0	0.1
Other (e.g. Dams)	2.7	6.0	2.1	12.4	7.8	1.4	1.9	1.5	0.9	1.7	1.4	5.0	2.1

Table 4.2: Land use distributions in the WMUs of the Luvuvhu Catchment (adapted from NLC, 2000)

Present Land Use (%)	Upper reaches				Middle reaches								Lower reaches	
	Goedehoop	Albasini	Livhungwa	Weltevrede	Vondo	Nandoni	Mutshindudi	Mhinga	Matsaringwe	Upper Mutale	Mutale	Mbadi	Lower Mutale	Lower Luvuvhu
Natural Vegetation	71.0	90.4	13.8	5.2	6.0	21.1	33.1	59.0	96.8	60.6	68.0	60.4	78.5	95.7
Agriculture														
- Commercial	9.6	0.8	38.3	24.7	1.0	1.2	0.7	1.1	0.0	2.6	0.2	0.0	0.0	0.0
- Subsistence	0.0	0.1	0.2	3.1	34.9	38.2	23.6	28.5	2.0	13.4	22.1	30.7	11.0	0.5
Comm. Forestry	16.7	3.7	36.5	54.9	14.3	0.0	16.8	0.0	0.0	12.7	0.0	0.0	0.0	0.0
Urban/Residential	0.5	2.7	7.0	4.0	30.2	11.7	9.4	9.1	0.5	4.3	6.8	6.6	9.0	3.1
Degraded Areas	0.1	0.4	1.2	6.3	12.5	26.9	15.7	1.7	0.0	6.2	2.3	1.8	0.8	0.0
Other (Wetlands, Dams)	2.1	2.0	3.0	1.8	1.1	0.9	0.7	0.6	0.6	0.2	0.6	0.5	0.7	0.7

The Upper Breede catchment (2 046 km^2) with 10 WMUs delineatedin its three reaches, forms part of the headwaters of the Breede River Catchment in the Western Cape province (Figure 4.1), and in this winter rainfall area commercial orchards and vineyards are the primary activity (Table 4.3) and only substantial land use besides natural vegetation.

Table 4.3: Land use distributions in the WMUs of the Upper Breede Catchment (adapted from NLC, 2000)

Present Land Use (%)	**Upper reaches**			**Middle reaches**					**Lower reaches**	
	Upper Breë	Koekedou	Breë	Witrivier	Upper Witrivier	Slanghoek	Elands	Stettynskloof	Jan Du Toits	Brandvlei
Natural Vegetation	66.4	77.8	100.0	83.2	71.6	58.2	97.6	95.4	82.1	45.0
Agriculture										
- Commercial Permanent	16.2	18.5	0.0	9.8	16.3	28.7	1.7	1.5	8.1	16.5
- Commercial Temporary	12.9	0.0	0.0	3.6	6.4	11.5	0.7	1.8	7.2	12.7
Commercial Forestry	0.4	0.2	0.0	1.7	2.9	0.0	0.0	0.0	0.0	0.0
Urban/Residential	1.5	0.0	0.0	0.7	1.2	0.2	0.0	0.0	1.4	0.5
Other (Wetlands, Dams)	2.5	3.5	0.0	0.9	1.6	1.4	0.0	1.4	1.2	25.3

The Mgeni, Luvuvhu and Upper Breede catchments each thus display a diverse range of land uses, with the dominant land uses of catchments varying. These catchments therefore provide an opportunity to assess the complex interactions between land use change and the streamflow component of hydrological responses, and how these interactions vary under different climates, different locations within a catchment and at different spatial scales.

4.3 Methodology

4.3.1 Model selection

The conceptual-physical, daily time-step and multi-purpose *ACRU* model (Schulze, 1995; Smithers and Schulze, 2004) which was developed in the School of Bioresources Engineering and Environmental Hydrology at the University of KwaZulu-Natal in South Africa was used in this study. A confirmation study assessing the ability of the model to simulate observed streamflows by Warburton *et al.* (2010) concluded that the *ACRU* model could successfully account for the diverse land uses presently within the Mgeni, Luvuvhu and Upper Breede catchments, thus lending confidence to the model's ability to assess the streamflow response to land use change. Beyond this confirmation study, the *ACRU* model has been applied to assess land use impacts and verified extensively in South Africa (Schulze and George, 1987; Tarboton and Schulze, 1990; Kienzle *et al*., 1997; Jewitt and Schulze, 1999; Schulze, 2000; Jewitt *et al*., 2004). A detailed description on how modelling of the land use component in the *ACRU* model is conceptualized, data sources and parameters used is given in Warburton *et al*. (2010), with a brief overview provided here.

4.3.2 Data sources and model configuration

The Luvuvhu, Mgeni and Upper Breede catchments were delineated into WMUs by DWA. These were further delineated into subcatchments, the Mgeni catchment by Kienzle *et al.* (1997) and the Luvuvhu and Upper Breede catchments by Warburton *et al*. (2010), which reflect the altitude, topography, soils properties, land cover, water management (water input and abstractions), and the location of streamflow gauging stations. These subcatchments were considered to be relatively homogeneous with respect to climate and soils. However, the land uses within each subcatchment varied. Thus, each subcatchment was further divided into hydrological response units based on land use (Warburton *et al*., 2010). These modelling units were configured to cascade into each other in a logical sequence representative of river flow (Figure 4.2).

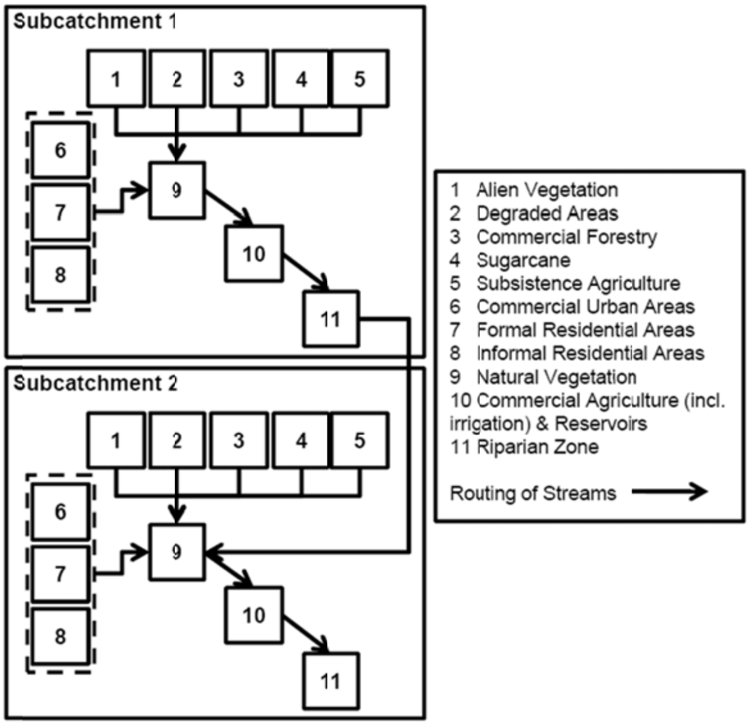

Figure 4.2: An example from the Mgeni catchment of cascading (i.e. routing) of flows between subcatchments and hydrological response units within each subcatchment (Warburton *et al.,* 2010)

For each of the subcatchments within the three study areas, a representative daily rainfall station was chosen and 40-year record (1960 – 1999) was extracted from a comprehensive database of daily rainfall for South Africa compiled by Lynch (2004). The station selection was based on the reliability of the record, the altitude of the rainfall station in comparison to that of the subcatchment, and the location with respect to the subcatchment. The daily rainfall records were adjusted to improve their representation of the subcatchments areal rainfall (Warburton *et al.*, 2010)[6]. The daily minimum and maximum temperatures for the same 40-year period as the rainfall were extracted from a one arc minute latitude/longitude gridded database of daily temperatures for South Africa (Schulze and Maharaj, 2004) for the centroid of each subcatchment. Daily A-pan equivalent potential evaporation values were derived from the Hargreaves and Samani (1985) equation which requires only daily maximum and minimum temperatures by way of climate inputs, as no daily measured evaporation records were available.

The *ACRU* model revolves around a daily multi-soil-layer water budget and operates with a surface layer and two active soil horizons, *viz.* the topsoil and subsoil, in which rooting development and extraction of soil water takes place through evaporation from the soil surface and transpiration, as well as by soil water uptake through capillary action, while other losses occur through stormflows and saturated drainage (Schulze, 1995). Values of the thickness of the topsoil and subsoil, as well as soil water content at the soil's lower limit, field capacity and saturation for both the topsoil and subsoil; as well as the fraction of saturated soil water above field capacity to be redistributed daily from the topsoil to the subsoil, and from the subsoil into the intermediate/groundwater store were obtained for the three study areas from Schulze (2008).

The portion of generated surface and near-surface runoff (i.e. stormflow) and the portion of the intermediate or groundwater stores which contributes the baseflow component to the total streamflow exiting a catchment on a particular day, are governed in *ACRU* by streamflow response variables dependent on subcatchment size, slope, typical rainfall intensities and other factors. Based on a previous study (Kienzle *et al.*, 1997) it was estimated that 30% of the total stormflow generated in the Mgeni and Luvuvhu catchments would exit on the same day as the rainfall event which generated it. Given the steepness of the Upper Breede catchment it was

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[6] Reasoning for the use of a driver station approach is provided in Chapter 3 of Schulze (1995).

assumed that 60% of the total stormflow generated in a subcatchment would exit on the same day (Schulze *et al.,* 2004; based on research by Kienzle *et al*., 1997). On any particular day it was assumed that 0.9% of the groundwater store would become baseflow (Schulze *et al.,* 2004). The depth of the soil from which stormflow generation occurred was set to the thickness of the topsoil, except in the sugarcane and commercial forestry land use units where it was set to 0.35 in accordance with the findings of Schulze (1995) and Schmidt *et al*. (1998).

Three land use specific components which affect evapotranspiration are considered by the *ACRU* model, *viz.* canopy interception losses per rainday (*ACRU* variable name = VEGINT), evaporation from vegetated surfaces (CAY), and evaporation from the soil surface (PCSUCO), with the latter two influenced by soil water extraction processes by plant roots (ROOTA) from the two soil horizons (Schulze, 1995). The rainfall abstracted by canopy and surface litter interception, surface detention storage and initial infiltration before stormflow commences is estimated in *ACRU* by the product of a coefficient of initial abstraction (COIAM) and soil water content (Schulze, 2004). The above input values vary from month-to-month and differ according to the land use (Appendix 4.A). Impervious areas were represented in the urbanised land use units by inputing the fraction of the subcatchment that is impervious, using the typical values for different types of urbanisation developed by Tarboton and Schulze (1992).

Surface areas of both the large reservoirs and smaller farm dams in the Mgeni, Luvuvhu and Upper Breede catchments were obtained from 1:50 000 topographic map sheets. From these surface areas the full supply capacity of the reservoirs was calculated using an algorithm developed by Tarboton and Schulze (1992). Seepage and environmental flow releases were set to equal 1/1500 of the dam's full supply capacity per day, as suggested in Schulze (1995) for dams where these amounts were not known. For the Midmar, Albert Falls and Inanda reservoirs in the Mgeni catchment the daily environmental releases were known. No seepage was assumed to occur from these dams. Irrigation areas were identified from the NLC (2000). Irrigation applications were assumed to be 20 mm net application in a 7 day cycle, with the cycle interrupted only following a 20 mm daily rainfall event. Evaporation and wind drift losses of 12% and conveyance losses of 10 % were input (Smithers and Schulze, 2004).

To assess the magnitude of the impacts of current land uses on water resources, hydrological attributes of a baseline land cover are required as a reference input to hydrological models, in order to be able to simulate changes in streamflow response that would occur between the baseline land cover and perturbed land use conditions.

4.3.3 Baseline land cover

For the purposes of this study the Acocks (1988) Veld Types were used as the baseline land cover against which current land use changes were assessed to determine the hydrological impacts of these changes. The monthly values of water use coefficients (CAY), interception per rainday (VEGINT), root mass distribution in the topsoil (ROOTA), coefficient of infiltration (COIAM) and the index of suppression of soil water evaporation by a litter/mulch layer (PCSUCO), for the Acocks Veld Types occurring in the Mgeni, Luvuvhu and Upper Breede catchments were developed by Schulze (2004) based on a set of working rules linking these parameters to climatically derived variables (MAP, monthly heat units, frost occurrence, soil water status in wet, average and dry years) and crop physiological characteristics. Values for these variables for the various Acocks Veld Types are given in Appendix 4.B.

The same climate data were used in both the current land use and baseline land cover simulations, any simulated changes to streamflows thus being attributable solely to changes in land use.

4.4 Results: Modelled Hydrological Responses to Land Use Change

To assess the impacts of current land uses on the streamflow and its components of baseflow and stormflow within the selected catchments, modelled streamflow generated under the current land use was compared to modelled streamflow generated under baseline land cover conditions. These results were then used to address the questions which follow.

4.4.1 To what extent are contributions from a specific land use proportional to the relative area of that land use in a catchment?

Model simulation results show that the contributions from a specific land use are not proportional to the relative area of that land use. Take, for example, the following hypothetical situation in the Mgeni catchment of a typical subcatchment with respect to soils, and which experiences the equivalent of the median annual precipitation and other climate variables, in which all nine of the considered land uses are present and each occupies an equal portion of the catchment (i.e. 11.1%). The contributions of streamflows generated on the individual land use components to the entire subcatchment's mean annual streamflow are varied (Figure 4.3), with urban built-up areas with their associated impervious areas contributing 23% of the total subcatchment's streamflow, which is more than double the relative area it occupies in the subcatchment (i.e. 11.1%). In contrast, commercial forestry and sugarcane with their high biomass contribute only 5% and 6%, respectively to the mean annual streamflow of the subcatchment, which is considerably less than the relative area they occupy in the subcatchment. As the MAP of the subcatchment changes, the contributions of streamflow generated on the individual land use components are altered.

Consider, on the other hand, a similar hypothetical situation of a typical Mgeni subcatchment, but where the subcatchment's MAP is much higher and is representative of the 95th percentile of MAP of the Mgeni catchment (Figure 4.4). Under such a MAP the contributions to streamflows generated from the urban and residential land use units still remain greater than the relative area the land use units occupy in the subcatchment. However, owing to the increased water available in the subcatchment, the relative contribution to streamflow from the higher biomass sugarcane and commercial forestry land use units is greater and closer to the relative area those land use units occupy within the subcatchment (Figure 4.4). Hence, as the MAP of a subcatchment increases, so the disparities between the relative areas a land use occupies and its contribution to catchment streamflow decrease.

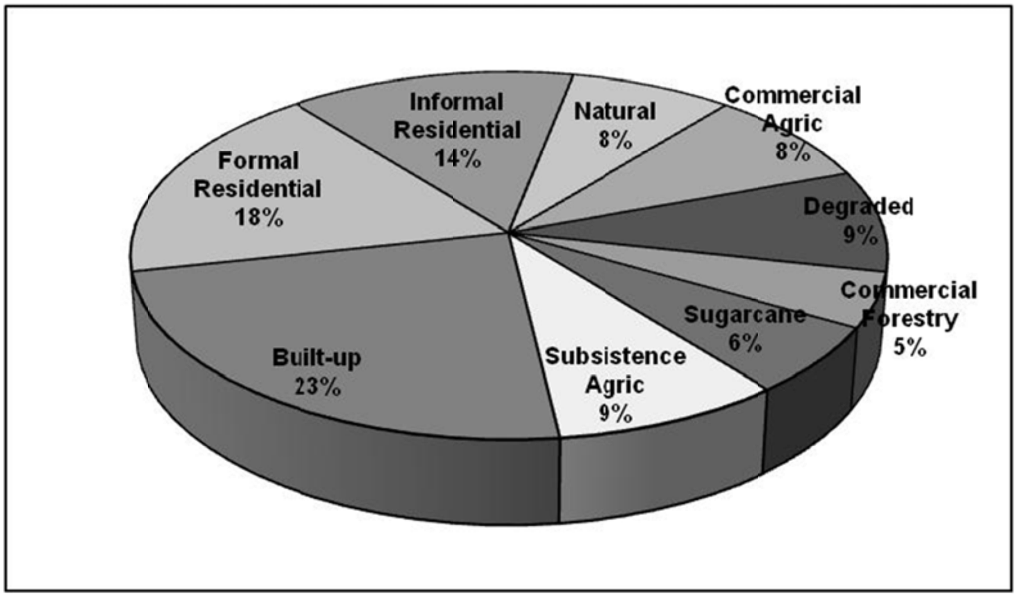

Figure 4.3: Percentage contributions of equally sized land use units to the mean annual streamflow from a hypothetical subcatchment within the Mgeni catchment which experiences an MAP equivalent to the median MAP of the Mgeni catchment

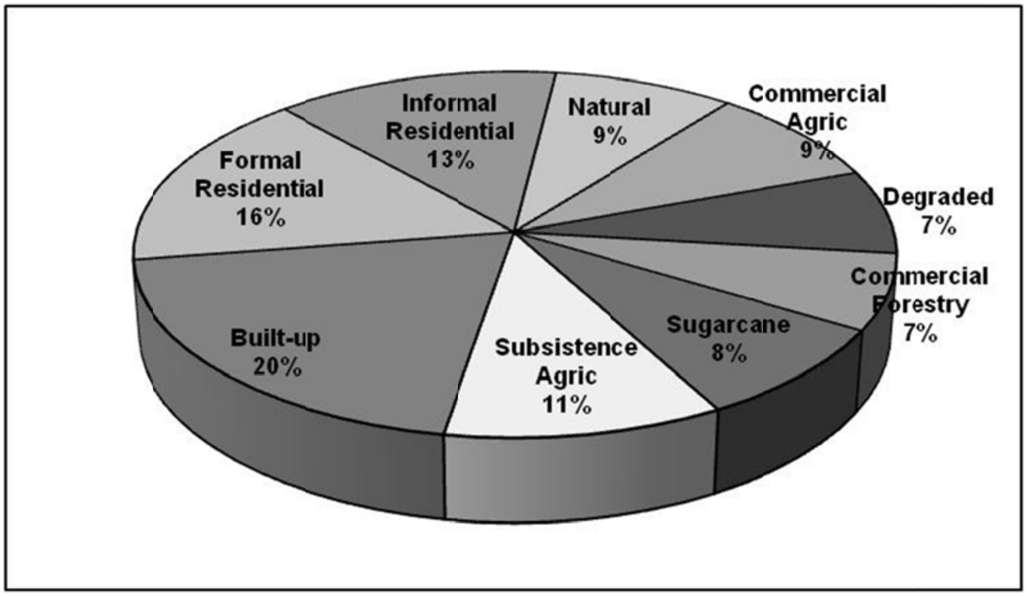

Figure 4.4: Percentage contributions of equally sized land use units to the mean annual streamflow from a hypothetical subcatchment within the Mgeni catchment which experiences an MAP equivalent to the 95th percentile of MAP of the Mgeni catchment

In terms of water resources management, if land uses within the catchments change at different rates the water yield of the catchment could be significantly altered, in particular if the changing land use is one whose contribution to streamflow is disproportionate to the land area occupied by that land use (e.g. urban areas). In addition, if the catchment in which the land use change occurs has a relatively lower MAP, the imbalance between the relative area that land use occupies and its contribution to the catchment's mean annual streamflow will be enhanced.

4.4.2 To what extent is the location of specific land uses within a catchment important to the streamflow response of that catchment?

The land uses within the Mgeni catchment are varied, with different land uses being dominant in the different WMUs. The impacts of these land uses are significant at both the subcatchment and accumulated catchment scale (Figure 4.5). As water moves through the Mgeni catchment the impacts of the various land uses are transmitted through the catchment, with the dominant land use in the WMU having the overriding effect on the direction of the change in streamflow at the outlet of that WMU. In the upper reaches of the catchment, decreases in mean annual accumulated streamflows of between 15 and 50 % are evident (Figure 4.5), and these decreases can be attributed to the high percentage of commercial plantation forestry and sugarcane in the upper reaches. The increases in streamflow in the middle reaches of the catchment (Figure 4.5) can be attributed to the high percentage of built-up urban areas, as well as formal and informal residential areas. In the highly urbanized subcatchments, streamflows increased by up to 75 %. Along the main river stem to the catchment outlet, decreases in streamflow are evident due to the accumulative effects of land use change and the regulating effects of the reservoirs in the catchment. The streamflow response at the outlet of the Mgeni catchment is a reflection of the various land use present within the catchment.

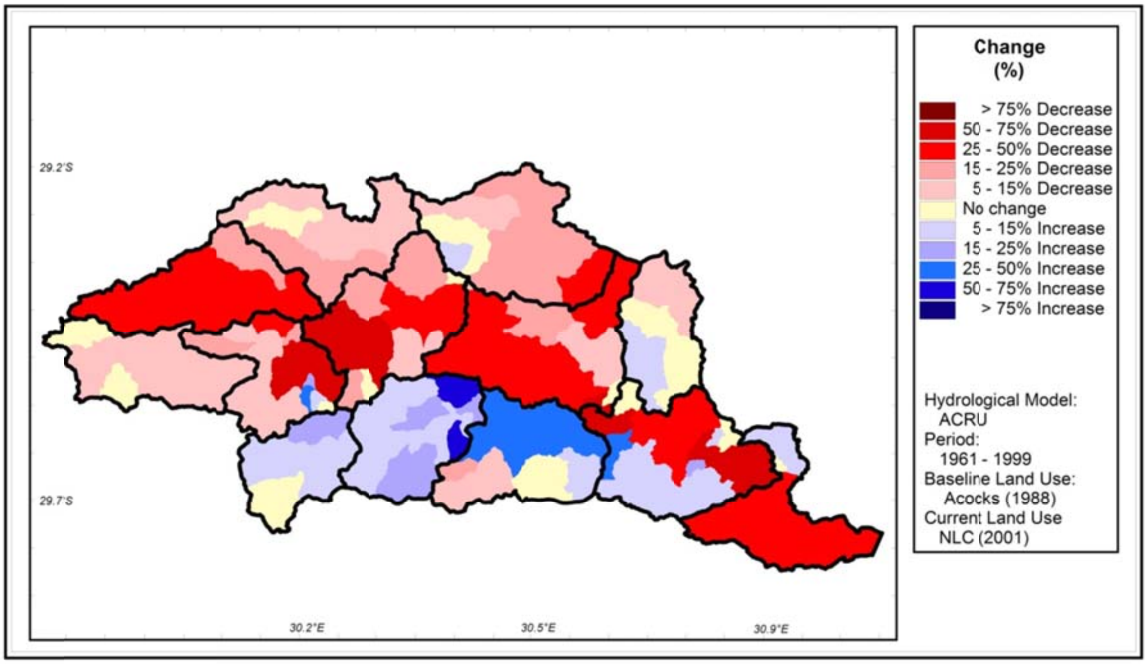

Figure 4.5: Impacts of current land uses on mean annual accumulated streamflows in the Mgeni catchment, relative to the streamflows under baseline land cover conditions

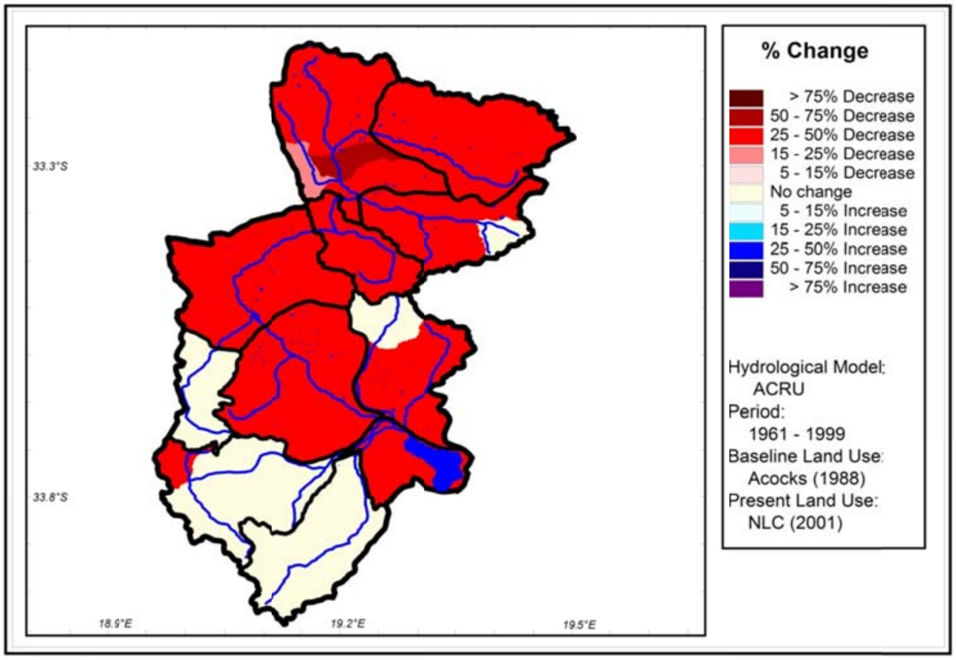

Figure 4.6: Impacts of current land uses on mean annual accumulated streamflows in the Upper Breede catchment, relative to the streamflows under baseline land cover conditions

Unlike the Mgeni catchment where numerous hydrologically sensitive land uses are represented, the only significant change in land use in the Upper Breede catchment is to commercial permanent irrigated agriculture. Currently, ~ 13 % of the catchment is under permanent commercial irrigation, with a large portion of the areas located near the main river stems. Although the percentage of change in land use in the Upper Breede catchment is relatively small, the impact on the streamflow has been significant, at both subcatchment and catchment scale, owing to the nature and location of the land use change (Figure 4.6). In the upper reaches of thecatchment, and following the main river stem to the outlet of the catchment, decreases in mean annual accumulated streamflows between baseline and current land use of between 25 and 50 % are evident (Figure 4.6).These decreases are attributed to the irrigated permanent commercial agriculture located in the upper reaches and along the river main stem.

In Luvuvhu catchment the impacts of the current land uses on the streamflow response are evident at the subcatchment scale, and in certain instances at the WMU scale, but when considering the accumulated outflow of the entire Luvuvhu catchment the impacts of the current land use are hardly evident owing to the balancing/self-cancelling effects of the different land uses (Figure 4.7). Furthermore, the direction of the change in the streamflow response differed between the high flow and low flow seasons, with the magnitude of the impact of the land use changes on streamflow being greater on the low flows (10^{th} percentile) than on the high flows (90^{th} percentile), as shown in Figure 4.7. In the high flow season, *viz*. the summer months of December, January and February (D, J, F), virtually no changes are evident in the mean accumulated high flows (Figure 4.7b). However, commercial plantation forestry in the upper reaches of the catchment resulted in a decrease in the mean accumulated high season low flows of up to 50 % (Figure 4.7a).

In the middle reaches of the catchment increases of between 15 and 50 % in the mean accumulated high season low flows between the current and baseline land uses are evident (Figure 4.7a), and these have been shown to be due to the urban and residential areas in those areas. These impacts of land use, however, are attenuated through the catchment with virtually no discernible impacts (i.e. less than 5% change) being evident at the catchment outlet.

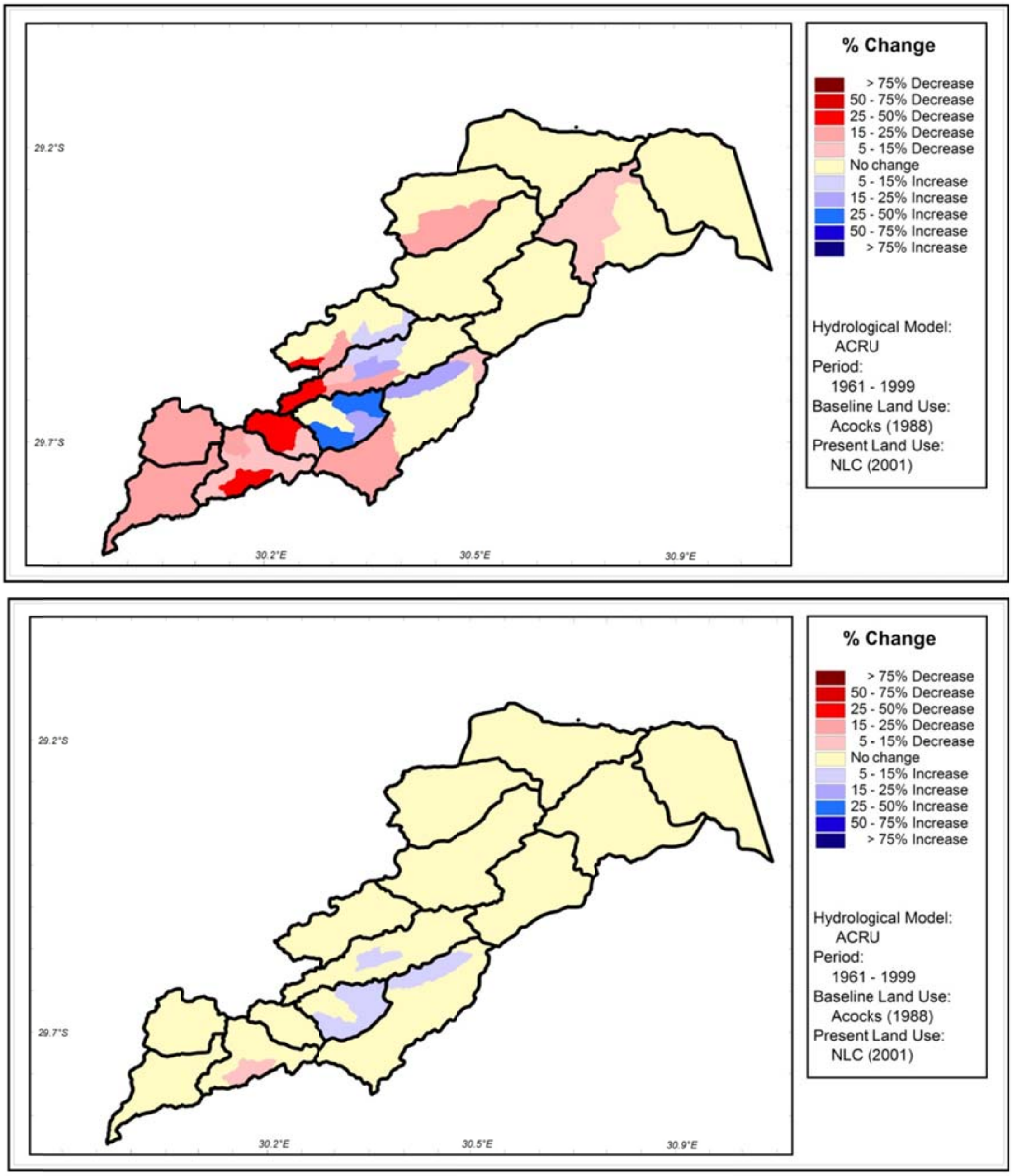

Figure 4.7: Impacts of current land uses in the Luvuvhu catchment on the (a) 10th percentile low flows and (b) 90th percentile high flows (bottom) of accumulated flows in the high flow summer season (D, J, F), relative to the flows under baseline land cover conditions

A further example of the balancing /self-cancelling effect of the accumulation of streamflows generated under different land uses for the Vondo and Nandoni WMUs in the Luvuvhu catchment is shown in Figure 4.8. When comparing the streamflow response of each of the land use units against the baseline land cover for that unit, the impacts of land use are evident. However, as flows from these land use units are routed through the natural land cover and riparian areas of the subcatchments the impacts are dampened. As an example, consider Subcatchment 14. In the degraded natural vegetation, commercial plantation forestry, subsistence agriculture and informal residential units the changes in mean annual streamflow are +4%, -5.9%, +10.6% and +7.1% respectively. However, once the streamflow has been routed through the natural vegetation and riparian land use units the change in mean annual streamflow is only +2.1%. Following the routing of the flows from the subcatchments according to the natural flow paths, the balancing effects of different land uses are even more evident at the WMU scale, where little difference between the streamflows generated under current land uses and those under baseline land cover is evident.

The streamflow at the outlet of a catchment is, *inter alia*, a representation of the accumulation of the impacts of the land uses present within that catchment. The location, for example, of a land use in the headwaters or along the main stem of the river, and nature of the land use changes, for example commercial production afforestation or subsistence agriculture, present within the catchment determine the influence of the land use changes on the streamflow response of the catchment. Furthermore, although the streamflow response at the outlet of a catchment may not necessarily reflect a marked change, there may be significant influences on streamflow at a local scale further upstream due to land use changes. When considering water resources planning, cognizance should therefore be taken not only of the impacts of land use change on the streamflow at the outlet of the catchment or at the WMU scale, but at the local scale as well.

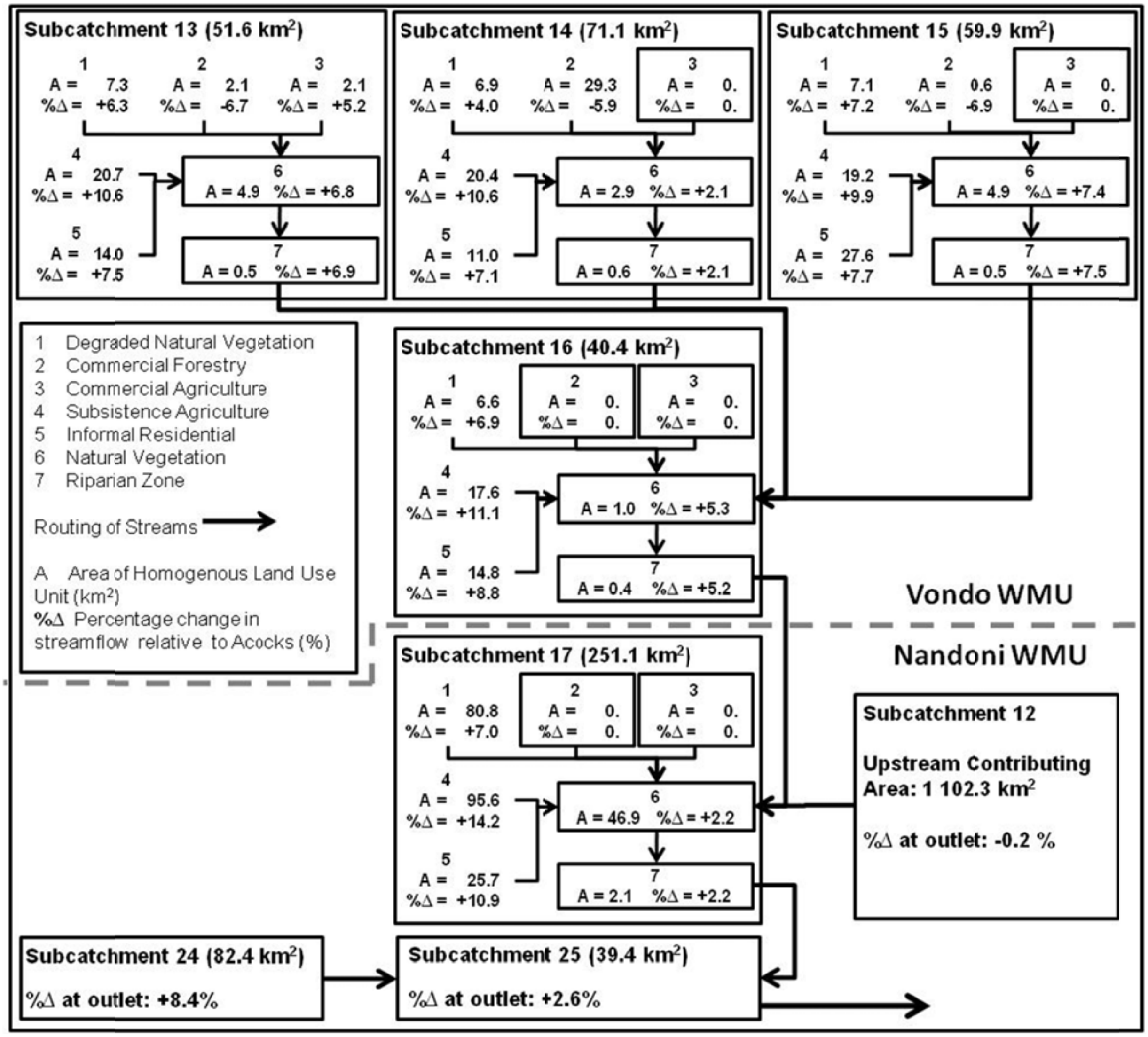

Figure 4.8: Impacts of current land use on mean annual streamflows compared to flows from baseline land cover at a homogeneous land use unit, subcatchment and WMU scales in the Luvuvhu catchment

4.4.3 To what extent do specific land uses have relatively greater impacts on different components of the hydrological response of a catchment?

Different land uses partition rainfall into the components of stormflow, baseflow and evapotranspiration in different ways. Consider four hydrologically important land uses, *viz.* urban areas, degraded areas, commercial production forestry and sugarcane, and how rainfall is partitioned into stormflow and baseflow components under these land uses. Figure 4.9 shows simulated results of the mean monthly ratio of stormflow to total runoff (i.e. stormflow and baseflow combined) for these four hydrologically relevant land uses in comparison to baseline vegetation for a hypothetical subcatchment which contains soils and a climatic regime typical of that of the Mgeni catchment, and where the considered land uses each occupy an equal portion of the subcatchment. Of the streamflow which is generated from an urban land use, and as a result of the high percentage of impervious areas, stormflow makes up more than 80% of the streamflow in wet months, and remains a relatively high proportion during the drier months. The contribution of degraded areas to streamflow is similar to the percentage area of the catchment it occupies (Figure 4.3) and is comparable to natural vegetation. However, the make-up of the streamflow has been significantly altered in that the simulated stormflow component is more than 80% of the streamflow in summer months. This finding agrees with that of Blignaut *et al.* (2010), where degraded areas in the upper Thukela River basin were found to increase stormflows significantly.

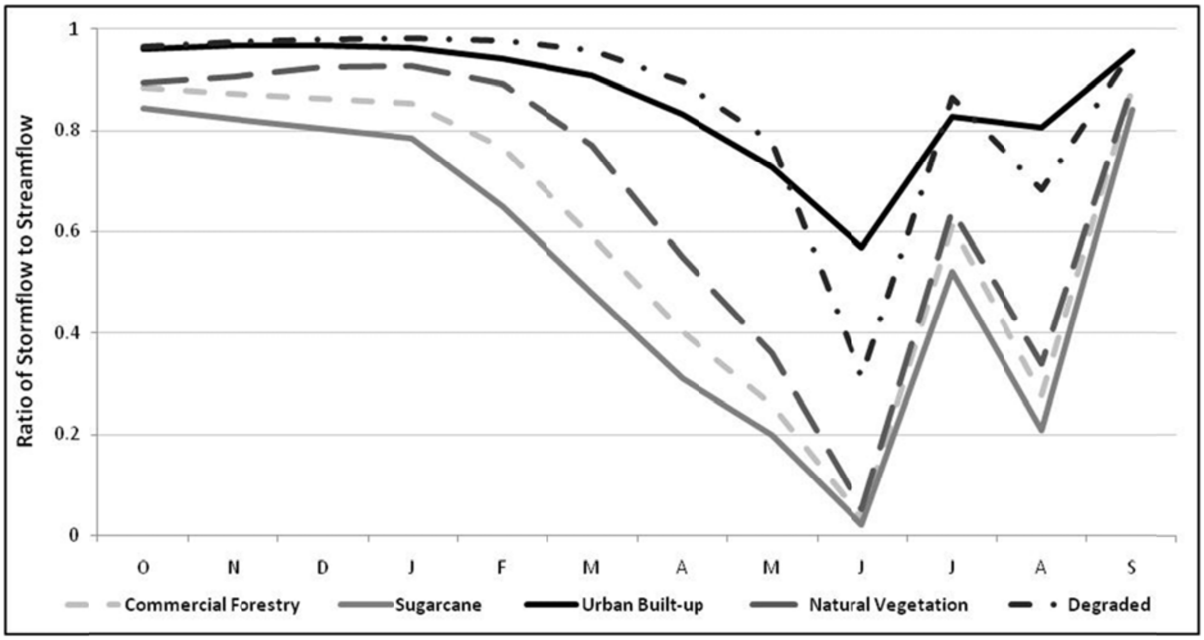

Figure 4.9: Mean monthly ratios of stormflow to total streamflow for commercial plantation forestry, sugarcane, degraded areas, urban areas and natural vegetation in a hypothetical subcatchment of the Mgeni catchment

In comparison to natural vegetation, a smaller portion of rainfall is partitioned to stormflow under commercial plantation forestry and sugarcane mainly because these two land uses have higher interception and initial infiltration rates. This partitioning, however, gives no indication of the volumes of streamflow generated under the different land uses.

Following the above hypothetical case, consider the differences in how baseline land cover and current land uses partition rainfall. This case study is undertaken by evaluating the relationship between the runoff coefficient and mean annual precipitation (MAP), for baseline land cover (Figure 4.10) and current land uses (Figure 4.11). This relationship highlights the effects of individual land uses on the partitioning of rainfall. Under baseline land cover the relationship between the runoff coefficient and MAP is a relatively tight and near-linear scatter (Figure 4.10), implying that a relationship exists in nature between the amount of rainfall received and the runoff generated under natural land cover, while under current land use the overall scatter is near random (Figure 4.11). Under urban and residential land uses the runoff coefficient is up to four times higher than under baseline conditions (Figure 4.11). For commercial production forestry, on the other hand, the runoff coefficient is significantly lower in comparison with that of baseline vegetation.

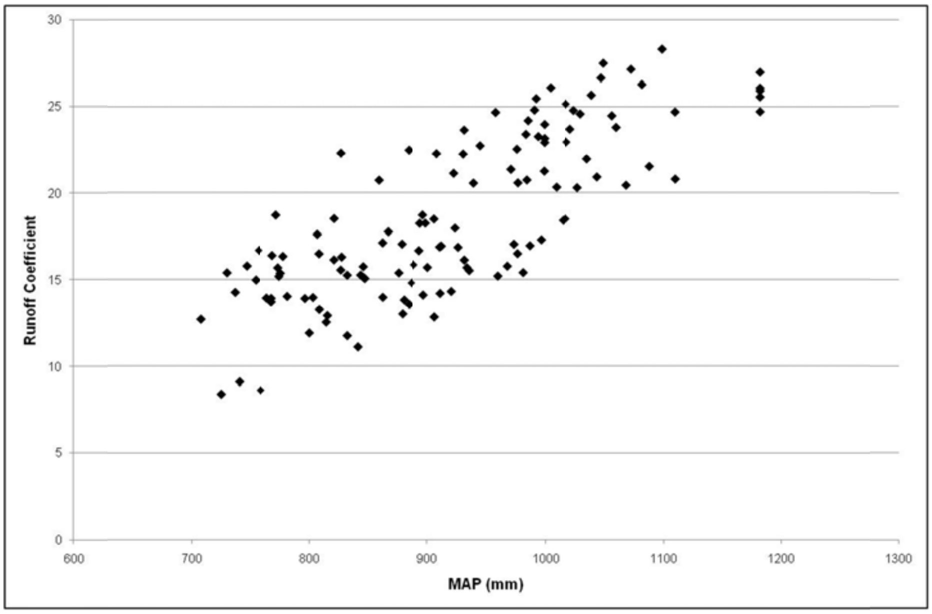

Figure 4.10: Relationship between the runoff coefficient and mean annual precipitation for baseline land cover in the Mgeni catchment

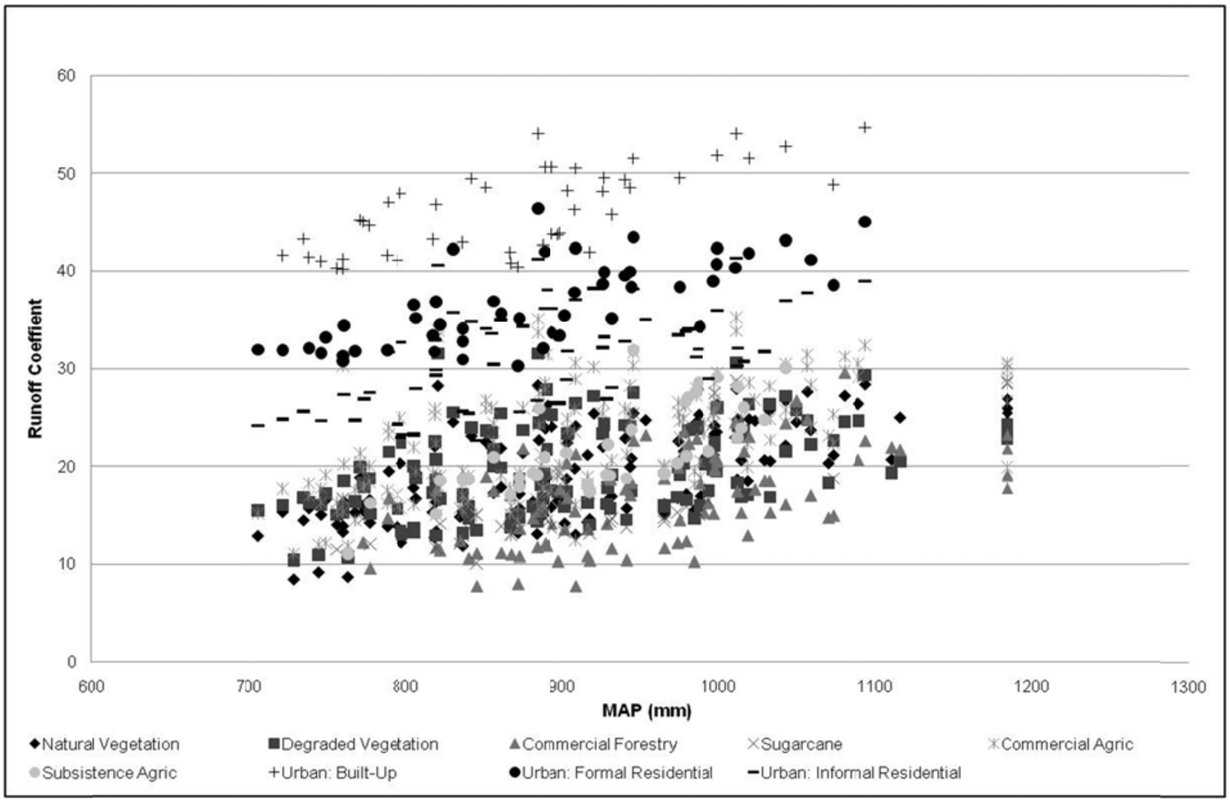

Figure 4.11: Relationship between the runoff coefficient and mean annual precipitation for current land uses in the Mgeni catchment

When compared to baseline vegetation, commercial permanent irrigated agriculture has a significant effect on the total evaporation of the land use unit. Figure 4.12 illustrates the impact of commercial permanent irrigated agriculture on total evaporation (mm) for a typical subcatchment in the winter rainfall Upper Breede catchment. During the summer growing months (October to March) the total evaporation from the commercial irrigated agriculture is substantially higher than that from the natural vegetation it has replaced (Figure 4.12) due to the addition of irrigation from the reservoir which increases available soil moisture for the evaporative process, while the natural vegetation is reliant only on the little rain that falls in that catchment during summer.

During the wet, winter months the total evaporation from the commercial permanent irrigated agriculture still remains higher than that from the natural vegetation, but the differences in evaporative losses between the two land uses are substantially reduced (Figure 4.12). Owing to the impact of commercial permanent irrigated agriculture on total evaporation, the streamflows downstream of the supplying reservoir from this land use unit are substantially decreased in comparison to those from natural vegetation, and these impacts are also evident further downstream at the subcatchment and WMU scales (Figure 4.6).

Land use change does not only influence the total flows, but alters the partitioning of rainfall into stormflows and baseflows. Thus to be able to make holistic and comprehensive decisions water resources planning needs to consider the effects of proposed land use changes not only in terms of impacts on total flows, but also on how the partitioning of rainfall into stormflows and baseflows could be altered, as well as the potential impacts on other components of the hydrological cycle such as evaporation.

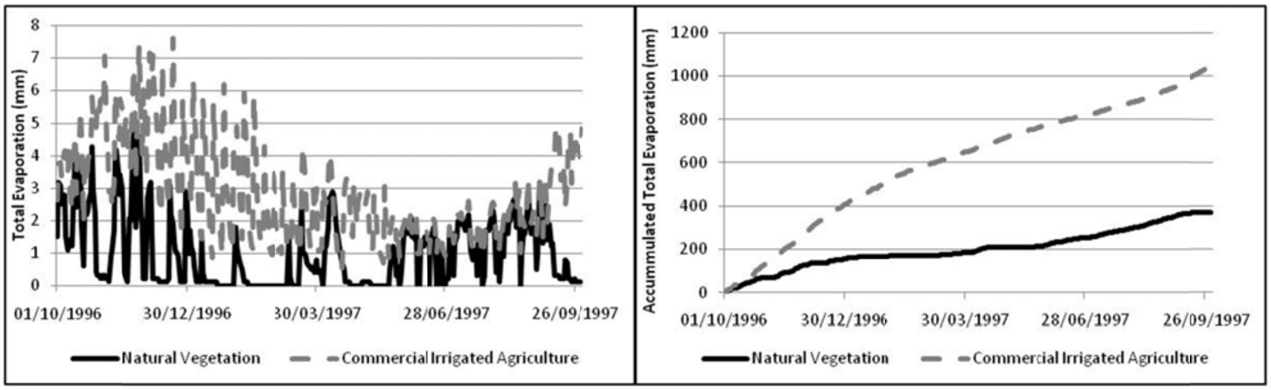

Figure 4.12: Simulated daily total evaporation (mm; left) and accumulated daily total evaporation (mm; right) in a typical subcatchment in the Breede under natural vegetation and commercial permanent irrigated agriculture for a representative hydrological year (1 October 1996 – 30 September 1997)

4.4.4 To what extent are influences of the water engineered system relatively more important in regard to total flows, stormflows and baseflows?

The Mgeni catchment contains four large dams, and numerous farm dams within the middle to upper reaches of the catchment. The water engineered system in the Mgeni catchment plays an important role in the catchment's hydrological response. For this reason examples from the Mgeni catchment are used to illustrate the influence of the water engineered system on total flows as well as on its components of stormflows and baseflows. The reservoirs in the Mgeni catchment have a significant regulating effect on the catchment, as shown in Figure 4.13, in which the 1:10 year low (10th percentile), the median (50th percentile) and the 1:10 year high (90th percentile) accumulated flows at the outlets of the Albert Falls and Inanda WMUs are compared between current land uses and baseline land cover conditions.

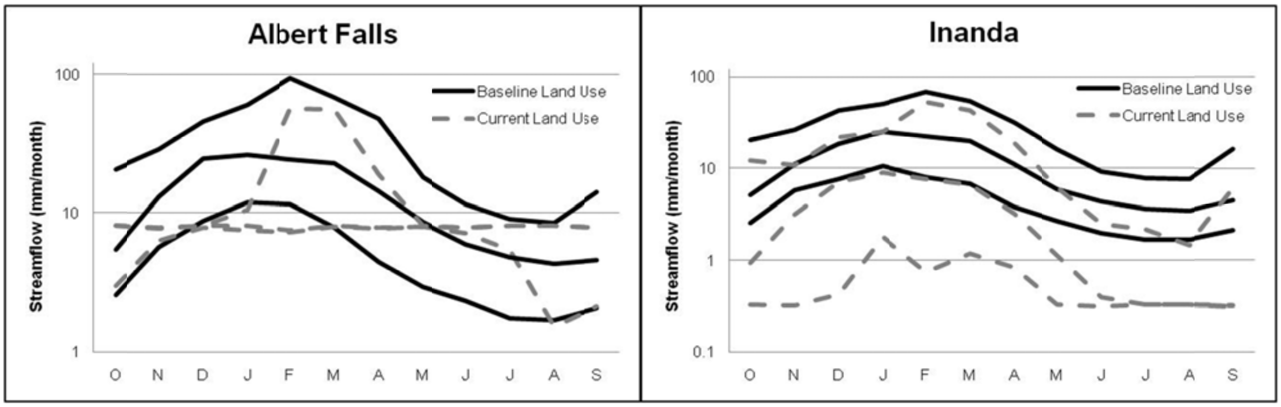

Figure 4.13: One in 10 year high (90th percentile), median (50th percentile) and 1 in 10 year low (10th percentile) monthly accumulated flows at the outlet of the Albert Falls and Inanda WMUs in the Mgeni catchment for baseline land cover (solid lines) and current land use/water engineered system (stippled lines)

The management approach to the reservoirs in the Mgeni catchment is to keep as much water as possible in the upper catchment reservoirs. Midmar dam (upper catchment) supplies water to the Pietermaritzburg and surrounding areas, and a constant release is allowed for downstream environmental maintenance (Still *et al*., 2010). In the case of the Albert Falls dam (middle reaches of the catchment), a constant amount of water is released to the downstream Nagle and Inanda Dams for the supply of water to the Durban metropolitan area (Still *et al*., 2010). Similarly a constant flow is released from the Inanda dam for environmental purposes. The flow releases from the reservoirs are equivalent to the average low flow during the dry months in a drier than average year, which for Albert Falls is equivalent to 5 $m^3.s^{-1}$ and for Inanda Dam 0.5 $m^3.s^{-1}$ (Still *et al*., 2010). At this stage, no environmental flow releases from dams which mimic natural variability have been implemented in the Mgeni Catchment, but there are plans to implement these soon, thus returning some of the natural variability to the river. The flows during the wet months are decreased and dampened owing to the regulating effect of the major reservoirs at the outlets of the two WMUs while flow reversals are evident between the dry and wet months for the median flows, which are reduced due to the accumulative effects of land use upstream and the regulating effect of the reservoirs (Figure 4.13). The high flows, however, especially in the wet months from January to March, are only marginally reduced due to the over-riding effect of the increased high flows due to urbanization in the areas upstream of these WMUs (Figure 4.13). A comparison of the flow duration curves of daily accumulated streamflows for baseline land cover and current land uses at the outlet of the Albert Falls WMU (Figure 4.14) provides further evidence of the regulating effect of reservoirs, with no variation apparent for 80% of the time in the daily accumulated flows which occur under current land uses and which include the effects of dams.

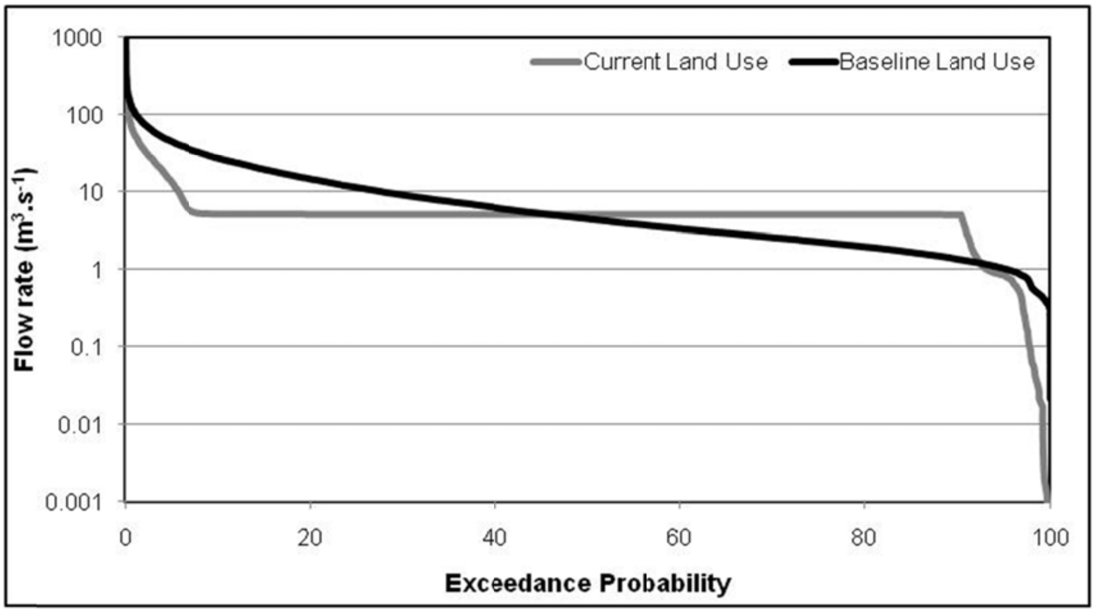

Figure 4.14: Comparison of flow duration curves of daily accumulated streamflows at the outlet of the Albert Falls WMU in the Mgeni catchment for baseline land cover (black line) and current land uses including the water engineered system (grey line)

4.5 Discussion

According to the NLC (2000), 40% of the Mgeni catchment, 38% of the Luvuvhu and 25% of the Upper Breede catchment have been altered from natural vegetation. This percentage change from natural vegetation provides little insight to the resultant impact on hydrological response as the impact of land use change on the hydrological response of a catchment is complex. The location of specific land uses within a catchment has a role in the response of the streamflow of the catchment to that land use change. The contributions of different land uses to the streamflow generated from a catchment is not proportional to the relative area of that land use, and the relative contribution of the land use to the catchment streamflow varies with the mean annual rainfall of the catchment. Furthermore, specific land use changes have a greater impact on different components of the hydrological response of a catchment, for example, urban areas have a greater impact on the stormflow response of a catchment than, for example, subsistence agriculture, while commercial irrigated agriculture has a significant impact on the total evaporation. Added to the complexity introduced by land use changes are the impacts of the water engineered system on the hydrological response of a catchment. In the Mgeni Catchment, for example, reservoirs dampen flow variability and can cause a reversal of the flows between the dry and wet months for both the median and low flows of a catchment when located near the outlet of the catchment.

In this simulation study, both the Mgeni and the Upper Breede catchments showed significant changes in the streamflow at the outlet of the catchments due to land use changes. The Luvuvhu catchment, however, showed no significant changes in the streamflow at the outlet of the catchment even though a greater percentage of the catchment land use has been altered from natural vegetation when compared to the Upper Breede catchment. The changes evident in the Upper Breede catchment are due to the nature of the land use change, viz. commercial irrigated agriculture, and the location of the changes along the main river stem. While in the Luvuvhu catchment, the significant areas of natural vegetation in the middle and lower reaches of the catchment have a balancing/self-correcting effect on the accumulated streamflows. In the context of water resources planning for the Luvuvhu catchment, the threshold beyond which land use changes become hydrologically significant is important to assess when considering future planning. This threshold will be dependent on the nature, scale and location of the land use change. However, with projected changes in climate this threshold point may be reached even if the land use were to remain constant, due to the combined impacts of land use and climate change.

The impacts of land change shown in this paper have been assessed by comparing the current land use (NLC, 2000) to a baseline land cover represented by Acocks' Veld Types (1988). However, by using the Acocks (1988) Veld Types as a baseline, certain uncertainties may be introduced. The broad scale resolution of the Acocks Veld Type (1988) maps is a first source of uncertainty. The natural vegetation is represented by 70 Veld Types mapped at a country scale with little local scale detail. A second source of uncertainty is introduced through the water use parameters associated with the Acocks vegetation. Although these parameters were developed on the basis of a consistent application of key climate related drivers of the cycle of vegetation water use throughout a year and on expert knowledge, there has to date been limited research undertaken to assess the water use of natural vegetation and thus to confirm these values (Jewitt *et al*., 2009). Recently, Mucina and Rutherford (2006) have developed a detailed natural vegetation map for South Africa with sufficient spatial resolution and detail for application in regional and local planning. Given the improved resolution of the Mucina and Rutherford (2006) natural vegetation map, it is recommended that this be assessed for use as the hydrological baseline land cover in South Africa. However, with the uncertainties around the hydrological parameterization of different natural vegetation types remaining, the question raised is whether the differences between the two baselines will be significant enough to alter any assessed impacts of current land uses.

Although hydrological models have drawbacks associated with them due to inherent uncertainties related to both insufficient knowledge of the processes represented, and simplification of processes, in the model, they are useful tools in assessing the impacts of land use on the hydrological response of a complex, operational catchment. In this study the *ACRU* model, which is conceptualized to adequately represent hydrological processes and is sensitive to land use changes, proved to be a useful tool to assess the impacts of land use change on the hydrological responses of the Mgeni, Upper Breede and Luvuvhu catchments. When considering any hydrological impacts of land use change, assessments need to consider the local scale where the individual impacts of a land use change may be evident, the progression of the impacts of land use changes through the catchment, and the impacts at the catchment scale where the accumulation of the effects of the land use change through the catchment are evident. Observed streamflow data are generally only available for a few gauged sites within a catchment, and often for short time periods. These gauged sites may not correspond spatially with where, or temporally with when, the land use change occurred nor do they allow the impacts of land use change at various scales to be assessed. A further temporal scale benefit of using a hydrological model is the extension of short time series of observed streamflow data where a longer time series of rainfall data exists. Thus, hydrological modelling studies using a model whose ability to simulate hydrological responses to land use change has been demonstrated, are valuable tools in water resources planning to determine potential impacts of land use change at various spatial scales and to use in land use change scenario modelling.

A further layer of complexity in managing the impacts of land use change on the water resources of a catchment will be introduced with a changing climate. Land use changes have been shown to have significant impacts on the hydrological responses of a catchment, and together with a changing climate will form a complex and interactive system, whereby both human influences and climate changes can perturb land use patterns, and changes in land use can, in turn, can feed back to influence the climate system (Turner *et al*., 1995), with both impacting on hydrological responses. Thus, an assessment of the combined impacts of land use change and climate change is needed. Effective water resources management now, and in the future, needs to take account of, and understand the interactions between land use change, climate change and hydrological responses.

4.6 Conclusion

The results shown contextualize the understanding of the impacts of land use on the hydrological response in three complex, operational South African catchments in a water scarce country where comprehensive, adaptive water resources planning is essential to ensuring adequate water resources. Further emphasis is given to the importance of the integration of land use planning into water resources planning. To adequately manage water resources the impacts of land use change needs to be assessed at various scales. Furthermore, the spatial progression of streamflow through the catchment should be included in the assessment. At the local scale the effects of land use on the hydrological response are easily distinguishable, however, at the subcatchment scale the effects of a single land use change are already difficult to distinguish due to the balancing or amplification effects of the land uses present within the subcatchment. At the WMU scale and catchment scale the effects become even more difficult to distinguish. However, it is at this scale that the accumulated streamflow reflects the combined effects of the land use changes. Each catchment is unique with its own complexities, feed forwards and feed backs, thus each catchment will have a unique threshold of where land use change begins to have a significant influence of the hydrological response. With climate change, the full integration of land use planning into water resources planning becomes even more critical. Observed data to support such studies are limited and hydrological models do, and will continue to, form a key component of any such study. This study has illustrated the benefits of applying a daily time-step, land use sensitive model on which a high level of confidence in its ability to provide realistic results exists, to better understand the complex interactions of land use change at different spatial and temporal scales. It thus provides a sound basis for similar studies in other catchments as well as studies in which the relative importance of both climate and land use changes are to be assessed.

4.7 Acknowledgements

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4.9 Appendix

Appendix 4.A: Monthly values of water use coefficients, canopy interception per rain day, root mass distribution in the topsoil, coefficient of initial abstractions and index of suppression of soil water evaporation by a litter/mulch layer, for the land uses occurring in the Mgeni, Luvuvhu and Upper Breede catchment (Schulze, 2004)

		Monthly values											
Land Use	**Variable**	**Jan**	**Feb**	**Mar**	**Apr**	**May**	**Jun**	**Jul**	**Aug**	**Sep**	**Oct**	**Nov**	**Dec**
Commercial Forestry													
- *Acacia*	CAY	0.90	0.90	0.90	0.88	0.85	0.86	0.89	0.90	0.92	0.92	0.90	0.90
	VEGINT	2.00	2.00	2.00	2.00	1.90	1.85	1.85	1.85	1.90	1.95	2.00	2.00
	ROOTA	0.83	0.83	0.83	0.83	0.83	0.83	0.83	0.83	0.83	0.83	0.83	0.83
	COAIM	0.25	0.25	0.25	0.30	0.30	0.30	0.30	0.30	0.30	0.30	0.25	0.25
	PCSUCO	100	100	100	100	100	100	100	100	100	100	100	100
- *Eucalyptus*	CAY	0.95	0.95	0.95	0.95	0.95	0.95	0.95	0.95	0.95	0.95	0.95	0.95
	VEGINT	2.50	2.50	2.50	2.50	2.50	2.50	2.50	2.50	2.50	2.50	2.50	2.50
	ROOTA	0.65	0.65	0.65	0.65	0.65	0.65	0.65	0.65	0.65	0.65	0.65	0.65
	COAIM	0.35	0.35	0.35	0.35	0.35	0.35	0.35	0.35	0.35	0.35	0.35	0.35
	PCSUCO	100	100	100	100	100	100	100	100	100	100	100	100
- *Pinus*	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
	VEGINT	3.50	3.50	3.50	3.50	3.50	3.50	3.50	3.50	3.50	3.50	3.50	3.50
	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
	COAIM	0.35	0.35	0.35	0.35	0.35	0.35	0.35	0.35	0.35	0.35	0.35	0.35
	PCSUCO	100	100	100	100	100	100	100	100	100	100	100	100
Agriculture													
- Dryland temporary commercial agriculture	CAY	0.99	0.84	0.30	0.30	0.30	0.30	0.30	0.30	0.30	0.30	0.48	0.78
	VEGINT	1.40	1.40	1.40	1.20	1.00	1.00	1.00	0.80	0.00	0.00	0.80	1.40
	ROOTA	0.78	0.91	1.00	1.00	1.00	1.00	1.00	1.00	1.00	0.92	0.79	0.74
	COAIM	0.20	0.20	0.25	0.30	0.30	0.30	0.30	0.30	0.30	0.35	0.30	0.25
	PCSUCO	65.0	65.0	65.0	65.0	65.0	65.0	65.0	65.0	65.0	65.0	65.0	65.0
- Irrigated temporary commercial agriculture	CAY	0.70	0.70	0.70	0.70	0.70	0.70	0.70	0.70	0.70	0.70	0.70	0.70
	VEGINT	1.40	1.40	1.40	1.20	1.00	1.00	1.00	0.80	0.00	0.00	0.80	1.40
	ROOTA	0.78	0.91	1.00	1.00	1.00	1.00	1.00	1.00	1.00	0.92	0.79	0.74
	COAIM	0.20	0.20	0.25	0.30	0.30	0.30	0.30	0.30	0.30	0.35	0.30	0.25
	PCSUCO	65.0	65.0	65.0	65.0	65.0	65.0	65.0	65.0	65.0	65.0	65.0	65.0
- Irrigated permanent commercial agriculture	CAY	0.80	0.80	0.80	0.70	0.60	0.50	0.50	0.50	0.60	0.70	0.80	0.80
	PCSUCO	65.0	65.0	65.0	65.0	65.0	65.0	65.0	65.0	65.0	65.0	65.0	65.0
	VEGINT	1.40	1.40	1.40	1.40	1.20	1.00	1.00	1.20	1.30	1.40	1.40	1.40
	ROOTA	0.80	0.80	0.80	0.90	1.00	1.00	1.00	1.00	0.90	0.90	0.80	0.80
	COAIM	0.30	0.30	0.30	0.30	0.30	0.30	0.30	0.30	0.30	0.30	0.30	0.30
	PCSUCO	65.0	65.0	65.0	65.0	65.0	65.0	65.0	65.0	65.0	65.0	65.0	65.0
- Commercial Sugarcane	CAY (inland)	0.83	0.83	0.83	0.83	0.83	0.83	0.83	0.83	0.83	0.83	0.83	0.83
	CAY (coastal)	0.86	0.86	0.86	0.86	0.86	0.86	0.86	0.86	0.86	0.86	0.86	0.86

	VEGINT (inland)	1.70	1.70	1.70	1.70	1.70	1.70	1.70	1.70	1.70	1.70	1.70	1.70
	VEGINT (coastal)	1.90	1.90	1.90	1.90	1.90	1.90	1.90	1.90	1.90	1.90	1.90	1.90
	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
	COAIM	0.35	0.35	0.35	0.35	0.35	0.35	0.35	0.35	0.35	0.35	0.35	0.35
	PCSUCO	100	100	100	100	100	100	100	100	100	100	100	100
- Pasture grass	CAY	0.55	0.55	0.55	0.55	0.35	0.20	0.20	0.20	0.35	0.45	0.55	0.55
	VEGINT	0.70	0.70	0.70	0.70	0.70	0.70	0.70	0.70	0.70	0.70	0.70	0.70
	ROOTA	0.95	0.95	0.95	0.95	0.95	1.00	1.00	1.00	0.95	0.95	0.95	0.95
	COAIM	0.15	0.15	0.15	0.25	0.30	0.30	0.30	0.30	0.30	0.30	0.20	0.15
	PCSUCO	64.0	64.0	64.0	64.0	64.0	64.0	64.0	64.0	64.0	64.0	64.0	64.0
- Subsistence agriculture	CAY	0.80	0.70	0.30	0.30	0.30	0.30	0.30	0.30	0.30	0.30	0.35	0.60
	VEGINT	1.00	1.00	0.60	0.50	0.50	0.50	0.50	0.50	0.50	0.00	0.50	0.80
	ROOTA	0.74	0.78	0.91	1.00	1.00	1.00	1.00	1.00	1.00	1.00	0.92	0.79
	COAIM	0.20	0.20	0.25	0.30	0.30	0.30	0.20	0.20	0.20	0.35	0.30	0.25
	PCSUCO	50.0	50.0	50.0	50.0	50.0	50.0	50.0	50.0	50.0	50.0	50.0	50.0
Urbanised Areas													
- Built-up (CBD, industrial areas)	CAY (inland)	0.70	0.70	0.70	0.60	0.30	0.30	0.30	0.30	0.45	0.65	0.70	0.70
	CAY (coastal)	0.80	0.80	0.80	0.70	0.50	0.50	0.50	0.50	0.55	0.75	0.80	0.80
	VEGINT (inland)	1.40	1.40	1.40	1.40	1.20	1.20	1.20	1.20	1.30	1.40	1.40	1.40
	VEGINT (coastal)	1.60	1.60	1.60	1.60	1.40	1.40	1.40	1.40	1.50	1.60	1.60	1.60
	ROOTA	0.80	0.80	0.80	0.90	1.00	1.00	1.00	1.00	0.95	0.80	0.80	0.80
	COAIM	0.15	0.15	0.20	0.25	0.30	0.30	0.30	0.30	0.30	0.25	0.20	0.15
	PCSUCO	50.0	50.0	50.0	50.0	50.0	50.0	50.0	50.0	50.0	50.0	50.0	50.0
- Formal Residential (Suburbs, flats, includes educational areas)	CAY (inland)	0.80	0.80	0.70	0.60	0.40	0.40	0.40	0.40	0.60	0.70	0.80	0.80
	CAY (coastal)	0.80	0.80	0.80	0.70	0.60	0.50	0.50	0.50	0.50	0.60	0.80	0.80
	VEGINT (inland)	1.40	1.40	1.30	1.20	1.10	1.00	1.00	1.00	1.00	1.30	1.40	1.40
	VEGINT (coastal)	1.50	1.50	1.50	1.50	1.30	1.20	1.20	1.20	1.20	1.30	1.50	1.50
	ROOTA	0.85	0.85	0.85	0.90	0.95	0.95	0.95	0.95	0.90	0.85	0.85	0.85
	COAIM	0.20	0.20	0.20	0.30	0.30	0.30	0.30	0.30	0.30	0.30	0.25	0.20
	PCSUCO	60.0	60.0	60.0	60.0	60.0	60.0	60.0	60.0	60.0	60.0	60.0	60.0
- Informal Residential	CAY	0.65	0.65	0.65	0.55	0.30	0.20	0.20	0.20	0.30	0.50	0.55	0.65
- Urban & Rural Informal	VEGINT	1.50	1.50	1.50	1.50	1.50	1.50	1.50	1.50	1.50	1.50	1.50	1.50
(differentiation in impervious areas)	ROOTA	0.90	0.90	0.90	0.94	0.98	1.00	1.00	1.00	1.00	0.95	0.90	0.90
	COAIM	0.15	0.15	0.15	0.20	0.30	0.30	0.30	0.30	0.30	0.30	0.20	0.15
	PCSUCO	64.0	64.0	64.0	64.0	64.0	64.0	64.0	64.0	64.0	64.0	64.0	64.0
	CAY	0.55	0.55	0.55	0.45	0.25	0.20	0.20	0.20	0.40	0.45	0.55	0.55
Degraded Natural Vegetation	VEGINT	0.80	0.80	0.80	0.70	0.60	0.60	0.60	0.60	0.65	0.75	0.80	0.80
	ROOTA	0.90	0.90	0.90	0.95	0.95	1.00	1.00	1.00	0.95	0.90	0.90	0.90
	COAIM	0.10	0.10	0.10	0.15	0.15	0.20	0.20	0.20	0.20	0.15	0.10	0.10
	PCSUCO	10.0	10.0	10.0	10.0	10.0	10.0	10.0	10.0	10.0	10.0	10.0	10.0
	CAY	0.90	0.90	0.90	0.90	0.90	0.90	0.90	0.90	0.90	0.90	0.90	0.90
Alien Vegetation	VEGINT	1.70	1.70	1.70	1.70	1.70	1.70	1.70	1.70	1.70	1.70	1.70	1.70
	ROOTA	0.70	0.70	0.70	0.70	0.70	0.70	0.70	0.70	0.70	0.70	0.70	0.70
	COAIM	0.35	0.35	0.35	0.35	0.35	0.35	0.35	0.35	0.35	0.35	0.35	0.35
	PCSUCO	85.0	85.0	85.0	85.0	85.0	85.0	85.0	85.0	85.0	85.0	85.0	85.0

Appendix 4.B: Monthly values of water use coefficients, canopy interception per rainday, root mass distribution in the topsoil, coefficient of initial abstractions and index of suppression of soil water evaporation by a litter/mulch layer, for the Acocks Veld Types (1988) occurring in the Mgeni, Upper Breede and Luvuvhu catchment (Schulze, 2004)

		Monthly values											
Acocks Veld Type	**Variable**	**Jan**	**Feb**	**Mar**	**Apr**	**May**	**Jun**	**Jul**	**Aug**	**Sep**	**Oct**	**Nov**	**Dec**
Coastal Forest & Thornveld, Mgeni Catchment	CAY	0.85	0.85	0.85	0.85	0.75	0.65	0.65	0.75	0.85	0.85	0.85	0.85
	VEGINT	3.10	3.10	3.10	3.10	2.50	2.00	2.00	2.50	3.10	3.10	3.10	3.10
	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
	COAIM	0.30	0.30	0.30	0.30	0.30	0.30	0.30	0.30	0.30	0.30	0.30	0.30
	PCSUCO	100	100	100	100	100	100	100	100	100	100	100	100
Highland & Dohne Sourveld, Mgeni Catchment	CAY	0.70	0.70	0.70	0.50	0.30	0.20	0.20	0.20	0.50	0.65	0.70	0.70
	VEGINT	1.60	1.60	1.60	1.40	1.20	1.00	1.00	1.00	1.3	1.60	1.60	1.60
	ROOTA	0.90	0.90	0.90	0.95	1.00	1.00	1.00	1.00	0.95	0.90	0.90	0.90
	COAIM	0.15	0.15	0.25	0.30	0.30	0.30	0.30	0.30	0.30	0.30	0.2	0.15
	PCSUCO	73.4	73.4	73.4	73.4	73.4	73.4	73.4	73.4	73.4	73.4	73.4	73.4
Natal Mist Belt 'Ngongoniveld, Mgeni Catchment	CAY	0.70	0.70	0.70	0.50	0.35	0.25	0.20	0.20	0.55	0.70	0.70	0.70
	VEGINT	1.50	1.50	1.50	1.30	1.10	1.10	1.10	1.10	1.40	1.50	1.50	1.50
	ROOTA	0.90	0.90	0.90	0.94	0.96	1.00	1.00	1.00	0.95	0.90	0.90	0.90
	COAIM	0.15	0.15	0.20	0.30	0.30	0.30	0.30	0.30	0.30	0.30	0.2	0.15
	PCSUCO	73.4	73.4	73.4	73.4	73.4	73.4	73.4	73.4	73.4	73.4	73.4	73.4
Ngongoni Veld – Zululand, Mgeni Catchment	CAY	0.70	0.70	0.70	0.65	0.55	0.50	0.50	0.55	0.60	0.65	0.65	0.70
	VEGINT	1.40	1.40	1.40	1.40	1.30	1.20	1.20	1.30	1.40	1.40	1.40	1.40
	ROOTA	0.90	0.90	0.90	0.90	0.95	0.95	0.95	0.95	0.90	0.90	0.90	0.90
	COAIM	0.20	0.20	0.25	0.30	0.30	0.30	0.30	0.30	0.30	0.30	0.25	0.20
	PCSUCO	73.4	73.4	73.4	73.4	73.4	73.4	73.4	73.4	73.4	73.4	73.4	73.4
Southern Tall Grassveld, Mgeni Catchment	CAY	0.75	0.75	0.75	0.5	0.40	0.20	0.20	0.20	0.55	0.70	0.75	0.75
	VEGINT	1.60	1.60	1.60	1.60	1.50	1.40	1.40	1.40	1.50	1.60	1.60	1.60
	ROOTA	0.90	0.90	0.90	0.95	0.95	1.00	1.00	1.00	0.95	0.90	0.90	0.90
	COAIM	0.15	0.15	0.2	0.30	0.30	0.30	0.30	0.30	0.30	0.30	0.20	0.15
	PCSUCO	82.3	82.3	82.3	82.3	82.3	82.3	82.3	82.3	82.3	82.3	82.3	82.3
Valley Bushveld, Mgeni Catchment	CAY	0.75	0.75	0.75	0.65	0.55	0.20	0.20	0.40	0.60	0.75	0.75	0.75
	VEGINT	2.50	2.50	2.50	2.20	2.00	2.00	1.90	1.90	2.20	2.50	2.50	2.50
	ROOTA	0.80	0.80	0.80	0.85	0.90	1.00	1.00	0.95	0.90	0.80	0.80	0.80
	COAIM	0.20	0.20	0.25	0.30	0.30	0.30	0.30	0.30	0.30	0.25	0.20	0.20
	PCSUCO	82.3	82.3	82.3	82.3	82.3	82.3	82.3	82.3	82.3	82.3	82.3	82.3
Coastal Rhenosterbosveld Upper Breede Catchment	CAY	0.40	0.40	0.40	0.45	0.50	0.50	0.50	0.50	0.50	0.45	0.40	0.40
	VEGINT	0.80	0.80	0.80	1.00	1.20	1.20	1.20	1.20	1.00	0.80	0.80	0.80
	ROOTA	0.95	0.95	0.95	0.90	0.90	0.90	0.90	0.90	0.95	0.95	0.95	0.95

	COAIM	0.30	0.30	0.30	0.30	0.30	0.30	0.30	0.30	0.30	0.30	0.30	0.30
	PCSUCO	37.8	37.8	37.8	37.8	37.8	37.8	37.8	37.8	37.8	37.8	37.8	37.8
Macchia	CAY	0.45	0.45	0.50	0.60	0.60	0.60	0.60	0.60	0.60	0.55	0.50	0.45
Upper Breede Catchment	VEGINT	1.00	1.00	1.10	1.20	1.20	1.20	1.20	1.20	1.10	1.10	1.00	1.00
	ROOTA	0.80	0.80	0.80	0.80	0.80	0.80	0.80	0.80	0.80	0.80	0.80	0.80
	COAIM	0.30	0.30	0.30	0.30	0.30	0.30	0.30	0.30	0.30	0.30	0.30	0.30
	PCSUCO	55.6	55.6	55.6	55.6	55.6	55.6	55.6	55.6	55.6	55.6	55.6	55.6
Mountain Rhenosterbosveld	CAY	0.30	0.30	0.30	0.30	0.50	0.40	0.30	0.30	0.30	0.30	0.30	0.30
Upper Breede Catchment	VEGINT	0.30	0.30	0.30	0.30	0.30	0.30	0.30	0.30	0.30	0.30	0.30	0.30
	ROOTA	0.80	0.80	0.80	0.80	0.90	1.00	1.00	1.00	0.90	0.80	0.80	0.80
	COAIM	0.30	0.30	0.30	0.30	0.30	0.30	0.30	0.30	0.30	0.30	0.30	0.30
	PCSUCO	37.8	37.8	37.8	37.8	37.8	37.8	37.8	37.8	37.8	37.8	37.8	37.8
Arid Lowveld	CAY	0.80	0.75	0.60	0.50	0.45	0.40	0.40	0.40	0.40	0.50	0.75	0.80
Luvuvhu Catchment	VEGINT	2.10	2.10	2.10	2.00	1.90	1.80	1.80	1.80	1.90	2.00	2.10	2.10
	ROOTA	0.80	0.80	0.80	0.85	0.90	0.90	0.90	0.90	0.85	0.80	0.80	0.80
	COAIM	0.15	0.15	0.25	0.30	0.30	0.30	0.30	0.30	0.30	0.30	0.20	0.15
	PCSUCO	91.2	91.2	91.2	91.2	91.2	91.2	91.2	91.2	91.2	91.2	91.2	91.2
Arid Sweet Bushveld	CAY	0.75	0.60	0.50	0.45	0.35	0.30	0.20	0.20	0.40	0.55	0.65	0.75
Luvuvhu Catchment	VEGINT	1.60	1.60	1.60	1.50	1.30	1.20	1.10	1.10	1.20	1.40	1.60	1.60
	ROOTA	0.80	0.80	0.80	0.85	0.90	0.95	1.00	1.00	0.95	0.90	0.80	0.80
	COAIM	0.15	0.15	0.20	0.30	0.30	0.30	0.30	0.30	0.30	0.30	0.20	0.15
	PCSUCO	82.3	82.3	82.3	82.3	82.3	82.3	82.3	82.3	82.3	82.3	82.3	82.3
Mopani Veld	CAY	0.75	0.55	0.50	0.40	0.40	0.40	0.40	0.40	0.40	0.50	0.60	0.75
Luvuvhu Catchment	VEGINT	1.80	1.60	1.50	1.50	1.50	1.40	1.30	1.30	1.30	1.50	1.70	1.80
	ROOTA	0.80	0.80	0.80	0.85	0.90	0.90	0.90	0.90	0.85	0.80	0.80	0.80
	COAIM	0.15	0.15	0.20	0.30	0.30	0.30	0.30	0.30	0.30	0.30	0.20	0.15
	PCSUCO	82.3	82.3	82.3	82.3	82.3	82.3	82.3	82.3	82.3	82.3	82.3	82.3
Mixed Bushveld	CAY	0.75	0.75	0.65	0.55	0.40	0.20	0.20	0.30	0.55	0.60	0.75	0.75
Luvuvhu Catchment	VEGINT	2.60	2.60	2.40	2.20	2.00	2.00	2.00	2.20	2.40	2.40	2.60	2.60
	ROOTA	0.80	0.80	0.80	0.85	0.90	1.00	1.00	1.00	0.90	0.80	0.80	0.80
	COAIM	0.15	0.15	0.20	0.30	0.30	0.30	0.30	0.30	0.30	0.30	0.20	0.15
	PCSUCO	82.3	82.3	82.3	82.3	82.3	82.3	82.3	82.3	82.3	82.3	82.3	82.3
North-Eastern Mountain Sourveld	CAY	0.75	0.75	0.75	0.60	0.50	0.25	0.25	0.25	0.50	0.70	0.70	0.75
Luvuvhu Catchment	VEGINT	2.60	2.60	2.60	2.40	2.20	2.00	2.00	2.00	2.20	2.60	2.60	2.60
	ROOTA	0.80	0.80	0.80	0.85	0.90	1.00	1.00	1.00	0.87	0.80	0.80	0.80
	COAIM	0.20	0.20	0.25	0.30	0.30	0.30	0.30	0.30	0.30	0.30	0.25	0.20
	PCSUCO	82.3	82.3	82.3	82.3	82.3	82.3	82.3	82.3	82.3	82.3	82.3	82.3
Lowveld Sour Bushveld	CAY	0.75	0.75	0.75	0.70	0.65	0.60	0.55	0.55	0.60	0.75	0.75	0.75
Luvuvhu Catchment	VEGINT	2.50	2.50	2.50	2.40	2.20	2.00	2.00	2.20	2.40	2.50	2.50	2.50
	ROOTA	0.80	0.80	0.80	0.85	0.85	0.90	0.90	0.90	0.85	0.80	0.80	0.80
	COAIM	0.15	0.15	0.20	0.30	0.30	0.30	0.30	0.30	0.30	0.30	0.20	0.15

	PCSUCO	82.3	82.3	82.3	82.3	82.3	82.3	82.3	82.3	82.3	82.3	82.3	82.3
Sourish Mixed Bushveld	CAY	0.75	0.75	0.75	0.60	0.45	0.20	0.20	0.20	0.55	0.70	0.75	0.75
Luvuvhu Catchment	VEGINT	2.70	2.70	2.60	2.20	2.00	2.00	2.00	2.00	2.20	2.50	2.70	2.70
	ROOTA	0.80	0.80	0.80	0.85	0.90	1.00	1.00	0.90	0.85	0.80	0.80	0.80
	COAIM	0.15	0.15	0.20	0.30	0.30	0.30	0.30	0.30	0.30	0.30	0.20	0.15
	PCSUCO	82.3	82.3	82.3	82.3	82.3	82.3	82.3	82.3	82.3	82.3	82.3	82.3
Sour Bushveld	CAY	0.75	0.75	0.75	0.60	0.45	0.20	0.20	0.20	0.55	0.70	0.75	0.75
Luvuvhu Catchment	VEGINT	2.70	2.70	2.60	2.20	2.00	2.00	2.00	2.00	2.20	2.50	2.70	2.70
	ROOTA	0.80	0.80	0.80	0.85	0.90	1.00	1.00	0.90	0.85	0.80	0.80	0.80
	COAIM	0.15	0.15	0.20	0.30	0.30	0.30	0.30	0.30	0.30	0.25	0.20	0.15
	PCSUCO	82.3	82.3	82.3	82.3	82.3	82.3	82.3	82.3	82.3	82.3	82.3	82.3

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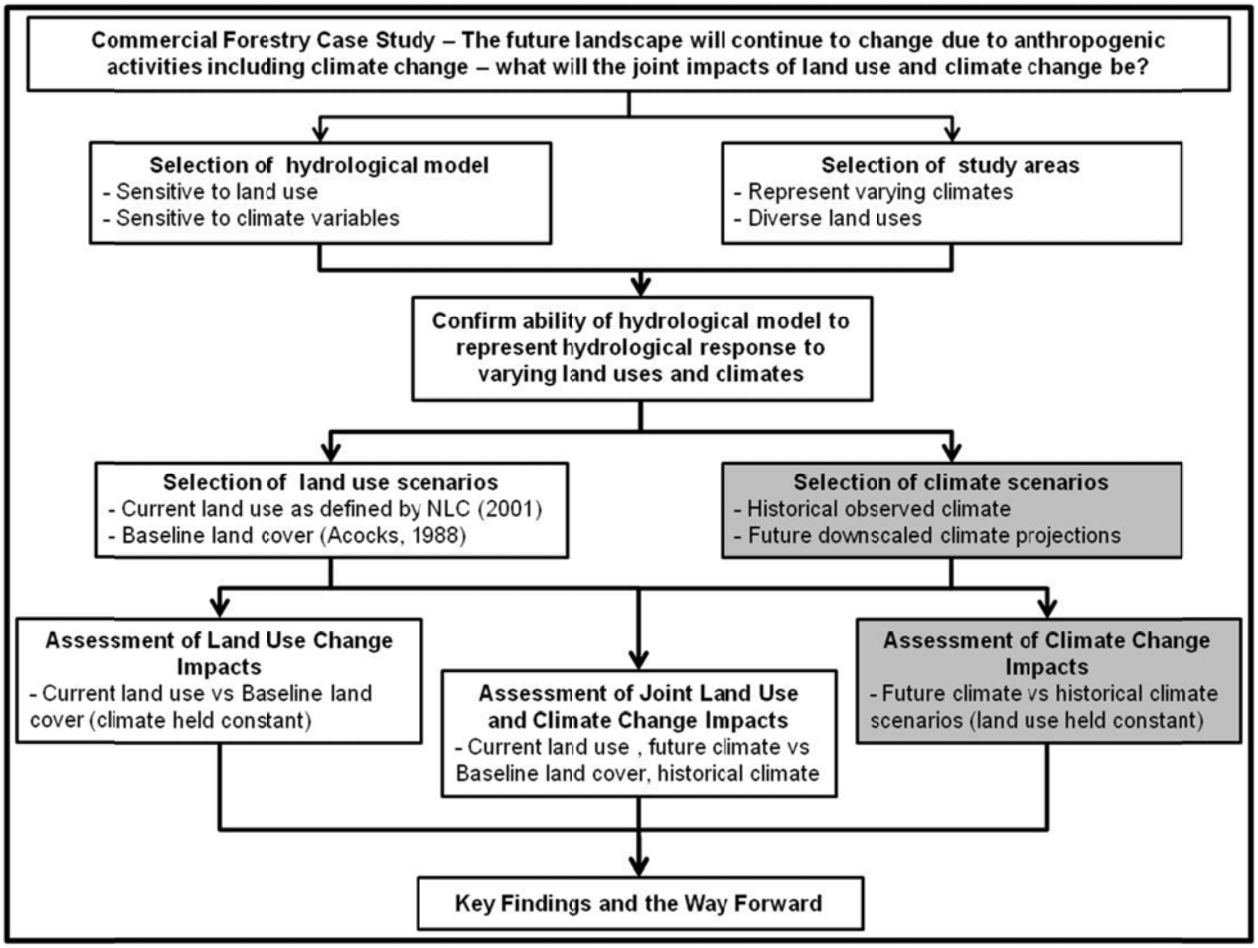
Lead in to Chapter 5

With the ability of the hydrological model to represent hydrological responses under varying land uses and climates confirmed (Chapter 3), and an improved understanding of the complex interactions between hydrological responses and land use gained (Chapter 4), the objective of Chapter 5 was to assess the impacts of climate change on the streamflow responses of the selected study areas at a timeframe appropriate to assist and inform water resources planning and management (as highlighted in the figure below).



5. IMPACTS OF CLIMATE CHANGE ON HYDROLOGICAL RESPONSES OF THREE DIVERSE SOUTH AFRICAN CATCHMENTS[7]

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Abstract

Climate change will be an additional stressor on the already highly stressed water resources of southern Africa, a region which is considered to be at high risk to the impacts of climate change. To date hydrological climate change impact assessments for South Africa have only considered the regional or national scale. This study assesses the impacts of climate change on hydrological response at the catchment scale at a timeframe appropriate to inform water resources planning and management.

The selected catchments were the semi-arid sub-tropical Luvuvhu, the sub-humid Mgeni and the winter rainfall Upper Breede. Five plausible future climate projections from three coupled atmosphere-ocean global climate models covering three SRES emissions scenarios which were downscaled with the RCA3 regional climate model and adjusted using the distribution-based scaling (DBS) approach for bias correction were used as climate input (1961 – 2050) to the daily ACRU agrohydrological model. To assess the impacts of climate change on the hydrological response of the catchments, the hydrological response simulated under these five future projections applied to a baseline land cover scenario was compared to historical climate applied to the same baseline land cover scenario.

No consistent direction of change was evident in the Mgeni and Luvuvhu catchments. However decreases in rainfall resulting in streamflow decreases were evident for all five scenarios for the

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[7] Warburton, M.L., Schulze, R.E., Jewitt, G.P.W., Graham, L.P. and Yang, W. 2012. Impacts of climate change on hydrological responses of three diverse South African catchments. *Submitted to WaterSA*.

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Upper Breede. Lack of consensus and uncertainty in climate change impacts on hydrological response should be seen as a stimulus to improve the understanding processes, and to develop resilient and adaptive water management strategies.

5.1 Introduction

Southern Africa experiences a highly variable climate (Schulze 1997) which ranges from desert and semi-desert regions in the west to humid, sub-tropical regions along the wetter eastern seaboard of the country. The mean annual precipitation (MAP) for the country of 480 mm is well below the world average of 860 mm, with the potential evaporation exceeding rainfall over approximately 90 % of the area (Schulze 1997). Consequently, South Africa's water resources are limited as well as being distributed unevenly.

In order to meet the development demands of the country, the natural river flow has been significantly altered both in quantity and quality. These alterations are attributable to the construction of reservoirs, diversion structures, inter-basin transfers, and abstractions for domestic, industrial and agricultural use and associated return flows, as well as resulting from land use changes ranging from plantation forestry to urbanization. These land cover changes have significant impacts on the hydrological system (e.g. Falkenmark et al. 1999; Legesse et al. 2003; Schulze et al. 2004). According to the National Water Resource Strategy (2004), of the 19 designated water management areas in South Africa, 10 were by 2000 already considered water stressed. With continued population growth, increasing urbanization and continued economic development, further pressure will be placed on the water resources through impacts associated with changing land uses.

Additionally, climate is the primary driver of the hydrological system (e.g. Schulze 2000; Chiew 2007; Kundzewicz et al. 2007) and has significant influence on land use and land cover (e.g. Turner et al. 1995; Wasson 1996). Thus, changes in the climate and the climate variability will be an additional stressor on the already stressed water resources of South Africa, placing further pressures on water availability, water accessibility and water demand (Ashton 2002; Arnell 2004).

For South Africa, a warming of 0.1 to 0.3°C per decade has been observed between 1960 and 2003 (Kruger and Shongwe 2004). It has also emerged that the minimum temperatures have risen slightly faster than the maximum and mean temperatures (Kruger and Shongwe 2004). Additionally, an increasing number of warm spells and a decreasing number of cold spells have been observed over southern Africa between 1961 and 2000 (New et al. 2006). Although no long-term trends in precipitation have been observed, increased inter-annual variability in precipitation has been observed for southern Africa since the 1970's (Richard et al. 2001; Fauchereau et al. 2003). Furthermore, Tadross et al. (2005) and New et al. (2006) showed evidence of changing rainfall seasonality and extreme events.

According to Kundzewicz et al. (2007) water resources in semi-arid and arid regions such as South Africa are highly exposed to the impacts of climate change. Downscaled future projections of climate indicate increased summer rainfall for the central and eastern regions of South Africa (Hewitson and Crane 2006). However, Tadross et al. (2005) show changes in the distribution of summer rainfall for the eastern regions of South Africa, with early summer (October – December) rainfall decreasing and late summer (January – March) rainfall increasing. Lumsden et al. (2009) evaluated potential changes in hydrologically relevant rainfall statistics for six A2 downscaled projections of future climate. Findings indicated an increase in rainfall for the eastern region of South Africa in the form of more rain days and more days with larger rainfall events. However, decreases in rainfall were projected for the west coast regions of South Africa and adjacent interior (Lumsden et al. 2009). With wetter antecedent condition and larger rainfall events, runoff generation would likely increase, having far reaching water management implications.

However, assessments of climate change impacts have been primarily undertaken at macro and regional scales, masking the complex hydrological interactions at the local, catchment scale (Schulze 2000). For example, owing to differences in land use, soils and slope between catchments, two catchments may respond differently to the same change in climate (Schulze 2000; Kundzewicz et al. 2007). Detailed catchment scale assessments of the impacts of climate change on water resources are required to improve understanding, inform water resources management, and provide appropriate scenarios for the development of adaptation strategies.

Given the above introductory remarks, the objective of this study was to assess the impacts of climatic changes on the streamflow responses of three different, yet regionally representative South African catchments, *viz.* the Mgeni, the Luvuvhu and the Upper Breede, at a timeframe appropriate to assist and inform water resources planning and management. This is achieved through the application of a hydrological model, the *ACRU* Agrohydrological Model (Schulze 1995), which is conceptualized to adequately represent hydrological processes, and has been shown to adequately represent catchment responses to climate and changes thereof (Warburton et al. 2010).

5.2 Modelling Approach to Assess Climate Change Impacts

5.2.1 Study catchments

Three climatically divergent South African catchments have been selected for this study. The *ACRU* model's ability to assess the responses to the various climates in these catchments has been confirmed by Warburton et al. (2010). The catchments are the Mgeni catchment located in the KwaZulu-Natal province, the Luvuvhu catchment in the Limpopo province and the Upper Breede catchment in the Western Cape province (Figure 5.1). These catchments were selected as their historical climates differ and the dominant land uses represented in the catchments vary, providing a range where the streamflow responses to change may differ in response to climate change. Table 5.1 shows the relevant climate statistics for the three catchments.

The Mgeni catchment (4 349 km^2) is located on the wetter eastern seaboard of the country and falls within the summer rainfall region. The rainfall throughout the catchment is highly variable (Table 5.1). The Mgeni catchment is a complex catchment, both in terms of its land use and water engineered system. Although the Mgeni catchment only occupies 0.33% of South Africa's land surface, it is economically and strategically important as it provides water resources to an area which produces *ca*. 20% of the country's gross domestic product (Schulze et al. 2004), yet according to Summerton (2008) is considered a stressed system.

The Luvuvhu catchment (5 940 km^2) is situated in the semi-arid, sub-tropical, north-eastern parts of the country. The catchment is drained by the Luvuvhu and Mutale Rivers, which flow in an easterly direction to the confluence with the Limpopo River on the border of South Africa and Mozambique. The lower reaches of the catchment form part of the Kruger National Park, an important ecotourism area of South Africa. The climate of the Luvuvhu catchment is variable, both spatially and temporally (Table 5.1).

The Upper Breede catchment (2 046 km^2) falls within the winter rainfall area, southern area of the country. The catchment forms part of the headwaters of the Breede River Catchment in the mountainous areas of the Western Cape province. The catchment rainfall is highly variable (Table 5.1). The agricultural products exported from this region, make it a key economic region for the country.

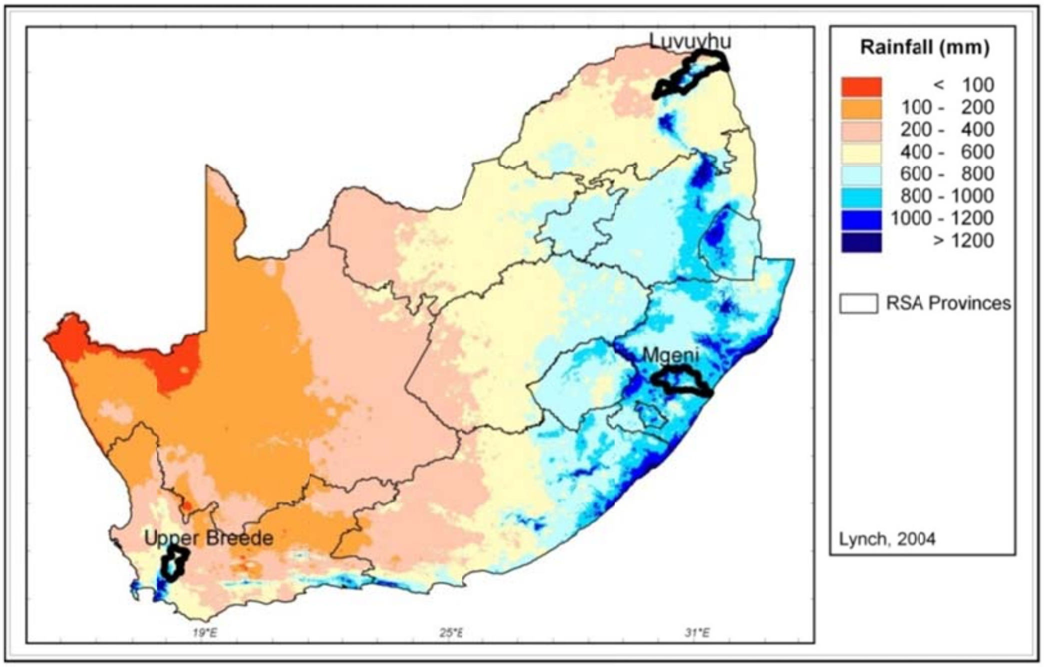

Figure 5.1: Mean annual precipitation (MAP) of South Africa (after Lynch, 2004), with the location of the study catchments

Table 5.1: Climate statistics for Mgeni, Luvuvhu and Upper Breede catchments (after Schulze, 1997)

	Catchments		
	Mgeni	**Luvuvhu**	**Upper Breede**
MAP range	1 550 mm – 700 mm	1 870 mm - 300 mm	1 190 mm - 350 mm
Mean Annual Temperature range	12°C - 20°C	17°C - 24°C	6.3°C - 17.7°C
Mean Annual Potential Evaporation range	1 570 mm - 1 740 mm	1 900 mm - 2 250 mm	760 mm - 2 290 mm

5.2.2 The *ACRU* hydrological model

The model selected to assess the impacts of climate change on the hydrological response was the conceptual-physical, daily time-step and multi-purpose *ACRU* model (Schulze 1995; Schulze and Smithers 2004) which was developed in the School of Bioresources Engineering and Environmental Hydrology at the University of KwaZulu-Natal in South Africa. The *ACRU* model has been applied extensively in South Africa for climate change impact assessments (Perks and Schulze 1999; Perks 2001; Schulze et al. 2005; Schulze et al. 2010). A recent confirmation study by Warburton et al. (2010) concluded that the ACRU model could successfully account for changes in streamflow from the diverse climates presently within and between the Mgeni, Luvuvhu and Upper Breede catchments, thus lending confidence to the model's ability to assess the streamflow response to climate change.

A detailed description of the conceptualization of the land use component in the ACRU model can be found in Schulze (1995), with a summary given in Warburton et al. (2010). The model configuration and inputs used in the study have been applied in other studies by Warburton et al. (2010) and Warburton et al. (2012); a brief description is thus given below.

5.2.3 Model configuration

The three study catchments were delineated into water management units (WMUs), and further subdivided into subcatchments which reflect the altitude, topography, soils properties, land cover and water management, as well as the presence of streamflow gauging stations. These subcatchments were relatively homogeneous in terms of climate, soils and natural land cover and are analogous to Hydrological Response Units used in similar studies. The modelling units were configured to cascade into each other in a logical sequence representative of flow through the catchment's river network.

To assess the impacts of climate change on the hydrological response of the catchments, changes are assessed relative to historical climate applied to a baseline land cover scenario. In this study, the baseline land cover selected was that represented by the Acocks' (1988) Veld Types. These are the most scientifically respected and generally accepted maps of natural vegetation for South Africa. Estimates of hydrological responses from the Acocks Veld Types have formed the basis for which streamflow reductions due to land use change, as outlined in the South African National Water Act (NWA 1998), have been assessed since 1998 (Gush et al. 2002).

The *ACRU* model revolves around a daily multi-soil-layer water budget (Schulze 1995). Values of the thickness of the topsoil and subsoil, as well as soil water content at the soil's lower limit, field capacity and saturation for both the topsoil and subsoil; also the fraction of saturated soil water above field capacity to be redistributed daily from the topsoil to the subsoil, and from the subsoil into the groundwater store were obtained for the three study areas from Schulze *et al*. (2008). Based on previous studies (e.g. Kienzle et al. 1997) it was assumed that 30% of the total stormflow generated in subcatchments in the Mgeni and Luvuvhu catchments would exit on the same day as the rainfall event which generated the stormflow, while for the Upper Breede catchment it was assumed that 60% of the total stormflow generated in a subcatchment would exit on the same day (Schulze et al. 2004) given the steepness of the catchment. On any particular day it is assumed that 0.9% of the groundwater store will become baseflow (Kienzle et al. 1997; Schulze et al. 2004). It was further assumed that the soils and streamflow response variables are unchanged under the historical and future climate scenarios.

When modelling the land use component, the *ACRU* model considers four processes, *viz.* canopy interception loss, evaporation from vegetated surfaces and from the soil surface, and soil water extraction by plant roots (Schulze 1995). Canopy interception losses per rainday were set using the interception loss variable for each month of the year for each baseline land cover considered (*ACRU* variable name = VEGINT). To estimate vegetation water use within the *ACRU* model, the crop coefficient (CAY) is used. Soil water extraction from both soil horizons takes place simultaneously in the model according to the proportion of active roots within each soil horizon and the relative wetness of each horizon (Schulze 1995). Thus, monthly values of the fraction of active roots in the topsoil horizon (ROOTA) are required. The rainfall abstracted by soil surface interception, surface detention storage and initial infiltration before stormflow commences is estimated by the coefficient of initial abstraction (COIAM) variable in *ACRU* (Schulze 1995), with this value varying from month- to- month according to typical rainfall intensity and differing according to the land use (Schulze 2004). The VEGINT, CAY, ROOTA and COIAM variables are given in Appendix A for each baseline land cover found in this study.

5.2.4 Model climate data requirements

For each of the subcatchments within the three study catchments, a representative rainfall station was selected. For model simulations using historical climate, a daily rainfall record (1961 – 2000) was extracted from a daily rainfall database for South Africa (Lynch 2004) for each selected station. To improve the rainfall stations' representation of the areal rainfall of the subcatchment, the daily rainfall record was adjusted by a month-by-month multiplication factor obtained by dividing the subcatchment's mean monthly rainfall, derived from a 1 arc minute raster of monthly rainfalls developed by Lynch (2004), by the rainfall station's mean monthly rainfall. These monthly rainfall adjustments were applied to the future climate scenarios as well. Historical daily temperatures for the period 1961 – 2000 were extracted from a gridded database of daily temperatures for South Africa (Schulze and Maharaj 2004) for the centroid of each subcatchment. As no daily measured evaporation records were available for each subcatchment and to make the historical climate simulations comparable with the future climate simulations, daily A-pan equivalent potential evaporation were derived from the Hargreaves and Samani (1985) equation which requires only daily maximum and minimum temperatures as its climatic input. The Hargreaves and Samani (1985) equation was used as it was shown by Bezuidenhout (2005) to mimicked the daily values of reference evaporation well for South Africa.

Five possible future climate projections obtained from the Swedish Meteorological and Hydrological Institute (SMHI) were used in this study (Graham et al. 2011). The projections originated from three coupled atmosphere-ocean global climate models (AOGCMs), namely the Community Climate Systems Model (CCSM3) developed at the National Centre of Atmospheric Research in the USA, and the ECHAM4 and ECHAM5/MPI-OM both developed at the Deutsches Klimarechenzentrum (DKRZ) in Germany. Model simulations considered three SRES emissions scenarios, *viz*. A1B used for the CCSM3 and ECHAM5/MPI-OM model experiments, A2 used only for the ECHAM4 model experiment and B2 used for the CCSM3 and ECHAM4 model experiments. The A1B storyline represents a market-orientated world with fast per capita growth, strong regional interaction, a tendency towards a convergence of incomes and a balanced dependence on fossil and non-fossil fuels. Population growth peaks in 2050 and then begins to decline (Carter et al. 2007). The A2 storyline describes a heterogeneous world with regionally orientated economic development that is highly fragmented and slower than the other storylines, with populations continuing to grow. Self-reliance and the preservation of local identities are the underlying theme of this storyline (Carter et al. 2007). The B2 scenario describes a world where population growth continues to increase, but at slower rates than the A2 scenario, and where technological developments are more rapid than A2, but slower and less diverse than A1b. Government is more orientated towards environmental protection and social equity, with solutions being more locally and regionally focused (Carter et al. 2007). In terms of greenhouse gas emissions, these three scenarios can be ranked in order of severity with A2 emitting the most, followed by A1B and B2 emitting the least.

Owing to the coarse horizontal resolution of AOGCMs (~200-300 km) the scope for the direct use of their outputs in impact models, such as catchment-based hydrological models, is limited. Downscaling is therefore needed and this study used dynamically downscaled climate projections from a regional climate model (RCM). All five projections were downscaled with the RCA3 regional climate model (Jones et al. 2004; Samuelsson et al. 2011) over a model domain covering all of southern Africa using a horizontal resolution of 50 km. RCA3 was adjusted for southern African conditions in terms of atmospheric physics and land-surface physiography (Andersson et al. 2011). Global boundary forcing was derived from the three AOGCM simulations mentioned above. All of the projections covered the period 1961-2050. The two A1B projections also covered the remaining part of the 21st century up to 2100.

Even with the use of RCMs, there are often biases in the statistics of key downscaled variables such as precipitation and temperature. Such biases originate from both the driving AOGCM and parameterisations in the RCM (Kotlarski et al. 2005; Kay et al. 2006). For this reason, variables need to be adjusted before use in local impact studies (Graham et al. 2007; Lenderink et al. 2007). Precipitation and temperature for all of the RCM projections used here were adjusted using the distribution-based scaling (DBS) approach for bias correction (Yang et al. 2010). With the DBS approach, correction factors are derived by comparing the RCM output with observed climate variables in a control period (here 1961-1990) and then applied to RCM output for the future climate period. For each future climate scenario used in the study, a daily rainfall, daily minimum and maximum temperature record downscaled to the historical rainfall station was obtained for the period 1961 – 2050. The downscaled temperature values were adjusted to be representative of the altitude of the centroid of the subcatchment based on lapse rate adjustments following the methodology described in Lumsden et al. (2010). The future climate projections for the three catchments are discussed below, with the potential impacts of these future climates on streamflow outlined.

5.3 Projections of Future Climates and Impacts on Streamflows of the Three Study Catchments

5.3.1 Projections of future climates and impacts on streamflows of the Mgeni catchment

Currently the Mgeni catchment experiences a warm sub-humid climate, falls within the summer rainfall region of South Africa, and has high inter- and intra-annual rainfall variability. A summary of the projected future climate changes for the period 2021 to 2050 as deviations from the period 1961 – 1990 is presented in Table 5.2, together with projected changes in mean annual streamflow under baseline land use and future climate projections. Also shown in Table 5.2 are the historical climate 1961 – 1990 means from observations. Both mean annual minimum and maximum temperatures are projected to be higher in the future, with stronger increases occurring in the minimum temperatures. Although the temperatures are increasing, the mean annual total evaporation is projected to decrease in three of the future scenarios in which decreases in the rainfall are projected.

The observed mean annual precipitation (MAP) of the catchment for 1961 – 1990 is 931.7 mm. Projections of future rainfall ranged from a 19% increase under the CCSM3 B2 scenario to a decrease of 8% under the EC4 A2 scenario. Stronger changes are projected in mean summer (December, January and February) and mean winter (June, July and August) rainfall for the future in comparison with annual averages. Changes in projected mean summer rainfall range from an increase of 23% under the CCSM3 A1B scenario to a decrease of 10% under the EC4 A2 scenario. Four of the five scenarios projected a decrease in the average number of rain days per year for the period 2021 – 2050, with small to no changes in the average number of rain days per year with greater than 25 mm.

In the CCSM3 A1B and CCSM3 B2 scenarios where increases in the MAP, summer and winter rainfall are projected, the increases in mean annual accumulated streamflow at the catchments outlet are fairly substantial, with a 28.3% increase projected for the CCSM3 A1B scenario and a 64% increase for the CCSM3B2 scenario (Table 5.2). These increases are more than three times those projected for the MAP, thus showing the amplification the hydrological cycle has on any changes in rainfall. Although, the EC4 B2 scenario projected a decline in MAP, the mean winter rainfall is projected to increase by 39.1%, which explains the 13.5% increase projected in mean annual accumulated streamflow under this scenario. Decreases in the mean annual accumulated streamflows are projected under the EC4 A2 and EC5 A1B scenarios resulting from the decreases projected in rainfall for these scenarios.

As changes in the mean annual accumulated streamflows are not indicative of how the full flow regime has changed, flow duration curves of daily accumulated flows at the catchment outlet are presented. Figure 5.2 shows the flow duration curves resulting from a historical climate (1961 – 1990) compared to the flow duration curves produced for the future climate scenarios (2021 – 2050) at the outlet of the Mgeni catchment under natural land cover.

Table 5.2: Projections of future climates for the Mgeni catchment expressed as deviations in the mean between the periods 2021 – 2050 and 1961 – 1990

	1961 – 1990	2021 – 2050 Deviation from 1961 – 1990 mean				
	Historical Mean	**CCSM3 A1B**	**CCSM B2**	**EC4 A2**	**EC4 B2**	**EC5 A1B**
Mean Minimum Temperature	11.5°C	+ 1.6°C	+ 1.8°C	+ 1.3°C	+ 1.6°C	+ 1.1°C
Mean Maximum Temperature	23.6°C	+ 0.9°C	+ 0.8°C	+ 1.4°C	+ 1.4°C	+ 1.5°C
Mean Annual Total Evaporation	626.1 mm	+ 2.4%	+ 7.6%	- 7.0%	- 3.8 %	- 1.0%
Mean Annual Precipitation	931.7 mm	+ 7.0%	+ 19.3%	- 8.4%	- 0.2%	- 1.8%
Mean Summer Rainfall (D, J, F)	400.0 mm	+ 23.3%	+ 22.0 %	- 10.1%	- 6.7%	+ 5.5%
Mean Winter Rainfall (J, J, A)	53.8 mm	- 34.4%	+ 8.2 %	- 5.5%	+ 39.1%	- 12.5%
Average number of rain days/yr	88 days	-2.2 days	+ 6.9 days	-2.8 days	-1.7 days	-5.2 days
Average number of rain days > 25 mm/yr	8.4 days	+0.8 days	+ 2.9 days	- 0.9 days	- 0.1 days	+ 0.0 days
Mean Annual Accumulated Streamflow	198.9 mm	+ 28.3%	+64.0%	- 14.1%	+ 13.5%	- 0.4%

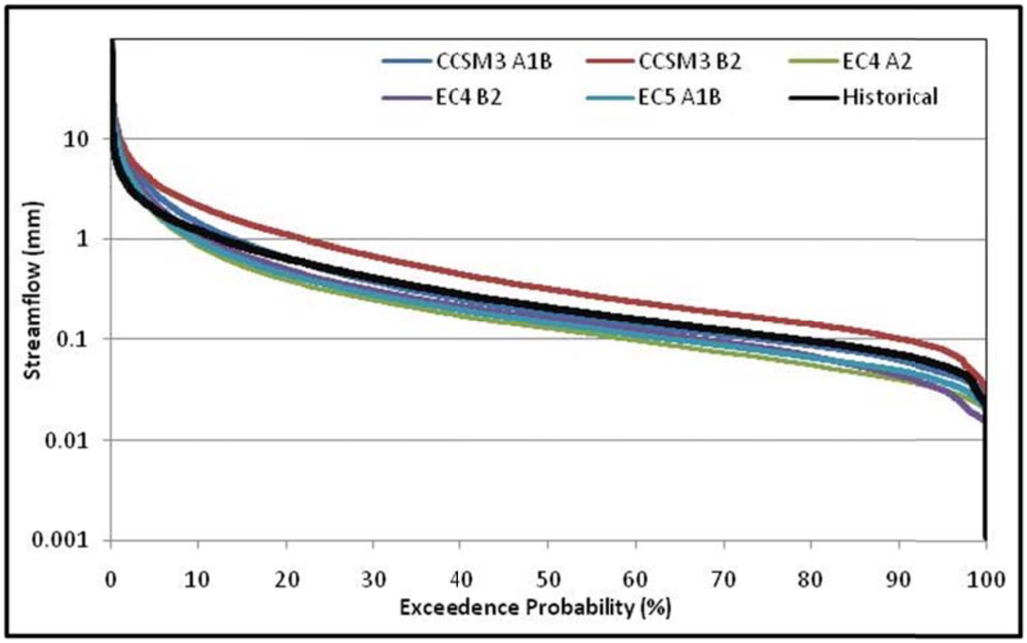

Figure 5.2: Comparison of flow duration curves of daily accumulated streamflows at the outlet of the Mgeni catchment for historical climate and future climate scenarios

Streamflows produced under the CCSM3 B2 scenario are consistently higher than historical streamflows. The streamflows produced under the CCSM3 A1B scenario appears to be similar to the historical streamflows, except for high flows (i.e. those exceeding the 10th percentile) where the flows generated under the CCSM3 A1B scenario are higher than the historical flows, which would account for the 28% increase in mean annual accumulated streamflows. A 13.5% increase in mean annual accumulated streamflows is indicated by the EC4 B2 scenario (Table 5.2). However, when considering the changes to the flow regime the flows are generally less then the historical flows particularly for low flows (Figure 5.2). The increase in mean annual accumulated streamflows is a result of the flows above the upper 10th percentile being greater than the corresponding historical flows. The remaining future climate scenarios, *viz.* EC 4 A2 and EC5 A1B, generated lower streamflows than the historical streamflows, except at the upper 5th percentile of flows where the future flows appear to be larger. The lowest streamflows are generated under the EC A2 scenario (Figure 5.2).

5.3.2 Projections of future climates and impacts on streamflows of the Luvuvhu catchment

The Luvuvhu catchment falls within the dry sub-tropical regions of the north-east of South Africa. A summary of projected future climate changes for the period 2021 to 2050 as deviations from the period 1961 to 1990 are shown in Table 5.3, together with changes in mean annual streamflows under baseline land use. Simulated flow duration curves under a historical climate (1961 – 1990) compared to the flow duration curves produced from the future climate scenarios (2021 – 2050) at the outlet of the Luvuvhu catchment are shown in Figure 5.3. Increases in both mean annual maximum and minimum temperatures are projected. However, unlike the Mgeni catchment, the future climate scenarios for the Luvuvhu show higher increases in the annual means of daily maximum temperatures than the annual means of daily minimum temperatures.

The observed MAP of the Luvuvhu catchment for the 1961 – 1990 period is 838.2 mm, however but with this being highly variable through the catchment. Three of the five scenarios of future climates projected a decrease in mean annual precipitation of up to 16%. However, three of the scenarios projected an increase in mean summer rainfall, with the largest projected increase being 25%. Mean winter rainfall is projected to decrease in four of the scenarios by fairly significant percentages. However, as the historical mean winter rainfall is low (31.1 mm) these percentages should be taken in context. All five scenarios projected decreases in the average number of rain days per year by the period 2021 – 2050, however, two scenarios projected small increases in the average number of rain days with greater than 25 mm of rain. Decreases in mean annual total evaporation are projected for all the scenarios excluding the EC5 A1B scenario which projects a slight increase in line with the changes in rainfall. For, the EC4 A2 scenario a decrease in the mean annual total evaporation is projected despite an increase being projected in the MAP. The relatively small decrease (3.6%) in the mean annual total evaporation can be attributed to the strong decrease in mean winter rainfall of 22.4% as well as the changes in the frequency of rain days and its influence on interception.

Table 5.3: Projections of future climates for the Luvuvhu catchment expressed as deviations in the mean between the periods 2021 – 2050 and 1961 – 1990

	1961 – 1990	**2021 – 2050 Deviation from 1961 – 1990 mean**				
	Historical Mean	**CCSM3 A1B**	**CCSM B2**	**EC4 A2**	**EC4 B2**	**EC5 A1B**
Mean Minimum Temperature	14.8°C	+ 1.1°C	+ 0.7°C	+ 1.3°C	+ 1.5°C	+ 0.8°C
Mean Maximum Temperature	26.8°C	+ 1.7°C	+ 1.1°C	+ 1.5°C	+ 1.7°C	+ 1.3°C
Mean Annual Total Evaporation	461.1 mm	- 13.8%	- 8.2%	- 3.6%	- 2.3%	+ 1.1%
Mean Annual Precipitation	838.2 mm	- 16.4%	- 16.1%	+ 8.1%	- 4.5%	+ 11.0%
Mean Summer Rainfall (D, J, F)	441.4 mm	- 17.5%	- 9.1%	+ 25.3%	+ 9.4%	+ 9.4%
Mean Winter Rainfall (J, J, A)	31.1 mm	- 74.1%	- 30.4%	- 22.4%	+ 14.4%	- 47.7%
Average number of rain days/yr	42.9 days	- 6.9 days	- 3.8 days	- 1.5 days	- 1.3 days	- 0.8 days
Average number of rain days > 25 mm/yr	10.2 days	- 1.5 days	- 2.1 days	+ 1.0 days	- 0.2 days	+ 0.8 days
Mean Annual Accumulated Streamflow	189.9 mm	- 18.4%	- 32.4%	+ 38.1%	- 8.9%	+ 38.4%

Decreases in mean annual accumulated streamflows (Table 5.3) and the full flow regime (Figure 5.3) are projected for those scenarios where decreases in the MAP are projected, *viz.* CCSM3 A1B, CCSM3 B2 and EC4 B2. The increases in mean annual accumulated streamflows projected for the EC4 A2 and EC5 A1B scenarios are more than three times those of the projected increases in MAP, again showing the amplification effect the hydrological cycle has on changes in rainfall. However, when considering the flow duration curves it becomes apparent that these increases in flows result from increases in flows above the upper 10th percentile and below the lower 30th percentile.

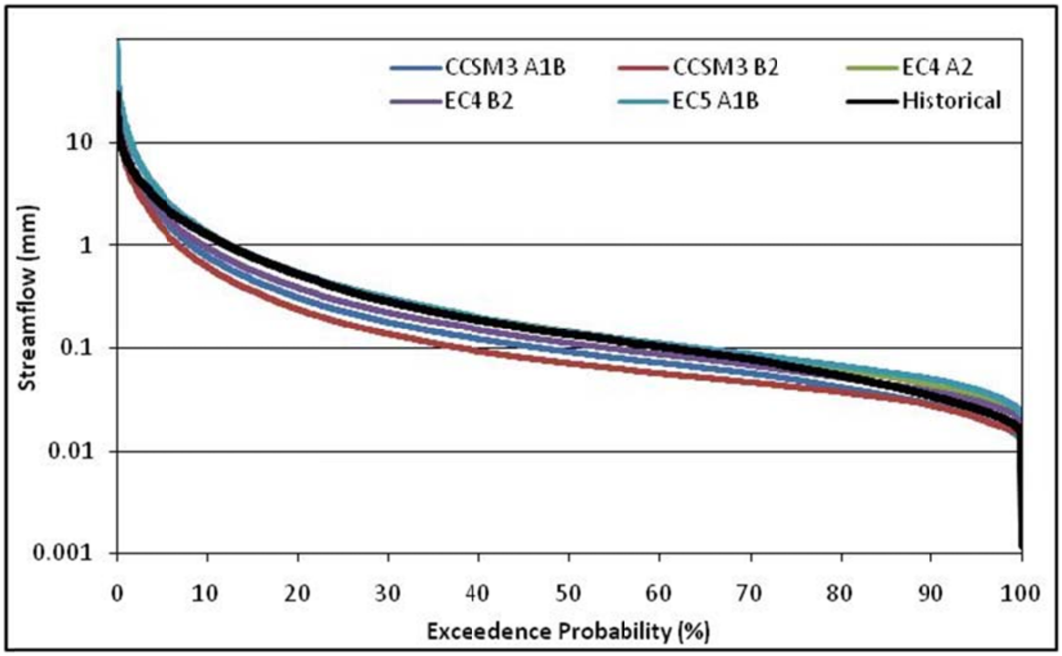

Figure 5.3: Comparison of flow duration curves of daily accumulated streamflows at the outlet of the Luvuvhu catchment for historical climate and future climate scenarios

5.3.3 Projections of future climates and impacts on streamflows of the Upper Breede catchment

The Upper Breede catchment falls within the winter rainfall region of South Africa. A summary of the five projections of future climate changes for the period 2021 to 2050, expressed as deviations from the period 1961 to 1990, are presented in Table 5.4, together with resulting changes in streamflows under baseline land use. Flow duration curves resulting from a historical climate (1961 – 1990) compared to the flow duration curves produced for the future climate scenarios (2021 – 2050) at the outlet of the Upper Breede catchment are shown in Figure 4.

Higher temperatures are projected for all five scenarios for the Upper Breede catchment, with the increases in annual means of daily maximum and minimum temperatures being generally similar magnitude. Even though increases in annual means of daily maximum and minimum temperatures are projected for each of the five scenarios, the mean annual total evaporation of the Upper Breede catchment is projected to decrease for the five scenarios due to the projected decrease in rainfall for the catchment, and subsequent decline in available soil water. The EC4 A2 scenario projected the greatest decrease of 22.6% in mean annual total evaporation.

For MAP, mean winter rainfall, mean summer rainfall, the average number of rain days and the average number of rain days with more than 25 mm of rain, all five of the scenarios projected decreases. The decreases in the mean winter rainfall range from 3.8% to 22.9% (Table 5.4). These decreases in rainfall are consistent with the IPCC (2007) projections of the southwest region of South Africa. The Western Cape is already a highly stressed water region, and decreases in high rainfall season will have significant impacts on the water resources of the region. As a consequence of the projected declines in rainfall, mean annual accumulated streamflows are projected to decrease in all five scenarios (Table 5.4). From the flow duration curves it is indicated that the reductions in mean annual accumulated flows are primarily due to decreases in flows above the 50th percentile of flow (Figure 5.4). The EC5 A1B scenario showed slight increases in the lower flows.

Table 5.4: Projections of future climates for the Upper Breede catchment expressed as deviations in the mean between the periods 2021 – 2050 and 1961 – 1990

	1961 – 1990	**2021 – 2050 Deviation from 1961 – 1990 mean**				
	Historical Mean	**CCSM3 A1B**	**CCSM B2**	**EC4 A2**	**EC4 B2**	**EC5 A1B**
Mean Minimum Temperature	8.0°C	+ 1.4°C	+ 1.4°C	+ 0.8°C	+ 0.9°C	+ 0.8°C
Mean Maximum Temperature	20.3°C	+ 1.6°C	+ 1.4°C	+ 0.8°C	+ 1.0°C	+ 1.4°C
Mean Annual Total Evaporation	612.1 mm	- 12.6%	- 7.1%	- 27.5%	- 24.3%	- 8.8%
Mean Annual Precipitation	300.3 mm	- 4.3%	- 1.5%	- 22.6%	- 16.1%	- 6.9%
Mean Summer Rainfall (D, J, F)	46.3 mm	- 4.6%	- 2.4%	- 62.3%	- 54.1%	+ 14.3%
Mean Winter Rainfall (J, J, A)	290.5 mm	- 12.1%	- 3.8%	- 21.5%	- 22.9%	- 8.6%
Average number of rain days/yr	42.6 days	- 5.9 days	-3.6 days	-7.1 days	- 6.9 days	- 5.6 days
Average number of rain days > 25 mm/yr	6.6 days	- 0.8 days	- 0.5 days	- 2.6days	- 2.3 days	- 0.6 days
Mean Annual Accumulated Streamflow	262.6 mm	- 20.7%	-12.1 %	- 34.6%	- 35.1%	- 8.5%

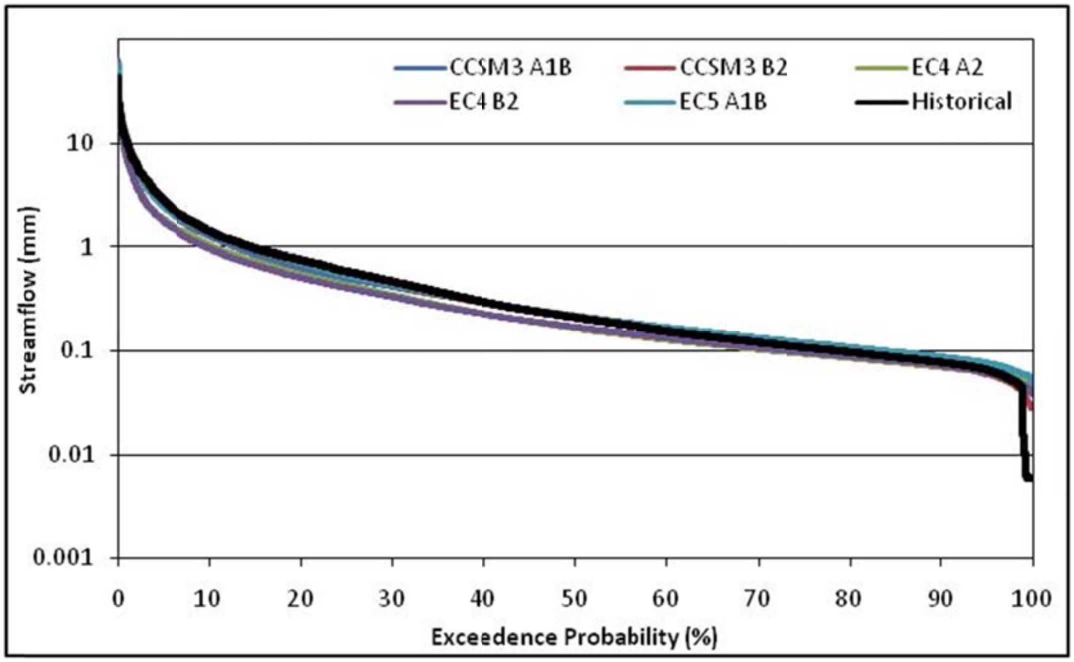

Figure 5.4: Comparison of flow duration curves of daily accumulated streamflows at the outlet of the Upper Breede catchment for historical climate and future climate scenarios

5.4 Discussion

In both the Mgeni and Luvuvhu catchments no consistent direction of change emerged from the analysis of the five RCM scenarios. However, in the Upper Breede, the direction of change was consistent between the five scenarios, with projected decreases in rainfall resulting in decreases in mean annual accumulated streamflows of up to 35%, depending on the future scenario considered. As the Upper Breede is a water generation area for the City of Cape Town and an important area of commercial irrigated agriculture, projected decreases in the current mean annual accumulated streamflow could have significant consequences for water resources planning in the region.

Of the five scenarios considered, three indicated increases in streamflows for the Mgeni catchment, with the highest increase being 64% by 2050. One scenario indicated no change and the fifth a 14% decrease in mean annual accumulated streamflows. All scenarios, however, indicated increases in the upper percentiles of flow, i.e. high flows. Changes in the high flows have consequences for water resources management in regards to increased flood risk and managing reservoirs to be able to capture a significant proportion of these events to minimize the effects of reduced average flows.

In the Luvuvhu catchment, two of the scenarios indicated increases in streamflows of up to 38% by 2050, while three indicated decreases of up to 32% by 2050. The majority of scenarios, however, indicated increases in low flows, while median and high flows are projected to decrease due to decreases in the number of rainfall days with greater than 25 mm. Decreases in median and high flows have potential negative implications for water storage, as these are the flows used to build up water reserves for supply.

Four levels of uncertainty are introduced in any study concerned with the impacts of climate change on water resources, such as this one. The first relates to uncertainty in the emission scenarios used to project future climate, the second to how the different GCMs respond to the emissions scenarios, the third is introduced by the downscaling method used, and lastly the fourth uncertainty is related to the hydrological model used to project the impacts of the downscaled climate scenarios on regional hydrology (Kundzewicz et al. 2007). According to Jenkins and Lowe (2003) for the relatively near time horizon used in this study the uncertainties in the climate model are more significant than the selection of emissions scenario; however for more distant future scenarios the choice of emissions scenario becomes increasingly important.

Covey et al. (2003) analysed outputs from eighteen GCMs for the Coupled Model Intercomparison Project. From this project Covey et al. (2003) found that although the temperature simulations of the various GCMs were highly similar, the simulation of precipitation was inconsistent. It is, however, well recognized that rainfall variability is projected to increase with a changing climate (Kundzewicz et al. 2007). Rainfall is the primary driver of hydrological responses. Furthermore, the output simulated by the *ACRU* agrohydrological model is most sensitive to input rainfall (Schulze 1995). Thus, the uncertainties in the impacts of climate change on water resources as described in this study are largely due to the uncertainties in the precipitation outputs from GCMs rather than the emissions scenario selected (Arnell 2004;

Kundzewicz et al. 2007) or uncertainties in the *ACRU* model. To partially account for the uncertainty introduced by the GCMs, a selection of downscaled GCM scenarios was used as suggested by Kundzewicz et al. (2007). The scale at which hydrological modelling is undertaken it at a relatively fine scale in comparison to the scale at which GCM projections are available, thus although downscaling introduces uncertainty into the scenarios used, it is necessary to use downscaled projections in order for the climate projections to be at a hydrologically relevant and useful scale.

Warburton et al. (2010) confirmed the ability of the *ACRU* model to simulate streamflow responses with past and present hydrological data under a range of climates. The confirmation of model results does not imply the model is a truthful representation of reality. Rather, it increases the confidence that the model is an acceptable representation of reality. This is no guarantee that the model will continue to simulate streamflow responses adequately in the future as the hydrological system is dynamic (Nordstrom et al. 2005), and under a future climate may change in unanticipated ways and possibly beyond the ranges for which the models ability to represent processes has been tested. However, by using a physical-conceptual model where the variables used have physical meaning and have been individually verified during model development (Schulze, 1995) the uncertainty is minimized. Furthermore, as the confirmation study by Warburton et al. (2010) used a robust method of configuration where national level databases as well as experience-based default parameters were used, the confidence of the models ability to be able to perform adequately under extrapolation conditions was increased. As plausible scenarios of streamflow responses to climate change are required to aid in future water resources planning this study builds on a philosophy that these uncertainties should be recognized and, where possible constrained (Beven 2006), rather than being a barrier to undertaking such impact studies.

By considering impacts of climate change on hydrological response under baseline land cover the uncertainties and complexities introduced by operating in a real, operational catchment were not included. However, this allowed for a better understanding of the climate interaction with streamflow responses to be gained. It is recognized, however, that further research needs to consider the compounding and interacting feedbacks between land use, climate and hydrological responses. Furthermore, future research needs to consider changes in the variability of rainfall and hydrological response over time, and whether these changes in variability are of greater concern in water resources planning than changes in the mean.

5.5 Conclusion

Divergent projections of future climates from the different GCM scenarios considered in the Mgeni and Luvuvhu catchments indicate that it is necessary to plan for an uncertain future. This uncertainty should not be a barrier to water resources planning in the catchments, but rather be seen as an imperative to improve understanding of the movement of water within those catchments, to be receptive and adaptive to new information, and to develop resilient and adaptive water management strategies for the future in a way that minimizes the risks and maximizes the benefits to potential impacts of climate change. In the Upper Breede catchment, where decreases in future streamflows seem likely given the consistency of the GCM output there is, in relative terms, less uncertainty, but a greater need to plan for a future with scarcer water resources. However, continual improvement in the understanding of catchment process, the ability to incorporate new knowledge and information, and to develop robust, adaptive strategies for the future remains essential.

5.6 Acknowledgements

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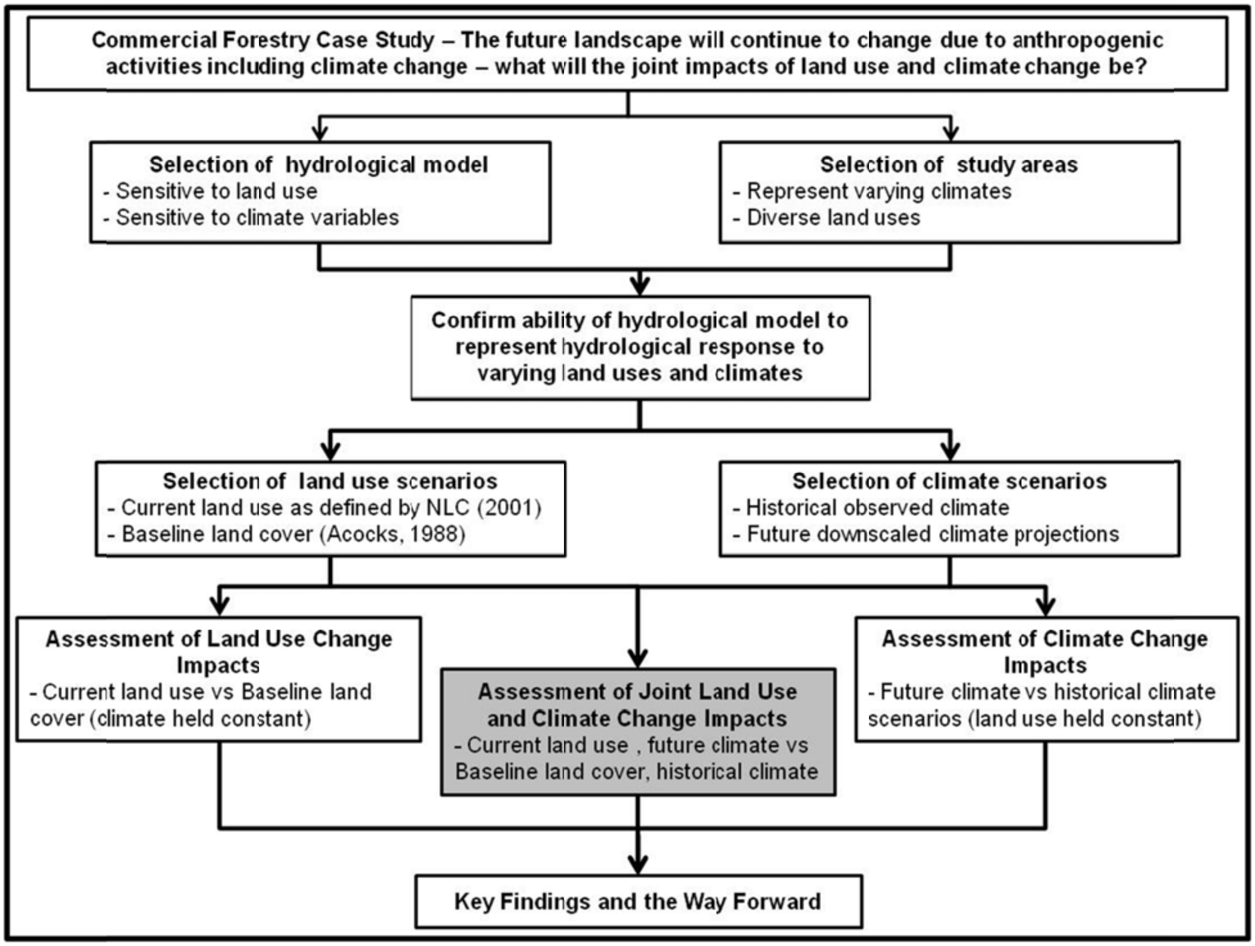
Lead in to Chapter 6

With the ability of the hydrological model to represent varying climates and land uses confirmed (Chapter 3), as well as an improved understanding of the impacts of land use change (Chapter 4) and climate change (Chapter 5) on hydrological responses gained, Chapter 6 addresses the overall objective to advance the understanding of the interactions between land use change, climate change and hydrological response to allow for improved integration of land use planning in conjunction with climate change adaptation into water resources management (as highlighted in the figure below).



6. HYDROLOGICAL RESPONSES TO COMBINED LAND USE AND CLIMATE CHANGE IN THREE DIVERSE SOUTH AFRICAN CATCHMENTS[8]

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ABSTRACT

When considering the impacts of environmental change, there is no consensus as to whether land use change or climate change will be the dominant driver of hydrological response. There is, however, agreement that the effect on hydrological response will be amplified. Given that South Africa is currently water stressed and considered highly exposed to climate change impacts, an understanding of the hydrological response to the complex interactions between land use and climate change is crucial to inform water resources planning and decision making.

To understand influences of land use and climate change on the hydrological response, the daily ACRU agrohydrological model was used to simulate the hydrological responses of three operational South African catchments under baseline land cover with historical climate and the current land use with five downscaled GCM projections of future climate. Consideration was given to the location of key land uses in the catchments and scale issues, from catchment to subcatchment.

The impact of environmental change on the hydrological response is complex, and no clear conclusion emerged as to whether land use change or climate change is more dominant in influencing the hydrological response of a catchment. The impacts of environmental change on the catchments hydrological response varied across both the temporal and spatial scales, with the nature of the land use and the magnitude of the projected climate change also having significant

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impacts on the hydrological response. Results indicated that the drier the climate becomes, the more relatively significant the role of land use becomes, as its impact becomes relatively greater. Analysis of the three catchments showed that as each catchment is unique with its own complexities; each catchment will have a unique threshold of where environmental change begins to have a significant influence on the hydrological response.

6.1 Introduction

Land use change and climate change are both major issues for this century, with both having a significant impact on the hydrological system (e.g. Chiew, 2007; Falkenmark *et al*., 1999; Kundzewicz *et al*., 2007; Legesse *et al*., 2003; Schulze, 2000; Schulze *et al*., 2004). Already, in the Pyrenees, abandonment of agricultural land has increased reforestation activities; this change in land use combined with the climate change which has already occurred has led to a reduction in runoff (Lòpez-Moreno *et al.*, 2008). Studies assessing, either separately or jointly, the effects of land use and climate change vary as to which is the dominant driver. For example, Stohlgren *et al*. (1998), Sala *et al.* (2000), Vörösmarty *et al.* (2000), De Fries and Eshleman (2004), Schulze *et al*. (2004) and Conway (2005) suggest that the consequences of land use change on water resources may be greater than those of climate change, while others (for example, Chang, 2003; Legesse *et al*., 2003; Andersson *et al.*, 2006), suggest the influence of climate change on hydrological response will be dominant. Studies such as that by Baron *et al*. (1997) have found, however, that the streamflow response is similar to both climate and land use change. These varying results suggest that the dominant driver may be dependant on the spatial scale the assessment was undertaken at (i.e. only consideration of flow at the outlet or assessment of distributed flows), the nature of the land use change, the characteristics of the regional and local climate, and the climate change scenario used. This is supported by the finding of Peel (2009) that the impacts of land use on the catchment streamflow are secondary to rainfall at the large catchment scale, but can be significant at the small scale.

For the Conestoga River Basin (1 217 km^2) in Pennsylvannia, USA, Chang (2003) found that mean runoff was more sensitive to Global Circulation Model (GCM)-derived climate change scenarios than to urban growth land use scenarios. Similarly, Hejazi and Moglen (2008) found that the hydrological response of six catchments (10 – 262 km^2) in the Maryland Piedmont region of the USA to scenarios of increasing urban land use to be minimal, while scenarios of GCM-derived climate change increased both peak and low flows. Climate change has also been found to be the dominant driver of hydrological response in comparison to land use change scenarios of urban growth for the Wu-Tu watershed (204 km^2) in Taiwan (Lin *et al.*, 2007) and the main branches of the lower Rhine and Meuse basins (Pfister *et al*., 2004).

Legesse *et al*. (2003), when using plausible future climate scenarios, found that the water resources of the Ketar river basin (3 220 km^2) in south central Ethiopia are more sensitive to changes in climate than to changes in the proportion of the catchment that is afforested. A 10% decrease in the daily rainfall amount year-round resulted in an average annual decrease in runoff at the outlet of approximately 30%; however, an increase of dense forest (to 50% of the catchment) resulted in a decrease in mean annual runoff of 8%. For the GCM-derived climate change scenarios applied to the Mt. Kenya region, it was found that climate change had a greater affect on the water resources than either scenarios of increased cultivation or increased degradation (Notter *et al*., 2007). For the Okavango River in southern Africa, Andersson *et al.* (2006) found that the impacts of climate change on long-term streamflow far outweighed the impacts of any future development scenario relating to irrigation and the development of a hydropower scheme on the river.

Few studies have considered the effect of climate variability when considering the impacts of climate and land use change on hydrological response, but according to the results of studies by Herron *et al*. (2002) as well as Ma *et al.* (2009) climate variability may play an important role in the interactions between climate and land use change. Herron *et al*. (2002) found that water availability in the Macquarie River catchment (75 000 km^2) NSW, Australia is more vulnerable to shifts in the rainfall regime over periods of several decades than it is to either afforestation or climate change. Land use change, climate change and climate variability negated each other resulting in little to no change to streamflow of the Kejie catchment (1755 km^2) in China (Ma *et al.*, 2009). Miaolin and Jun (2005) analyzed approximately 40 years of historical climate fluctuations and land cover changes in the middle reaches of the Yellow River Basin, China.

Their results showed a decrease in runoff of 31%, three fifths of which was attributed to land cover changes, and the remainder to climate fluctuations.

Land use change was found to be the dominant factor influencing the hydrological response of the lowlands of the Puget Sound catchment (30 000 km^2), USA, while both climate change and land use change had equal effects in the upper reaches. The dominance of the land use in the lowland was attributed to large urban areas (Cuo *et al.,* 2009). Under a range of climate change scenarios, land use change of either increasing agricultural areas or reforestation was found to have greater influence on the hydrology of the Chaudière River catchment (6 682 km^2), Canada during the growing season than climate (Quilbè *et al.,* 2008). For the upper Bhavani basin (4 100 km^2), India, Wilk and Hughes (2002) found the hydrological response to be more sensitive to changing land use scenarios of total conversion of the basin to agriculture which generated increased flows, and to total conversion to plantation forestry which decreased flows than to either an increase and decrease in precipitation of 10%. For the Nile River, Conway (2005) suggested that any changes in flow relating to climate change will be dwarfed by the impacts on the flow from non-climatic changes including land use change and population growth.

Results of studies considering the joint effect of climate and land use on streamflow responses tend to agree that the impacts are non-linear and have an amplification effect. For the Xinjiang River basin in China (Guo *et al.,* 2008), the Conestoga River basin, USA (Chang, 2003) and the Jacks Fork River basin, USA (Hu *et al.,* 2005) the streamflow response to impacts of joint climate and land use change was found be larger then the simple addition of the impacts of either climate or land use change; in all three basins climate played the dominant role. For the Driftless area of Wisconsin, USA Juckem *et al.* (2008) suggested that climatic change controlled the timing and direction of the streamflow response while land use changes amplified the streamflow response.

Although the various studies show that either land use or climate change may be the dominant driver of hydrological response when considering environmental change, there is agreement that when assessing the impacts of land use and climate change jointly there is an amplification effect on the hydrological response (Chang, 2003; Hu *et al.,* 2005; Guo *et al.,* 2008; Juckem *et al.*, 2008). Peel (2009) states that at the large scale catchment rainfall has the most significant effect on catchment streamflow with land use having a secondary order impact. However, at the small scale the land use impacts on the streamflow can be significant. Additionally, large scale changes in land use or land cover impacts on the global climate (e.g. Turner *et al*., 1995). Thus, land use, climate and hydrology form a complex and interlinked system with feedbacks and feed forwards (Turner *et al*., 1995), and this system is further complicated by changing climates and human influences as well as the changing dominance of different factors at different spatial and temporal scales. To the knowledge of the authors, no study to date has analysed such joint impacts of environmental change on the streamflow response of a South African catchment. With 10 of the 19 water management areas in South Africa currently water stressed (NWRS, 2004), and changes in future rainfall variability and seasonality projected (Tadross *et al*., 2005), it is crucial to gain an understanding of the complex interactions between land use and climate change. Modelling streamflow responses of a catchment to land use and climate change will aid in understanding these complex interactions (Choi and Deal, 2008), and assist water resource planners in coping with uncertainty introduced by both climate change and land use change impacts.

This study builds on three previous papers. The first, Warburton *et al.* (2010), dealt with the selection of a hydrological model and study areas, and the confirmation of the model's ability to represent the streamflow response to varying land uses and climates. The impacts of land use change on the streamflow responses of the Mgeni, Luvuvhu and Upper Breede catchments in South Africa were then presented in Warburton *et al*. (2012a). The selection of future climate scenarios and impacts of climate change on the baseline hydrology of the study catchments was the focus in Warburton *et al*. (2012b). The aim and focus of this paper is to assess the impacts of joint land use and climatic changes on the streamflow responses of the operationally complex Mgeni catchment, the Luvuvhu catchment and the Upper Breede catchment in order to inform water resources planning and decision making. The purpose is to determine whether land use change or climate change is more dominant in influencing the streamflow response, or whether a combination of both land use and climate change will have a stronger influence. Consideration is given to the location of key land uses in the catchment and scale issues, from catchment to subcatchment.

6.2 Modelling Combined Land Use and Climate Change

6.2.1 Study catchments

The South African catchments chosen for this study are the Mgeni catchment in the KwaZulu-Natal province, the Luvuvhu catchment in the Limpopo province and the Upper Breede catchment in the Western Cape province (Figure 6.1). These catchments were selected as both the climates and dominant land uses in the catchments vary. A description of the current land uses of catchments is presented here with a detail description of the catchments given in Warburton *et al*. (2010).

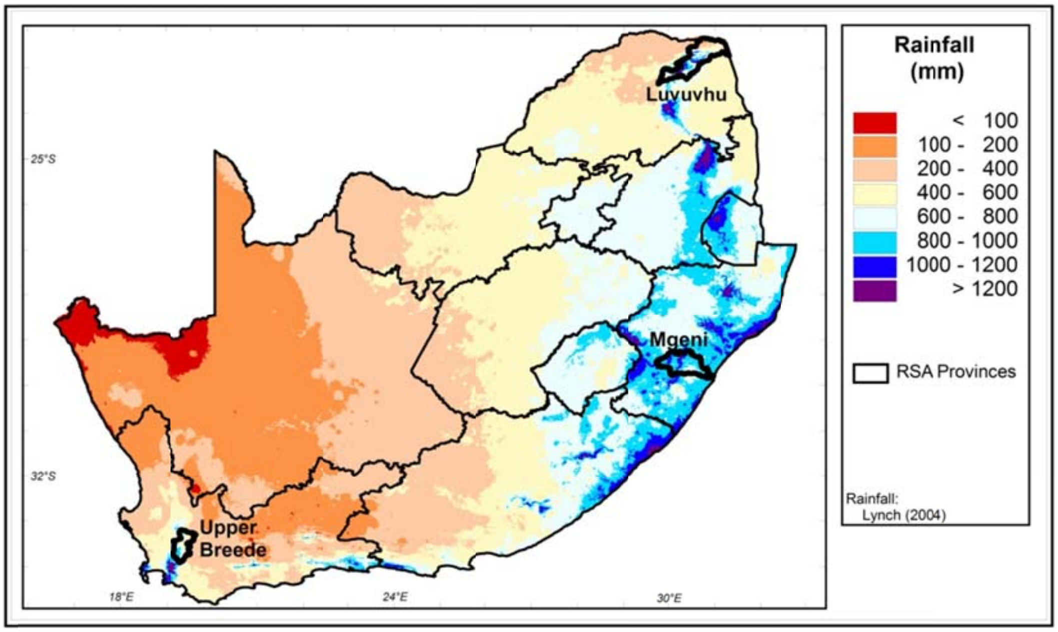

Figure 6.1: The location of the three study catchments in relation to mean annual precipitation (MAP) of South Africa (after Lynch, 2004)

The Mgeni catchment (4 349 km^2) is on the wetter eastern seaboard of the country and falls within the summer rainfall region (Figure 6.1). The Mgeni catchment has been delineated into thirteen water management units (WMUs) as shown in Figure 6.2. The land use of the catchment varies. In the upper areas of the catchment where the rainfall is generally higher, plantation forestry is a dominant land use (Figure 6.2). In the middle reaches of the catchment there are significant areas of sugarcane plantations and urban areas, while the lower reaches of the catchment have substantial urban areas (Figure 6.2) associated with the port city of Durban. The Mgeni catchment also contains four large reservoirs, *viz.* Midmar Dam (237 million m^3 at full supply capacity), Albert Falls Dam (289 million m^3), Nagle Dam (23 million m^3) and Inanda Dam (242 million m^3). Strategically, the Mgeni catchment is important as it supplies water to Pietermaritzburg, the capital city of the KwaZulu-Natal province and to Durban, the economic hub of the province. According to Summerton (2008) the Mgeni catchment is a stressed system which is closed to new streamflow reduction activities for the foreseeable future, thus making it imperative to assess the joint impacts of land use change and climate change on this catchment.

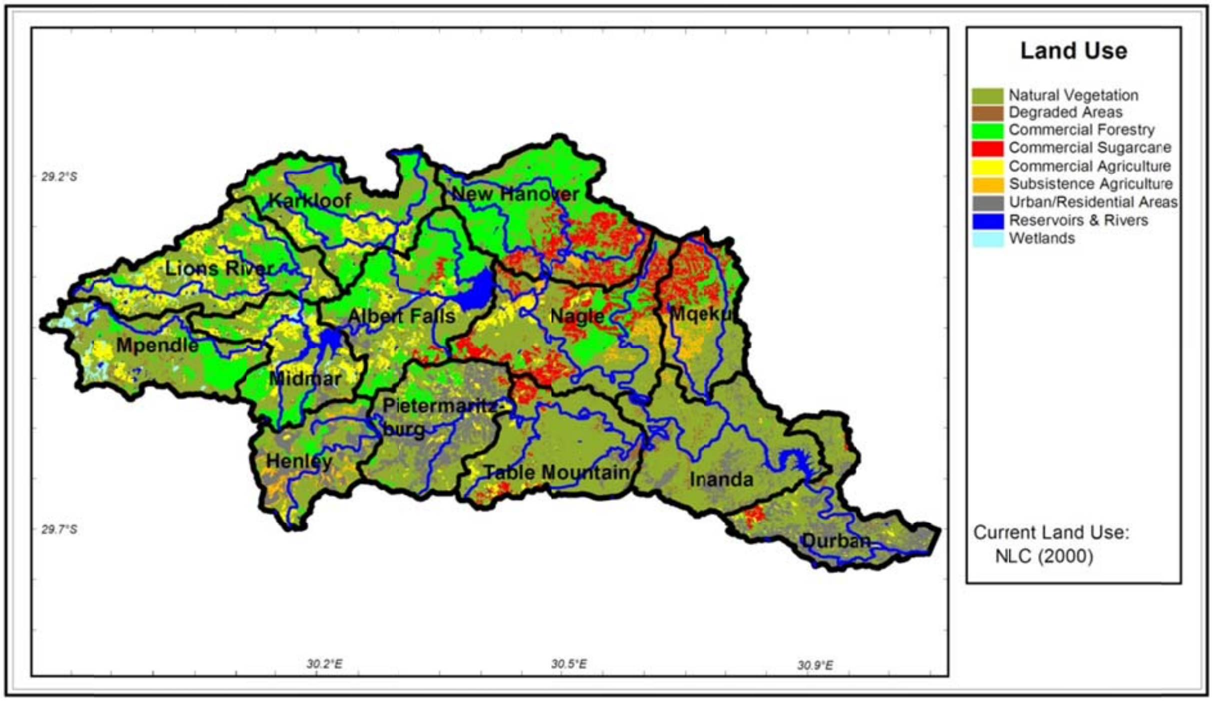

Figure 6.2: Land use distributions in the WMUs in the Mgeni catchment (adapted from NLC, 2000)

The Luvuvhu catchment (5 941 km^2) is situated in the semi-arid, sub-tropical, north-eastern parts of the country (Figure 6.1) and has been delineated into thirteen WMUs (Figure 6.3). The catchment is diverse in land uses, with the upper areas of the catchment containing large areas of plantation forestry, the middle areas are dominated by subsistence agriculture and informal residential areas, while the lower reaches of the catchment are under natural vegetation (Figure 6.3). Informal residential areas are, for the purposes of this study, considered as residential areas where non-permanent housing structures have been erected that do not comply with the current building and planning regulations of the South Africa, and in many cases do not have basic service provision. These areas are characterised by a high density of people and structures, resulting in a substantial portion of impervious areas which are not served by a stormwater system. The lower reaches of the catchment form part of the Kruger National Park, an important ecotourism area of South Africa.

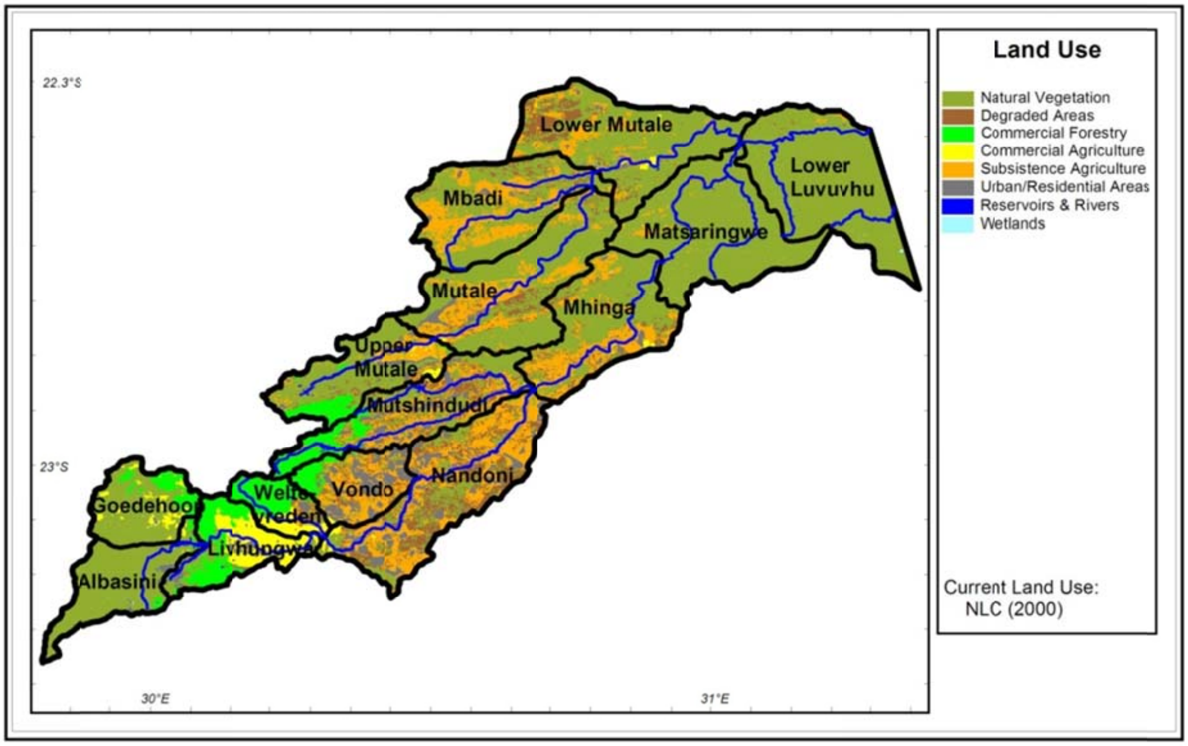

Figure 6.3: Land use distributions in the WMUs in the Luvuvhu catchment (adapted from NLC, 2000)

The Upper Breede catchment (2046 km^2) falls within the winter rainfall area and is located in the southern area of the country (Figure 6.1). The catchment forms part of the headwaters of the Breede River Catchment in the mountainous areas of the Western Cape province and is delineated into ten WMUs (Figure 6.4). The economic activity in the catchment is irrigated commercial agriculture, with the primary crop being high value vineyards for wine production and orchards growing fruit for export (Figure 6.4). The agricultural products exported from this region make it a key economic region, and as such an evaluation of the joint impacts of land use and climate change on the hydrological response of the catchment is considered necessary.

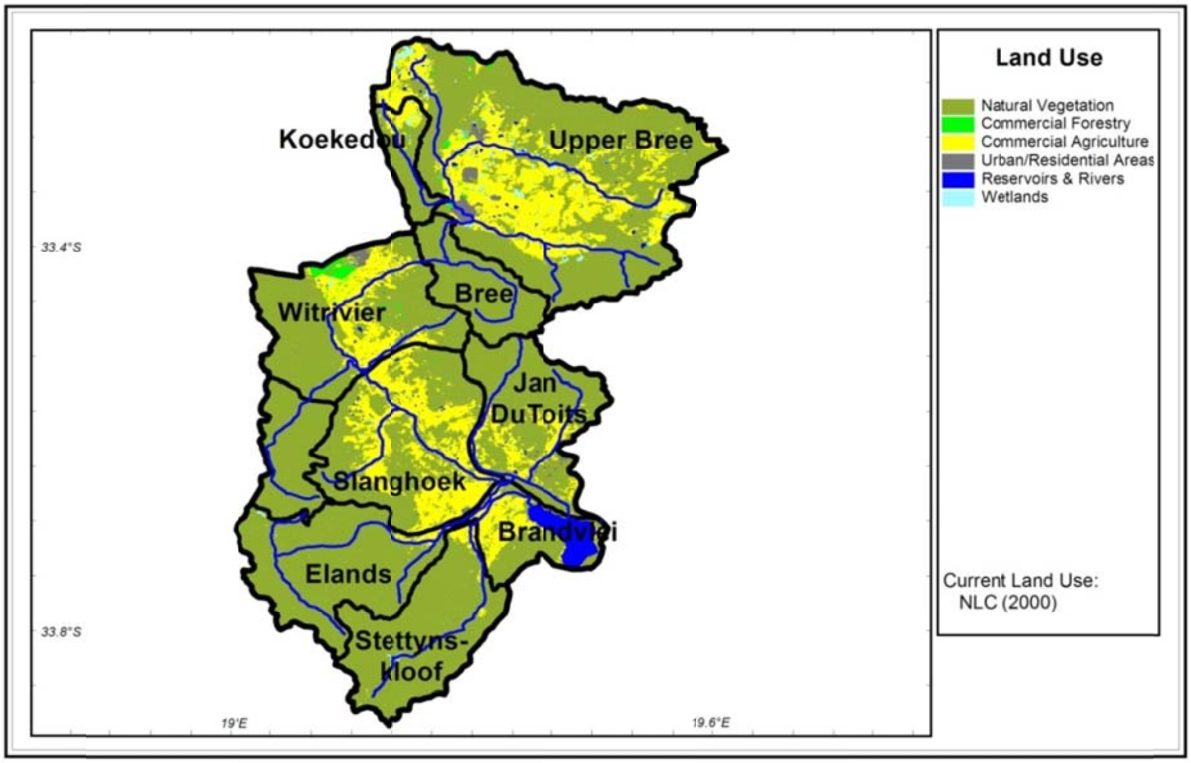

Figure 6.4: Land use distributions in the WMUs in the Upper Breede catchment (adapted from NLC, 2000)

6.2.2 Hydrological model configuration and land use scenarios

The *ACRU* model (Schulze, 1995; Schulze and Smithers, 2004) is used to assess the joint impacts of land use and climate change. The model has been applied extensively in South Africa for both land use impact studies (e.g. Schulze and George, 1987; Tarboton and Schulze, 1990; Kienzle and Schulze, 1995; Kienzle *et al*., 1997; Schulze *et al*., 1997; Jewitt and Schulze, 1999; Schulze, 2000; Jewitt *et al*., 2004) and climate change impact studies (Perks and Schulze, 1999;

Perks, 2001; Schulze *et al*., 2005; Schulze *et al*., 2010). Additionally, a recent confirmation study between simulated and observed streamflows by Warburton *et al.* (2010) concluded that the *ACRU* model could successfully account for both diverse land uses and current climates experienced by the Mgeni, Luvuvhu and Upper Breede catchments. A detailed description of the conceptualization of the land use component in the *ACRU* model can be found in Schulze (1995), with a summary given in Warburton *et al*. (2010). The model configuration and inputs used in the study are those given by Warburton *et al*. (2010) and Warburton *et al*. (2012a; 2012b), a brief description regarding the land use configuration is given here.

The three study catchments were delineated into WMUs, and further subdivided into subcatchments, which reflect the altitude, topography, soils properties, land cover, water management, and gauging stations. These subcatchments, although relatively homogeneous in terms of climate and soils, contained varying land uses. Thus, each subcatchment was further divided into homogenous hydrological response units based on land use. The modelling units were configured to cascade downstream in a logical sequence representative of river flow, as shown in Figure 6.5.

To assess the magnitude of the impacts of land use on water resources, a baseline land cover is required as input to hydrological models, in order to be able to simulate changes in streamflow responses that would occur between natural land cover and perturbed land use conditions (Schulze, 2007). Thus for the purposes of this study, two land use scenarios were considered, a current land use scenario as obtained from the National Land Cover satellite imagery (2001) and a baseline land cover scenario for which the Acocks' (1988) Veld Types were selected. The Acocks (1988) Veld Type maps are the most scientifically respected and generally accepted maps of natural vegetation for South Africa. Estimates of streamflow responses from the Acocks Veld Types have formed the basis for which streamflow reductions due to land use change as outlined in the South African National Water Act (NWA, 1998) are assessed since 1998 (Gush *et al*., 2002; Jewitt *et al*., 2009) and more recently streamflow changes due to climatic changes (Warburton *et al*., 2012b).

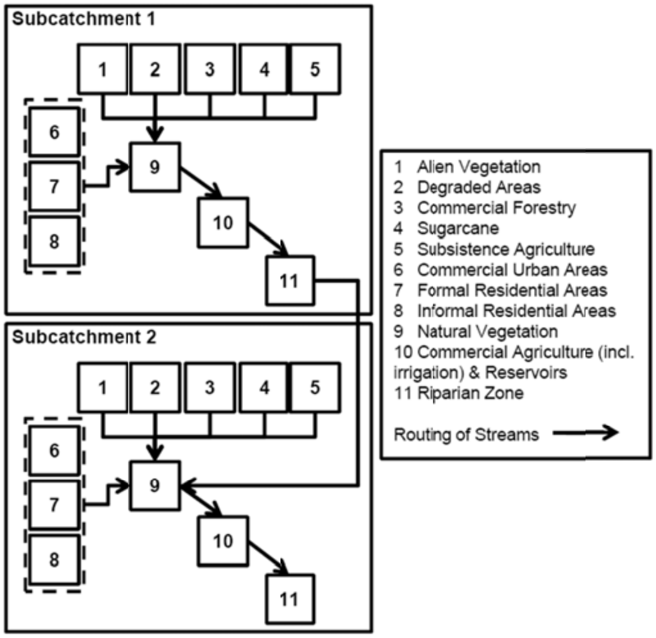

Figure 6.5: An example from the Mgeni catchment of cascading (i.e. routing) of flows between subcatchment and hydrological response units within each subcatchment (Warburton *et al.,* 2010)

When modelling the land use component, the *ACRU* model considers four processes, *viz.* canopy interception loss, evaporation from vegetated surfaces and from the soil surface, and soil water extraction by plant roots (Schulze, 1995). Canopy interception losses per rainday were set using the interception loss variable for each month of the year for each land use and baseline land cover considered (*ACRU* variable name = VEGINT). To estimate monthly vegetation water use within the *ACRU* model, the crop coefficient (K_{cm}) is used. Soil water extraction from both soil horizons takes place simultaneously in the model according to the proportion of active roots within each soil horizon and the relative wetness of each horizon (Schulze, 1995). Thus, values of the fraction of active roots in the topsoil horizon (ROOTA) are required and these are input on a month by month basis per land use. The rainfall abstracted by soil surface interception, surface detention storage and initial infiltration before stormflow commences is estimated by the coefficient of initial abstraction (COIAM) variable in *ACRU* (Schulze, 1995), with this value varying from month- to- month according to typical rainfall intensity and differing according to the land use (Schulze, 2004). The VEGINT, K_{cm}, ROOTA and COIAM variables are given in Appendix 6.A for each land use with baseline land cover variables given in Appendix 6.B.

6.2.3 Climate data requirements for the *ACRU* Model

For model simulations using historical climate, a daily rainfall record (1961 – 2000) was extracted from a daily rainfall database for South Africa (Lynch, 2004) for each selected rainfall station. Historical daily temperatures for the period 1961 – 2000 were extracted from a gridded database of daily temperatures for South Africa (Schulze and Maharaj, 2004) for the centroid of each subcatchment. As no daily measured evaporation records were available for each subcatchment, and in order to make the historical climate simulations comparable to those using future climate simulations, daily A-pan equivalent potential evaporation values were derived from the Hargreaves and Samani (1985) equation which requires only daily maximum and minimum temperatures. The future climate scenarios used in this study were downscaled to a point using a regional climate model (RCM). For each future climate scenario used in the study, a daily rainfall as well as daily minimum and maximum temperature record, downscaled to the historical rainfall station, was obtained. Five possible future climate projections obtained from the Swedish Meteorological and Hydrological Institute (SMHI) were used in this study, *viz.* CCSM3 A1B, CCSM3 B2, EC4 A2, EC4 B2 and EC5 A1B. Further information regarding the climate scenarios used can be found in Warburton *et al*. (2012b).

6.2.4 Soils and streamflow response variables

It was assumed that the soils and streamflow response variables, as described in Warburton *et al*. (2010; 2012a), remained constant under the baseline land use, current land use and future climate scenarios. The only variable which changed was the depth of the soil from which stormflow generation. This variable was set to the thickness of the topsoil, except under sugarcane and commercial plantation forestry in the current land use simulation where it was set to 0.35 m in accordance with results from studies by Schulze (1995) and Gush *et al.* (2002).

6.3 Results: Impacts of Combined Land Use and Climate Change on Streamflow Responses

The magnitude of the impacts of land use change on the hydrological responses of the Mgeni, Luvuvhu and Upper Breede catchments was assessed by Warburton *et al.* (2012a) The conclusion drawn from that study was that the nature and location of the land use changes, the effects of the land use changes on the partitioning of rainfall into stormflow and baseflow, as well as the effects of the water engineered system (i.e. reservoirs, abstractions, return flows, irrigation) combine at the catchment scale to reflect the impacts of changes to the original land cover on the accumulated catchment streamflow as it cascades from source to exit. For example, for both the Mgeni and Upper Breede catchments significant changes in the accumulated catchment streamflow due to land use changes were found; however no significant changes were evident for the Luvuvhu catchment. However, when climate change is also considered, these impacts of land use change on the streamflow response may be altered.

Warburton *et al*. (2012b) considered the potential impacts of five downscaled RCM projections of future climate on the baseline water resources of the Mgeni, Luvuvhu and Upper Breede catchments. In both the Mgeni and Luvuhu catchments no consistent direction of change in rainfall or streamflow emerged from the output of the five RCM projections. However, in the Upper Breede, the direction of change remained consistent between the five RCM scenarios, with projected decreases in rainfall resulting in decreases in mean annual accumulated streamflow. Although this study improved the understanding of the climate interaction with streamflow response, it was recognised that the compounding and interacting feedbacks between land use, climate and hydrological response need to be considered. The question then arises as to whether, when both land use change and climate change occur jointly, either climate change or land use change is dominant, or whether the interactions between them are complex.

Impacts of land use change were assessed by comparing streamflows produced under current land use with that produced under baseline land cover, with the climate held constant as the historical climate. Climate change impacts were assessed by comparing the streamflows produced under the plausible future climate scenarios against streamflows produced under the historical climate, but with the land use held constant as the baseline land cover. In order to assess the joint impacts of land use and climate change, current land use together with projections of future climate were compared to baseline land cover with historical climate. Given that the land use impacts on hydrological response vary across both spatial and temporal scales, the results of the analysis of joint land use and climate change are presented at both a coarse and fine spatial and temporal scale.

6.3.1 Results at a coarse spatial and temporal scale

Changes in mean annual accumulated streamflows at the outlets of the WMUs in the Mgeni catchment due to land use change, climate change and combined land use and climate change are shown in Table 6.1. Similarly, changes in mean annual accumulated streamflows due to land use change, climate change and combined land use and climate change at the outlets of the WMUs in the Luvuvhu and Upper Breede catchments are shown in Table 6.2 and 6.3, respectively.

When considering land use impacts separately, decreases in mean annual accumulated streamflows are shown for the Mpendle, Lions River, Karkloof and New Hanover WMUs in the Mgeni catchment due to changes to commercial plantation forestry and sugarcane (Table 6.1). The Midmar, Albert Falls and Nagle WMUs also show decreases in streamflow due to land use changes and the water engineered system. Increases in streamflow due to urban areas are shown for the Pietermaritzburg, Table Mountain and Mqeka WMUs. However, decreases in streamflow are shown at the Mgeni catchment outlet due to the accumulated impacts of land use change through the catchment. All WMUs in the Upper Breede show decreases in the mean annual accumulated streamflow (Table 6.3) due to irrigated commercial permanent agriculture. For the Luvuvhu catchment, although changes in streamflow due to land use changes were evident in the upper and middle reaches of the catchment at the subcatchment scale, no significant changes in the accumulated streamflow at the WMU or catchment scale were evident due to the natural vegetation regulating these impacts (Table 6.2). Projected changes in mean annual accumulated streamflows under future climate scenarios for the Mgeni, Luvuvhu and Upper Breede catchments are significant. Both CCSM3 future climate scenarios project increases in mean annual streamflows in each of the WMUs in the Mgeni catchment (Table 6.1), EC4 B2 projects increases in mean annual streamflows in all WMUs except the Mpendle WMU, the EC4 A2 scenario projects decreases in mean annual streamflows, and the EC5 A1B scenario projects either slight increases or decreases in the WMUs. Decreases in mean annual accumulated streamflows for each of the WMUs in the Luvuvhu catchment are projected for both CCSM3 scenarios and the EC4 B2 scenario, while the EC4 A2 and EC5 A1B scenarios project increases in mean annual streamflows (Table 6.2). All five future climate scenarios project decreases in mean annual accumulated streamflows for the Upper Breede catchment (Table 6.3).

Table 6.1: Projections of impacts of land use change, possible future climate change and joint land use and climate change on the mean annual accumulated streamflows at the outlets of the WMUs in the Mgeni Catchment

	Upper reaches						**Middle reaches**					**Lower reaches**	
	Mpen dle	Lions River	Kar kloof	Mid mar	Albert Falls	New Hanover	Nagle	Hen-ley	PMB	Table Mount	Mqeka	Inan-da	Dur-ban
Baseline Mean Annual Streamflow (mm)	253.0	212.0	280.0	217.0	220.0	192.8	199.5	232.8	216.9	182.2	151.4	194.0	194.4
Land use impact (% change)	-8	-26	-19	-47	-41	-19	-69	9	17	27	2	11	-44
Climate change impact (% change)													
CCSM3 A1B	8	25	22	16	17	26	20	36	34	37	39	42	28
CCSM3 B2	48	62	56	53	55	66	60	62	63	70	78	80	64
EC4 A2	-21	-16	-13	-17	-16	-14	-15	-14	-14	-14	-11	-12	-14
EC4 B2	-5	1	8	0	4	15	8	20	19	20	24	33	14
EC5 A1B	-6	1	-4	-3	-4	-5	-4	8	6	5	-3	7	0
Land use and climate change impact (% change)													
CCSM3 A1B	1	-4	3	-47	-31	8	-55	45	50	60	41	53	-16
CCSM3 B2	42	-5	39	-19	3	49	-15	73	82	96	81	95	20
EC4 A2	-29	-40	-32	-75	-57	-32	-83	-6	2	11	-10	0	-56
EC4 B2	-10	-21	-10	-57	-39	-2	-64	28	35	46	26	46	-30
EC5 A1B	-14	-25	-23	-65	-50	-20	-76	16	22	29	-1	18	-43

Table 6.2: Projections of impacts of land use change, possible future climate change and joint land use and climate change on the mean annual accumulated streamflows at the outlets of the WMUs in the Luvuvhu Catchment

	Upper reaches				**Middle reaches**								**Lower reaches**	
	Goede-hoop	Albasi ni	Livhu n-gwa	Welte-vrede	Vondo	Nandoni	Mutshin-dudi	Mhinga	Matsa-ringwe	Upper Mutale	Mutale	Mbadi	Lower Mutale	Lower Luvuvhu
Baseline Mean Annual Streamflow (mm)	175.5	151.5	181.0	484.0	395.6	384.6	235.0	253.7	232.8	355.2	291.4	213.9	168.2	201.8
Land use impact (% change)	-4	-4	-2	1	11	4	5	5	4	1	3	3	3	4
Climate change impact (% change)														
CCSM3 A1B	-29	-28	-26	-23	-22	-20	-23	-21	-18	-21	-22	-22	-23	-19
CCSM3 B2	-28	-28	-27	-27	-26	-31	-29	-30	-32	-29	-29	-29	-28	-32
EC4 A2	31	34	32	24	27	31	33	34	36	30	34	37	40	37
EC4 B2	-14	-14	-13	-11	-10	-7	-11	-10	-9	-6	-5	-6	-7	-9
EC5 A1B	21	25	23	20	22	29	27	31	35	27	29	34	37	37
Land use and climate change impact (% change)														
CCSM3 A1B	-34	-33	-30	-23	-13	-17	-20	-18	-16	-20	-20	-20	-21	-16
CCSM3 B2	-32	-31	-30	-26	-18	-27	-26	-27	-30	-28	-27	-27	-26	-30
EC4 A2	26	30	28	24	37	35	37	38	39	31	36	40	42	40
EC4 B2	-17	-18	-15	-10	1	-3	-7	-6	-6	-5	-3	-4	-6	-6
EC5 A1B	17	21	20	20	32	33	31	35	39	29	32	36	40	40

Table 6.3: Projections of impacts of land use change, possible future climate change and joint land use and climate change on the mean annual accumulated streamflows at the outlets of the WMUs in the Upper Breede Catchment

	Upper reaches			**Middle reaches**					**Lower reaches**	
	Upper Breë	Koekedou	Breë	Witrivier	Upper Witrivier	Slanghoek	Elands	Stettynskloof	Jan Du Toits	Brandvlei
Baseline Mean Annual Streamflow (mm)	420.9	194.0	205.4	232.3	454.8	252.6	474.6	368.8	95.5	268.3
Land use impact (% change)	-18	-42	-34	-34	0	-34	-3	-4	-37	-30
Climate change impact (% change)										
CCSM3 A1B	-20	-19	-19	-21	-19	-21	-20	-21	-22	-21
CCSM3 B2	-14	-12	-12	-13	-9	-13	-10	-11	-12	-12
EC4 A2	-34	-35	-34	-34	-26	-35	-31	-35	-47	-35
EC4 B2	-34	-35	-35	-35	-31	-36	-27	-34	-48	-35
EC5 A1B	-14	-11	-11	-11	-15	-10	-9	-6	3	-9
Land use and climate change impact (% change)										
CCSM3 A1B	-35	-44	-42	-45	-18	-47	-21	-22	-51	-44
CCSM3 B2	-31	-38	-35	-37	-8	-38	-11	-12	-41	-36
EC4 A2	-47	-57	-54	-56	-25	-59	-32	-38	-68	-58
EC4 B2	-47	-57	-54	-58	-31	-60	-29	-36	-68	-58
EC5 A1B	-31	-40	-36	-38	-15	-38	-9	-7	-27	-34

When considering the results presented in Tables 6.1, 6.2 and 6.3 two commonalities emerge. The first is that where the land use change impact on mean annual accumulated streamflows is relatively small, the impact of joint land use and climate change on mean annual streamflows appears to be additive. For example, consider the Mpendle WMU in the upper reaches of the Mgeni catchment where the land use change impact on mean annual accumulated streamflows is – 8 % and the climate change impact for the CCSM3 A1B scenario is + 8 %, the combined land use and climate change impact on mean annual streamflows is + 1 % (Table 6.1 and Figure 6.6). Similarly, in the Luvuvhu catchment where the land use change impacts on mean annual accumulated streamflows are relatively small, the joint land use and climate change impacts on mean annual streamflows are additive.

The second commonalty is that once the land use change impact on mean annual accumulated streamflows becomes significant, the impacts of joint land use and climate change on mean annual streamflows are not simply a sum of the land use change and climate change impacts; rather, there is either amplification or dampening of the impacts on streamflow. For example, consider the Midmar WMU where the land use change impact on mean annual accumulated streamflow is a 47 % decrease and the climate change impact for the CCSM3 A1B scenario on mean annual accumulated streamflow is a 16 % increase. If the impact of combined land use and climate change were a simple sum of these impacts the decrease in streamflow would be 31.3 %.

However, the simulated response to this joint land use and climate change is a 47 % decrease in mean annual accumulated streamflow (Table 6.1 and Figure 6.6). In the Upper Breede catchment where both the land use change and climate change impacts on mean annual accumulated streamflows are all negative, the results of jointly simulated land use and climate change indicate a lesser impact than the sum of the separate land use change and climate change (Table 6.3). For example, take the Koekedou WMU where the land use change decreases mean annual streamflow by 41.8 % and the projected decrease due to the EC4 A2 future climate scenario is 35 %. Summed this would result in a 76 % decrease in mean annual streamflow. However, the simulated impacts of joint land use and climate change for this scenario show a 57 % decrease in mean annual accumulated streamflows (Table 6.3).

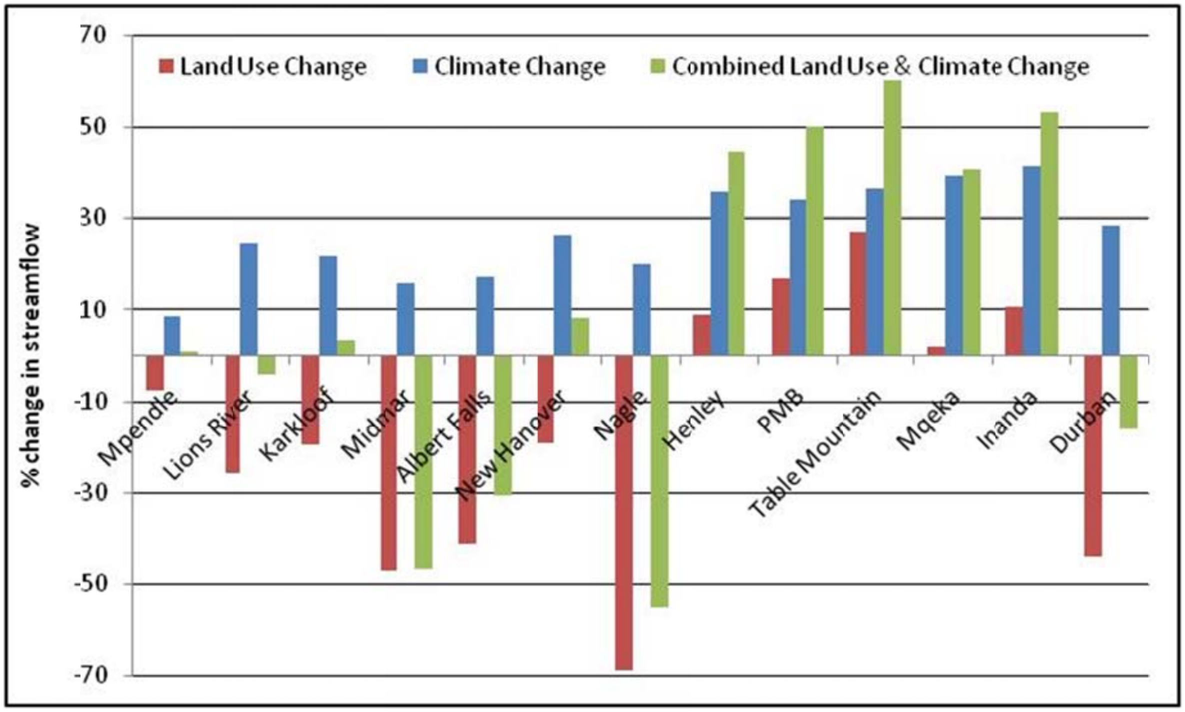

Figure 6.6: Percentage changes in the mean annual accumulated streamflows at the outlets of the WMUs in the Mgeni Catchment under projections of impacts of land use change, of possible future climate change (CCSM3 A1B) and of combined land use and climate change (CCSM3 A1B)

6.3.2 Results at a finer spatial and temporal scale

In order to gain a better understanding of the combined impacts of land use and climate change on streamflows, it is necessary to consider a sub-annual time scale and a subcatchment, and even a land use unit spatial scale. Figure 6.7 shows the impacts of separate land use change, separate climate change and combined land use and climate change on the 10th percentile low, median and 90th percentile high flows of accumulated streamflows in the wet summer season (D, J, F) relative to the flows under baseline land cover conditions for the Mgeni Catchment. The future climate scenario considered was the CCSM3 A1B scenario. Having already shown previously that the combined impacts of land use and climate change on the streamflow response are not simply the summed result of land use change and climate change impacts, this becomes more evident when considering low flows and high flows. For example, consider the subcatchments in the Mpendle WMU (ringed with a circle in Figure 6.7, top left) where land use changes have had negative impacts on the low flows, and negligible to slight negative impacts on median and high flows. The projected impacts of climate change (CCSM3 A1B scenario) on the high, median and low flows of the subcatchments range from no change to a 25% increase. When considering joint land use and climate change, no changes in median flows are evident as the impacts of land use change and those of climate change appear to cancel each other. However, for simulated low flows the combined impacts of land use and climate change are negative, with two subcatchments indicating a stronger negative response than is evident for land use change even though the climate change impact was positive. For high flows, the impacts of combined land use and climate change are positive for the majority of subcatchments, with certain subcatchments indicating a positive response similar to that experienced due to climate change alone even though the impacts of land use change in those subcatchments are negative.

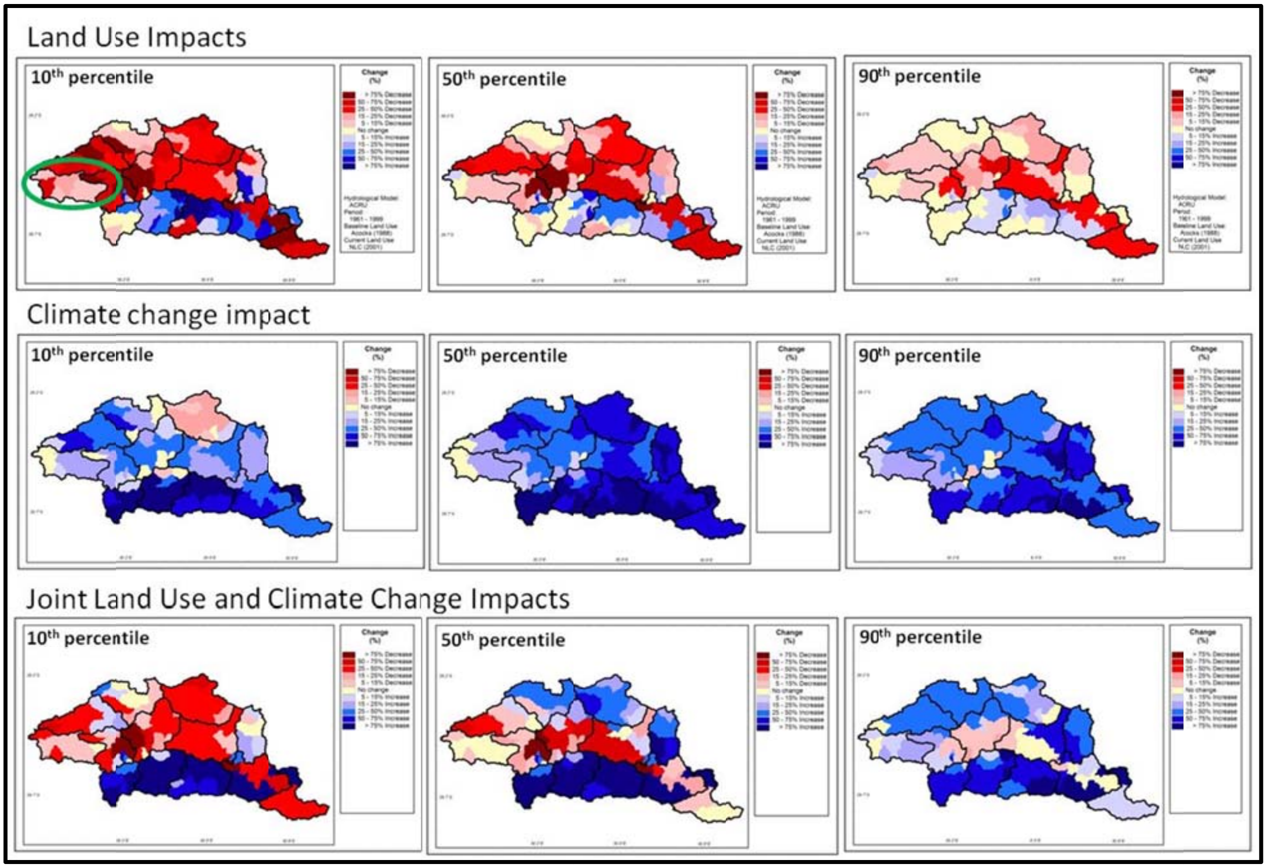

Figure 6.7: Simulated impacts of current land use (top), climate change (middle; CCSM3 A1B future climate scenario) and joint land use and climate change (bottom; CCSM3 A1B future climate scenario) on the 10th percentile low (left), 50th percentile (middle) and 90th percentile high flows (right) of accumulated streamflows in the wet summer season (D, J, F), relative to the flows under baseline land cover conditions for the Mgeni Catchment

Consider also the following two examples to demonstrate the impacts of separate and combined land use and climate change at the homogenous land use unit scale and the subcatchment scale. The first example is taken from the Luvuvhu catchment where the future climate scenario (CCSM3 B2) considered projects a 22 % decrease in MAP for subcatchment thirteen (Figure 6.8). The second example is from the Mgeni catchment where a 14 % increase in MAP for subcatchment 104 (Figure 6.9) is projected by the selected future climate scenario (CCSM3 B2). These examples further illustrate that the impacts of combined land use and climate change on the streamflow responses are complex and, depending on the land use, can have either amplifying or dampening effects.

In the example taken from the Luvuvhu catchment, the summed impacts of land use and climate change for degraded areas, plantation forestry and commercial agriculture are similar to the impacts of combined land use and climate change (Figure 6.8). However, the summed results for subsistence agriculture and informal residential areas are markedly different to those shown for combined land use and climate change (Figure 6.8). In the informal residential land use unit the combined impacts have a dampening effect in comparison to separate effects, however in the subsistence agricultural land use unit there is an amplification effect with combined land use and climate change relative to the separate impacts.

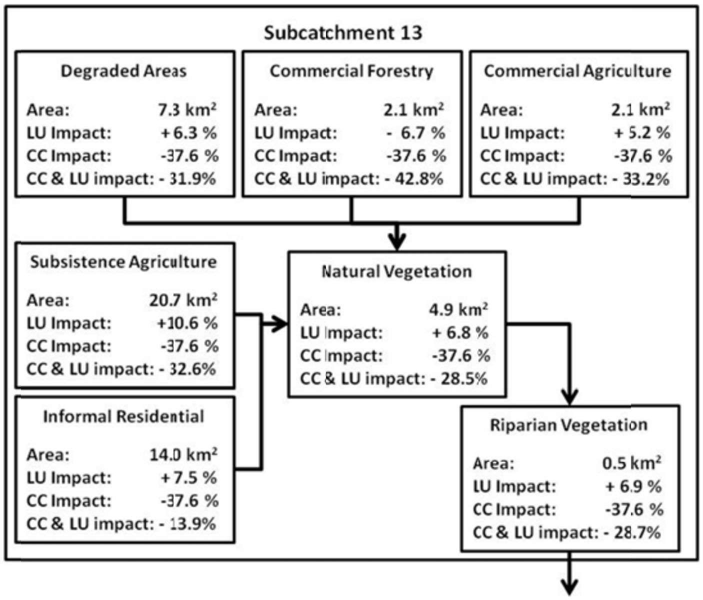

Figure 6.8: Impacts of current land use (LU impact), climate change (CC impact) and combined land use and climate change (LU & CC impact) on mean annual streamflows compared to flows from baseline land cover and historical climate at a homogeneous land use unit and accumulated flows at subcatchment scale shown in the riparian vegetation land use unit in the Luvuvhu catchment

Similarly, for the example from the Mgeni catchment (Figure 6.9), the combined impacts of land use and climate change on the streamflows from the urban land uses of built-up areas, formal residential and informal residential areas are markedly different from the summed results of separate changes. Furthermore, the only land use where the summed result of separate land use and climate change on streamflow is not markedly different from joint land use and climate change is the sugarcane land use unit (Figure 6.9). This finding supports the commonality indicated by Tables 6.1, 6.2 and 6.3 that as the impact of the land use change becomes more significant the combined impacts of land use and climate change are less likely to be a sum of the individual impacts, but that they rather have either an amplification or dampening effect. No general consensus has emerged to determine whether this will be an amplification or dampening effect; however, it appears evident that where urban land uses are present joint land use and climate change will amplify the changes.

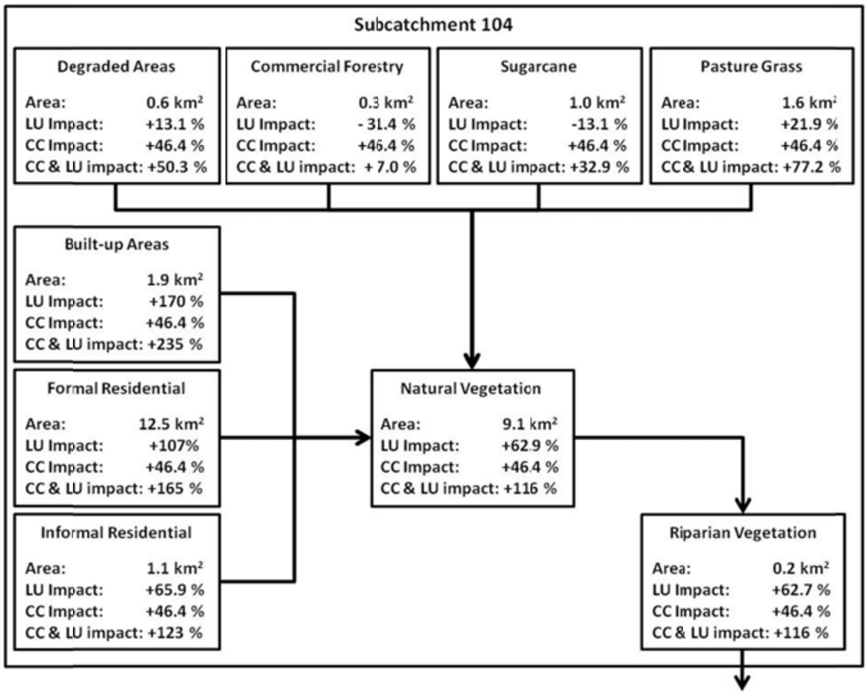

Figure 6.9: Impacts of current land use (LU impact), climate change (CC impact) and combined land use and climate change (LU & CC impact) on mean annual streamflows compared to flows from baseline land cover and historical climate at a homogeneous land use unit and accumulated flows at subcatchment scale shown in the riparian vegetation land use unit in the Mgeni catchment

6.3.3 Changes in land use unit contributions to streamflows under a changing climate

The generated streamflow at the outlets of subcatchments and ultimately at the entire catchment are a reflection of the land uses present within those subcatchments and catchments, as the individual land uses have different hydrological responses. However, as shown by Warburton *et al.* (2012a), the contributions to streamflow from the various land uses are not proportional to the relative area of the land use. In addition, Warburton *et al.* (2012a) showed that catchments with a relatively lower MAP display a greater imbalance between the relative area that the specific land use occupies and its contribution to the catchment mean annual streamflow. Thus, changes in climate may amplify the imbalance between the relative area that the land use occupies and its contribution to the mean annual streamflow.

Take, for example, the hypothetical situation in the Mgeni catchment which Warburton *et al.* (2012a) used, *viz.* a typical subcatchment in terms of soils, which experiences the equivalent of the catchment median annual precipitation and associated climate variables, and in which all nine of the considered land uses are present with each occupying an equal portion of the catchment (i.e. 11.1%). The contributions of streamflows generated on the individual land use components to the entire subcatchment's mean annual streamflow are highly varied (Figure 6.10). For example, the urban built-up areas with their associated impervious areas contribute 21% of the total subcatchment's mean annual streamflow, which is nearly double the relative area the land use occupies in the subcatchment (i.e. 11.1%). In comparison, plantation forestry and sugarcane plantations with their high biomass contribute considerably far less than the relative area they occupy to the mean annual streamflow. As the climate of the subcatchment changes, the relative contributions to streamflow generated on the various land use components will alter.

To understand how changes in climate may alter the contributions of a land use component to the streamflow of a subcatchment, consider an identical hypothetical subcatchment, but where the climate variables reflect plausible projections of future climate. Four plausible projections of future climate were considered in a sensitivity study, *viz.* two drier scenarios of a 10% and 20% decrease in MAP, and two wetter scenarios of a 10% and 20% increase in MAP. These scenarios were within the range of downscaled RCM projections for the subcatchment, for example, the

CCSM3 B2 scenario projects a 14% increase in MAP and the EC4 A2 scenario projects a 12% decrease in MAP. Temperature was not altered.

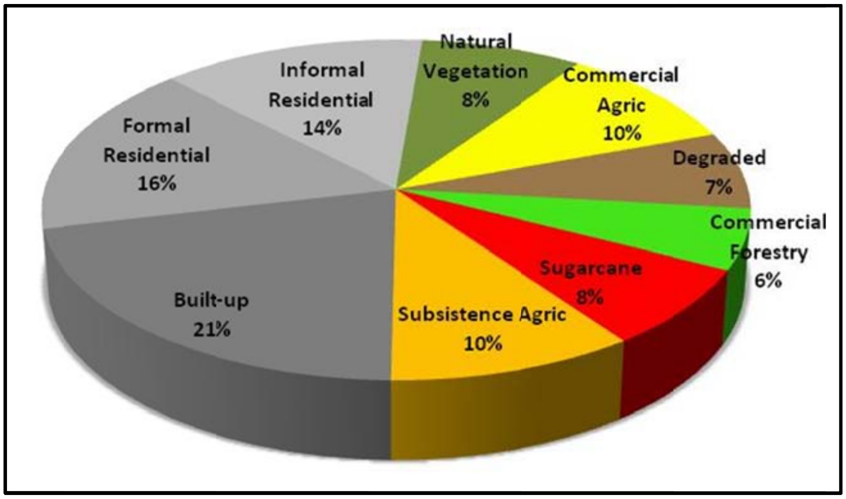

Figure 6.10: Percentage contributions of equally sized land use units to the mean annual streamflow from a hypothetical subcatchment within the Mgeni catchment which experiences a MAP equivalent to the median MAP of the Mgeni catchment under present climate conditions (Warburton *et al.*, 2011a)

Under a wetter future scenario (Figure 6.11) the contributions to streamflow generated from the built-up, formal and informal residential with their associated impervious areas remain greater than the relative area the land use units occupy in the subcatchment. However, due to the increased water availability in the subcatchment the relative contributions to streamflow from the remaining six land uses which have higher biomasses are greater and closer to the relative areas occupied by those land use components. As the projected climate becomes wetter, the disproportion between the relative area the land use occupies and the contribution to streamflow decreases. Under the drier future scenario (Figure 6.12), however the imbalance between the relative area the land use component occupies and its contribution to the mean annual streamflow becomes greater. The change in the proportion contribution to mean annual streamflow appears to be more sensitive to a drying scenario than a wetting scenario. Although this analysis used a typical Mgeni subcatchment, the findings are applicable to a subcatchment in any of the catchments considered in this study.

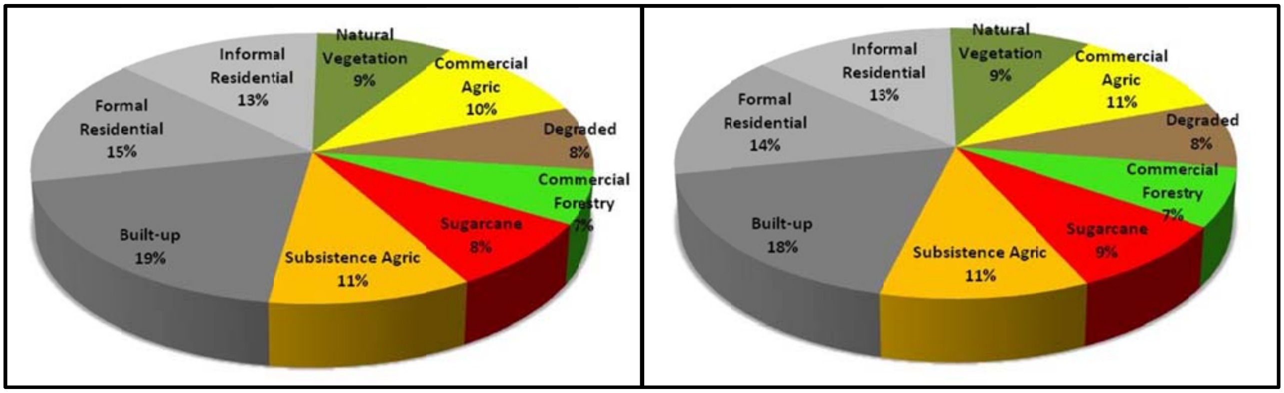

Figure 6.11: Percentage contributions of equally sized land use units to the mean annual streamflow from a hypothetical subcatchment within the Mgeni catchment which experiences a MAP equivalent to the median MAP of the Mgeni catchment under plausible wetter future climates with a 10% increase in MAP (left) and a 20% increase in MAP (right)

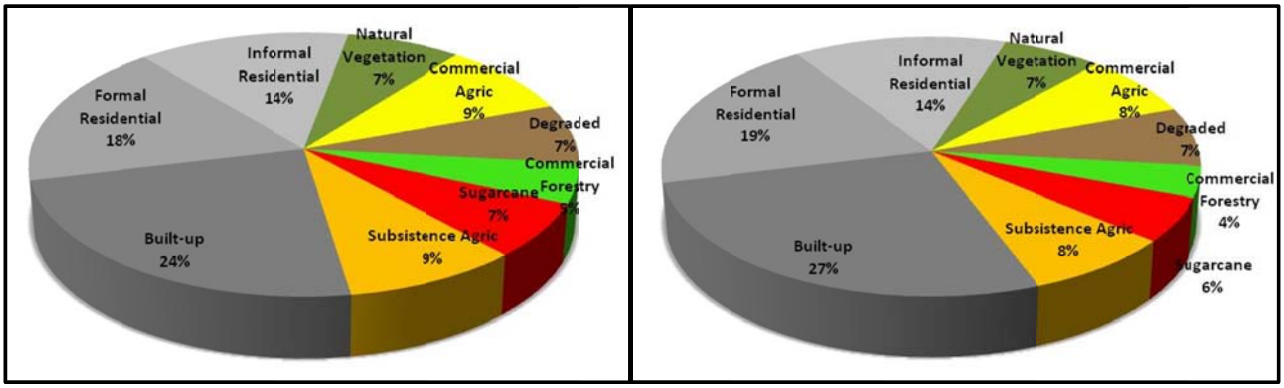

Figure 6.12: Percentage contributions of equally sized land use units to the mean annual streamflow from a hypothetical subcatchment within the Mgeni catchment which experiences a MAP equivalent to the median MAP of the Mgeni catchment under plausible drier future climates with a 10% decrease in MAP (left) and a 20% decrease in MAP (right)

6.4 Discussion

The hydrological system is complex as it is interlinked and connected with the ecological and human systems, with non-linear, dynamic process and feedbacks occurring within and between these systems (Stirzaker *et al*., 2010; Wagner *et al*., 2010). The interactions between land use, climate and streamflow responses are thus complex as they involve non-linear processes and responses with feedbacks between them. From the results presented in this study there is no clear conclusion that either land use change or climate change is more dominant in influencing the streamflow response. Both the temporal and spatial scale at which the assessment takes places influences which appears more dominant.

Furthermore, the nature of the land use change plays a significant role as does the magnitude of the projected climate change with regards to the relative contributions of various land uses to catchment flow. With a wetter climate the disproportion between the relative areas a land use occupies and its contribution to catchment streamflow would decrease. On the other hand, if a catchment's climate becomes drier in the future, the imbalance between the relative area the land use occupies and its contribution to the mean annual streamflow will be enhanced. Thus land uses which currently have significant impacts on catchment water resources will place proportionally greater impacts on the catchment's water resources if the climate were to become drier. For example, commercial irrigated agriculture will place greater relative pressure on water resources under a drier climate due to increased evaporative demands resulting from increased temperatures.

Land uses within catchments seldom remain static, but rather change to meet society's changing demands for food, fibre and housing. In terms of water resources management, the water yield of a catchment could be significantly altered when changes in climate are combined with changes in the land uses within the catchments. The impacts may be particularly great if the changing land use is one whose contribution to streamflow is disproportionate to the land area occupied by that land use (e.g. urban areas) and the change in climate is towards a drier climate. The drier the climate becomes, the more relatively significant the role of land use becomes, as its impact becomes relatively greater.

A number of uncertainties are introduced in a study such as this one which was concerned with the combined impacts of land use and climate change on streamflow response. There are sources of uncertainty related to the downscaled RCM future climate scenarios used (Kundzewicz *et al*., 2007), further uncertainties in the hydrological parameterization and classification of land use scenarios used and both the baseline against which impacts are assessed as well as the hydrological parameterization of that baseline, and lastly uncertainties introduced by the representation of processes in the hydrological model used to project the impacts of the downscaled climate scenarios on catchment streamflow. For the relatively near time horizon used in this study, *viz.* 2021 – 2050, the uncertainties in the climate model *per se* are more significant than the selection of emissions scenario; however, for more distant future scenarios the choice of emissions scenario becomes increasingly important (Jenkins and Lowe, 2003). It has been recognised that the simulation of precipitation from various GCMs is unreliable in comparison to temperature simulations (Covey *et al*., 2003). As rainfall is the primary driver of streamflow responses and is the variable to which the *ACRU* model is the most sensitive (Schulze, 1995), the uncertainties in the impacts of climate change on water resources as described in this study are largely due to the uncertainties in the precipitation outputs from GCMs rather than the emission scenario selected (Döll et al., 2003; Arnell, 2004) or uncertainties in the *ACRU* model.

Although hydrological models have drawbacks associated with them due to inherent uncertainties related to both insufficient knowledge of the processes represented and simplification of processes in the model, they are useful tools in assessing the impacts of land use and climate change on the hydrological response of a complex, operational catchment such as the three catchments used in this study. Confirmation of the ACRU model's ability to simulate streamflow response with past and present hydrological data under a range of climates and land uses by Warburton *et al*. (2010) increases the confidence that the model provides a suitably accurate representation of reality and reduces the uncertainty regarding the model's ability to simulate adequately under future climate scenarios. However, it is no guarantee that the model will continue to simulate streamflow responses adequately in the future, given the assumption made that the hydrological variables remain constant under the future climate scenarios.

When considering any hydrological impacts of land use change, climate change or combined land use and climate change, assessments need to consider the scale where the localized impacts may be evident, the progression of the impacts as the streamflow cascades through the catchment, as well as the impacts at the whole catchment scale where the accumulation of the effects through the catchment are evident. Thus, hydrological models which are able to simulate hydrological responses to land use change, climate change and joint changes thereof are valuable tools in water resources planning as they allow for an assessment of various scenarios and of the impacts of changes at various spatial scales. Furthermore, they provide a mechanism for communicating how a complex system responds to impacts in a simplified manner to allow the system to be appropriately managed (Stirzaker *et al*., 2010).

The impacts of land change shown here have been assessed by comparing the current land use (NLC, 2001) to a baseline land cover represented by Acocks' (1988) Veld Types as this is the reference currently accepted by the South African Department of Water Affairs (DWA) against which to assess land use impacts (Jewitt *et al*., 2009). However, by using the Acocks (1988) Veld Types as a baseline, certain uncertainties may be introduced. The broad scale resolution of the Acocks Veld Type (1988) maps is a first source of uncertainty. The natural vegetation is represented by 70 Veld Types mapped at a country scale with little local scale detail. A second source of uncertainty is introduced through the water use parameters associated with the Acocks Veld Types. Although these parameters were developed on the basis of a consistent application of key climate related drivers of the cycle of vegetation water use throughout a year (Schulze, 2004) and on expert knowledge, there has to date been limited research undertaken to assess the water use of natural vegetation and thus to confirm these values (Jewitt *et al*., 2009). Recently, Mucina and Rutherford (2006) have developed a detailed natural vegetation map for South Africa which defines 435 vegetation units with sufficient spatial resolution and detail for application in regional and local planning. Given the improved spatial resolution of the Mucina and Rutherford (2006) natural vegetation map, it is recommended that this be assessed for use as the hydrological baseline land cover in South Africa. However, with the uncertainties around the hydrological parameterization of different natural vegetation types remaining, the question raised is whether the differences between the two baselines will be significant enough to alter any assessed impacts of current land uses in that region. A further source of uncertainty is that with climate change the location and extent of natural vegetation could shift (Turner *et al.*, 1995; Wasson, 1996) as the regional and local climates are key factors in determining the vegetation. Additionally the optimum climatic locations for agricultural crops and commercial afforestation could shift (Wasson, 1996; Warburton and Schulze, 2008) changing the land use patterns within a catchment. Furthermore, changes in land use in turn influence the climate through alterations in surface roughness, albedo, latent and sensible heat flux, all of which are determined by the land cover. Any changes in the distribution of land covers have the potential to alter the regional and possibly the global balance of these fluxes (Turner *et al.*, 1995; Kueppers *et al.*, 2007).

Beyond land use and climate change, catchment water resources have numerous other demands placed on them through population growth and economic development. Water quality deterioration due to anthropogenic activities makes meeting water demands more difficult. Declining water quality and anthropogenic demands add further complexity to the dynamics between land use, climate and water resources and should be considered in further studies.

6.5 Conclusion

The results shown in this paper contextualise the understanding of the impacts of land use and climate change on the hydrological response of operational South African catchments in a water scarce country where comprehensive, adaptive water resources planning is essential to ensuring adequate water resources. Further emphasis needs to be given to the importance of the integration of land use and climate change assessments into water resources planning. To adequately manage water resources, the impacts of land use and climate change need to be assessed at various scales. Furthermore, the accumulation of streamflow through the catchment should be included in the assessment. Each catchment is unique with its own complexities, feed forwards and feedbacks, thus each catchment will have a unique threshold of where land use change or climate change begins to have a significant influence of the hydrological response. This study has illustrated the benefits of applying a daily time-step, model which is sensitive to both climate and land use with a high level of confidence in its ability to provide realistic results exists, to better understand the interactions of land use change and climate change at different spatial and temporal scales. It thus provides a sound basis for similar studies in other catchments.

6.6 Acknowledgements

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6.8 Appendix

Appendix 6.A: Monthly values of water use coefficients, canopy interception per rain day, root mass distribution in the topsoil, coefficient of initial abstractions and index of suppression of soil water evaporation by a litter/mulch layer, for the land uses occurring in the Mgeni, Luvuvhu and Upper Breede catchment (Schulze, 2004)

		Monthly values											
Land Use	**Variable**	**Jan**	**Feb**	**Mar**	**Apr**	**May**	**Jun**	**Jul**	**Aug**	**Sep**	**Oct**	**Nov**	**Dec**
Commercial Forestry													
- *Acacia*	CAY	0.90	0.90	0.90	0.88	0.85	0.86	0.89	0.90	0.92	0.92	0.90	0.90
	VEGINT	2.00	2.00	2.00	2.00	1.90	1.85	1.85	1.85	1.90	1.95	2.00	2.00
	ROOTA	0.83	0.83	0.83	0.83	0.83	0.83	0.83	0.83	0.83	0.83	0.83	0.83
	COAIM	0.25	0.25	0.25	0.30	0.30	0.30	0.30	0.30	0.30	0.30	0.25	0.25
	PCSUCO	100	100	100	100	100	100	100	100	100	100	100	100
- *Eucalyptus*	CAY	0.95	0.95	0.95	0.95	0.95	0.95	0.95	0.95	0.95	0.95	0.95	0.95
	VEGINT	2.50	2.50	2.50	2.50	2.50	2.50	2.50	2.50	2.50	2.50	2.50	2.50
	ROOTA	0.65	0.65	0.65	0.65	0.65	0.65	0.65	0.65	0.65	0.65	0.65	0.65
	COAIM	0.35	0.35	0.35	0.35	0.35	0.35	0.35	0.35	0.35	0.35	0.35	0.35
	PCSUCO	100	100	100	100	100	100	100	100	100	100	100	100
- *Pinus*	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
	VEGINT	3.50	3.50	3.50	3.50	3.50	3.50	3.50	3.50	3.50	3.50	3.50	3.50
	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
	COAIM	0.35	0.35	0.35	0.35	0.35	0.35	0.35	0.35	0.35	0.35	0.35	0.35
	PCSUCO	100	100	100	100	100	100	100	100	100	100	100	100
Agriculture													
- Dryland temporary commercial agriculture	CAY	0.99	0.84	0.30	0.30	0.30	0.30	0.30	0.30	0.30	0.30	0.48	0.78
	VEGINT	1.40	1.40	1.40	1.20	1.00	1.00	1.00	0.80	0.00	0.00	0.80	1.40
	ROOTA	0.78	0.91	1.00	1.00	1.00	1.00	1.00	1.00	1.00	0.92	0.79	0.74
	COAIM	0.20	0.20	0.25	0.30	0.30	0.30	0.30	0.30	0.30	0.35	0.30	0.25
	PCSUCO	65.0	65.0	65.0	65.0	65.0	65.0	65.0	65.0	65.0	65.0	65.0	65.0
- Irrigated temporary commercial agriculture	CAY	0.70	0.70	0.70	0.70	0.70	0.70	0.70	0.70	0.70	0.70	0.70	0.70
	VEGINT	1.40	1.40	1.40	1.20	1.00	1.00	1.00	0.80	0.00	0.00	0.80	1.40
	ROOTA	0.78	0.91	1.00	1.00	1.00	1.00	1.00	1.00	1.00	0.92	0.79	0.74
	COAIM	0.20	0.20	0.25	0.30	0.30	0.30	0.30	0.30	0.30	0.35	0.30	0.25
	PCSUCO	65.0	65.0	65.0	65.0	65.0	65.0	65.0	65.0	65.0	65.0	65.0	65.0
- Irrigated permanent commercial agriculture	CAY	0.80	0.80	0.80	0.70	0.60	0.50	0.50	0.50	0.60	0.70	0.80	0.80
	PCSUCO	65.0	65.0	65.0	65.0	65.0	65.0	65.0	65.0	65.0	65.0	65.0	65.0
	VEGINT	1.40	1.40	1.40	1.40	1.20	1.00	1.00	1.20	1.30	1.40	1.40	1.40
	ROOTA	0.80	0.80	0.80	0.90	1.00	1.00	1.00	1.00	0.90	0.90	0.80	0.80

	COAIM	0.30	0.30	0.30	0.30	0.30	0.30	0.30	0.30	0.30	0.30	0.30	0.30
	PCSUCO	65.0	65.0	65.0	65.0	65.0	65.0	65.0	65.0	65.0	65.0	65.0	65.0
- Commercial Sugarcane	CAY (inland)	0.83	0.83	0.83	0.83	0.83	0.83	0.83	0.83	0.83	0.83	0.83	0.83
	CAY (coastal)	0.86	0.86	0.86	0.86	0.86	0.86	0.86	0.86	0.86	0.86	0.86	0.86
	VEGINT (inland)	1.70	1.70	1.70	1.70	1.70	1.70	1.70	1.70	1.70	1.70	1.70	1.70
	VEGINT (coastal)	1.90	1.90	1.90	1.90	1.90	1.90	1.90	1.90	1.90	1.90	1.90	1.90
	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
	COAIM	0.35	0.35	0.35	0.35	0.35	0.35	0.35	0.35	0.35	0.35	0.35	0.35
	PCSUCO	100	100	100	100	100	100	100	100	100	100	100	100
- Pasture grass	CAY	0.55	0.55	0.55	0.55	0.35	0.20	0.20	0.20	0.35	0.45	0.55	0.55
	VEGINT	0.70	0.70	0.70	0.70	0.70	0.70	0.70	0.70	0.70	0.70	0.70	0.70
	ROOTA	0.95	0.95	0.95	0.95	0.95	1.00	1.00	1.00	0.95	0.95	0.95	0.95
	COAIM	0.15	0.15	0.15	0.25	0.30	0.30	0.30	0.30	0.30	0.30	0.20	0.15
	PCSUCO	64.0	64.0	64.0	64.0	64.0	64.0	64.0	64.0	64.0	64.0	64.0	64.0
- Subsistence agriculture	CAY	0.80	0.70	0.30	0.30	0.30	0.30	0.30	0.30	0.30	0.30	0.35	0.60
	VEGINT	1.00	1.00	0.60	0.50	0.50	0.50	0.50	0.50	0.50	0.00	0.50	0.80
	ROOTA	0.74	0.78	0.91	1.00	1.00	1.00	1.00	1.00	1.00	1.00	0.92	0.79
	COAIM	0.20	0.20	0.25	0.30	0.30	0.30	0.20	0.20	0.20	0.35	0.30	0.25
	PCSUCO	50.0	50.0	50.0	50.0	50.0	50.0	50.0	50.0	50.0	50.0	50.0	50.0
Urbanised Areas													
- Built-up (CBD, industrial areas)	CAY (inland)	0.70	0.70	0.70	0.60	0.30	0.30	0.30	0.30	0.45	0.65	0.70	0.70
	CAY (coastal)	0.80	0.80	0.80	0.70	0.50	0.50	0.50	0.50	0.55	0.75	0.80	0.80
	VEGINT (inland)	1.40	1.40	1.40	1.40	1.20	1.20	1.20	1.20	1.30	1.40	1.40	1.40
	VEGINT (coastal)	1.60	1.60	1.60	1.60	1.40	1.40	1.40	1.40	1.50	1.60	1.60	1.60
	ROOTA	0.80	0.80	0.80	0.90	1.00	1.00	1.00	1.00	0.95	0.80	0.80	0.80
	COAIM	0.15	0.15	0.20	0.25	0.30	0.30	0.30	0.30	0.30	0.25	0.20	0.15
	PCSUCO	50.0	50.0	50.0	50.0	50.0	50.0	50.0	50.0	50.0	50.0	50.0	50.0
- Formal Residential (Suburbs, flats, includes educational areas)	CAY (inland)	0.80	0.80	0.70	0.60	0.40	0.40	0.40	0.40	0.60	0.70	0.80	0.80
	CAY (coastal)	0.80	0.80	0.80	0.70	0.60	0.50	0.50	0.50	0.50	0.60	0.80	0.80
	VEGINT (inland)	1.40	1.40	1.30	1.20	1.10	1.00	1.00	1.00	1.00	1.30	1.40	1.40
	VEGINT (coastal)	1.50	1.50	1.50	1.50	1.30	1.20	1.20	1.20	1.20	1.30	1.50	1.50
	ROOTA	0.85	0.85	0.85	0.90	0.95	0.95	0.95	0.95	0.90	0.85	0.85	0.85
	COAIM	0.20	0.20	0.20	0.30	0.30	0.30	0.30	0.30	0.30	0.30	0.25	0.20
	PCSUCO	60.0	60.0	60.0	60.0	60.0	60.0	60.0	60.0	60.0	60.0	60.0	60.0
- Informal Residential													
- Urban & Rural Informal (differentiation in impervious areas)	CAY	0.65	0.65	0.65	0.55	0.30	0.20	0.20	0.20	0.30	0.50	0.55	0.65
	VEGINT	1.50	1.50	1.50	1.50	1.50	1.50	1.50	1.50	1.50	1.50	1.50	1.50
	ROOTA	0.90	0.90	0.90	0.94	0.98	1.00	1.00	1.00	1.00	0.95	0.90	0.90
	COAIM	0.15	0.15	0.15	0.20	0.30	0.30	0.30	0.30	0.30	0.30	0.20	0.15
	PCSUCO	64.0	64.0	64.0	64.0	64.0	64.0	64.0	64.0	64.0	64.0	64.0	64.0
Degraded Natural Vegetation	CAY	0.55	0.55	0.55	0.45	0.25	0.20	0.20	0.20	0.40	0.45	0.55	0.55
	VEGINT	0.80	0.80	0.80	0.70	0.60	0.60	0.60	0.60	0.65	0.75	0.80	0.80
	ROOTA	0.90	0.90	0.90	0.95	0.95	1.00	1.00	1.00	0.95	0.90	0.90	0.90
	COAIM	0.10	0.10	0.10	0.15	0.15	0.20	0.20	0.20	0.20	0.15	0.10	0.10
	PCSUCO	10.0	10.0	10.0	10.0	10.0	10.0	10.0	10.0	10.0	10.0	10.0	10.0
Alien Vegetation	CAY	0.90	0.90	0.90	0.90	0.90	0.90	0.90	0.90	0.90	0.90	0.90	0.90

	VEGINT	1.70	1.70	1.70	1.70	1.70	1.70	1.70	1.70	1.70	1.70	1.70	1.70
	ROOTA	0.70	0.70	0.70	0.70	0.70	0.70	0.70	0.70	0.70	0.70	0.70	0.70
	COAIM	0.35	0.35	0.35	0.35	0.35	0.35	0.35	0.35	0.35	0.35	0.35	0.35
	PCSUCO	85.0	85.0	85.0	85.0	85.0	85.0	85.0	85.0	85.0	85.0	85.0	85.0

Appendix 6.B: Monthly values of water use coefficients, canopy interception per rainday, root mass distribution in the topsoil, coefficient of initial abstractions and index of suppression of soil water evaporation by a litter/mulch layer, for the Acocks Veld Types (1988) occurring in the Mgeni, Upper Breede and Luvuvhu catchment (Schulze, 2004)

		Monthly values											
Acocks Veld Type	**Variable**	**Jan**	**Feb**	**Mar**	**Apr**	**May**	**Jun**	**Jul**	**Aug**	**Sep**	**Oct**	**Nov**	**Dec**
Coastal Forest & Thornveld, Mgeni Catchment	CAY	0.85	0.85	0.85	0.85	0.75	0.65	0.65	0.75	0.85	0.85	0.85	0.85
	VEGINT	3.10	3.10	3.10	3.10	2.50	2.00	2.00	2.50	3.10	3.10	3.10	3.10
	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
	COAIM	0.30	0.30	0.30	0.30	0.30	0.30	0.30	0.30	0.30	0.30	0.30	0.30
	PCSUCO	100	100	100	100	100	100	100	100	100	100	100	100
Highland & Dohne Sourveld, Mgeni Catchment	CAY	0.70	0.70	0.70	0.50	0.30	0.20	0.20	0.20	0.50	0.65	0.70	0.70
	VEGINT	1.60	1.60	1.60	1.40	1.20	1.00	1.00	1.00	1.3	1.60	1.60	1.60
	ROOTA	0.90	0.90	0.90	0.95	1.00	1.00	1.00	1.00	0.95	0.90	0.90	0.90
	COAIM	0.15	0.15	0.25	0.30	0.30	0.30	0.30	0.30	0.30	0.30	0.2	0.15
	PCSUCO	73.4	73.4	73.4	73.4	73.4	73.4	73.4	73.4	73.4	73.4	73.4	73.4
Natal Mist Belt 'Ngongoniveld, Mgeni Catchment	CAY	0.70	0.70	0.70	0.50	0.35	0.25	0.20	0.20	0.55	0.70	0.70	0.70
	VEGINT	1.50	1.50	1.50	1.30	1.10	1.10	1.10	1.10	1.40	1.50	1.50	1.50
	ROOTA	0.90	0.90	0.90	0.94	0.96	1.00	1.00	1.00	0.95	0.90	0.90	0.90
	COAIM	0.15	0.15	0.20	0.30	0.30	0.30	0.30	0.30	0.30	0.30	0.2	0.15
	PCSUCO	73.4	73.4	73.4	73.4	73.4	73.4	73.4	73.4	73.4	73.4	73.4	73.4
Ngongoni Veld – Zululand, Mgeni Catchment	CAY	0.70	0.70	0.70	0.65	0.55	0.50	0.50	0.55	0.60	0.65	0.65	0.70
	VEGINT	1.40	1.40	1.40	1.40	1.30	1.20	1.20	1.30	1.40	1.40	1.40	1.40
	ROOTA	0.90	0.90	0.90	0.90	0.95	0.95	0.95	0.95	0.90	0.90	0.90	0.90
	COAIM	0.20	0.20	0.25	0.30	0.30	0.30	0.30	0.30	0.30	0.30	0.25	0.20
	PCSUCO	73.4	73.4	73.4	73.4	73.4	73.4	73.4	73.4	73.4	73.4	73.4	73.4
Southern Tall Grassveld, Mgeni Catchment	CAY	0.75	0.75	0.75	0.5	0.40	0.20	0.20	0.20	0.55	0.70	0.75	0.75
	VEGINT	1.60	1.60	1.60	1.60	1.50	1.40	1.40	1.40	1.50	1.60	1.60	1.60
	ROOTA	0.90	0.90	0.90	0.95	0.95	1.00	1.00	1.00	0.95	0.90	0.90	0.90
	COAIM	0.15	0.15	0.2	0.30	0.30	0.30	0.30	0.30	0.30	0.30	0.20	0.15

	PCSUCO	82.3	82.3	82.3	82.3	82.3	82.3	82.3	82.3	82.3	82.3	82.3	82.3
Valley Bushveld, Mgeni Catchment	CAY	0.75	0.75	0.75	0.65	0.55	0.20	0.20	0.40	0.60	0.75	0.75	0.75
	VEGINT	2.50	2.50	2.50	2.20	2.00	2.00	1.90	1.90	2.20	2.50	2.50	2.50
	ROOTA	0.80	0.80	0.80	0.85	0.90	1.00	1.00	0.95	0.90	0.80	0.80	0.80
	COAIM	0.20	0.20	0.25	0.30	0.30	0.30	0.30	0.30	0.30	0.25	0.20	0.20
	PCSUCO	82.3	82.3	82.3	82.3	82.3	82.3	82.3	82.3	82.3	82.3	82.3	82.3
Coastal Rhenosterbosveld Upper Breede Catchment	CAY	0.40	0.40	0.40	0.45	0.50	0.50	0.50	0.50	0.50	0.45	0.40	0.40
	VEGINT	0.80	0.80	0.80	1.00	1.20	1.20	1.20	1.20	1.00	0.80	0.80	0.80
	ROOTA	0.95	0.95	0.95	0.90	0.90	0.90	0.90	0.90	0.95	0.95	0.95	0.95
	COAIM	0.30	0.30	0.30	0.30	0.30	0.30	0.30	0.30	0.30	0.30	0.30	0.30
	PCSUCO	37.8	37.8	37.8	37.8	37.8	37.8	37.8	37.8	37.8	37.8	37.8	37.8
Macchia Upper Breede Catchment	CAY	0.45	0.45	0.50	0.60	0.60	0.60	0.60	0.60	0.60	0.55	0.50	0.45
	VEGINT	1.00	1.00	1.10	1.20	1.20	1.20	1.20	1.20	1.10	1.10	1.00	1.00
	ROOTA	0.80	0.80	0.80	0.80	0.80	0.80	0.80	0.80	0.80	0.80	0.80	0.80
	COAIM	0.30	0.30	0.30	0.30	0.30	0.30	0.30	0.30	0.30	0.30	0.30	0.30
	PCSUCO	55.6	55.6	55.6	55.6	55.6	55.6	55.6	55.6	55.6	55.6	55.6	55.6
Mountain Rhenosterbosveld Upper Breede Catchment	CAY	0.30	0.30	0.30	0.30	0.50	0.40	0.30	0.30	0.30	0.30	0.30	0.30
	VEGINT	0.30	0.30	0.30	0.30	0.30	0.30	0.30	0.30	0.30	0.30	0.30	0.30
	ROOTA	0.80	0.80	0.80	0.80	0.90	1.00	1.00	1.00	0.90	0.80	0.80	0.80
	COAIM	0.30	0.30	0.30	0.30	0.30	0.30	0.30	0.30	0.30	0.30	0.30	0.30
	PCSUCO	37.8	37.8	37.8	37.8	37.8	37.8	37.8	37.8	37.8	37.8	37.8	37.8
Arid Lowveld Luvuvhu Catchment	CAY	0.80	0.75	0.60	0.50	0.45	0.40	0.40	0.40	0.40	0.50	0.75	0.80
	VEGINT	2.10	2.10	2.10	2.00	1.90	1.80	1.80	1.80	1.90	2.00	2.10	2.10
	ROOTA	0.80	0.80	0.80	0.85	0.90	0.90	0.90	0.90	0.85	0.80	0.80	0.80
	COAIM	0.15	0.15	0.25	0.30	0.30	0.30	0.30	0.30	0.30	0.30	0.20	0.15
	PCSUCO	91.2	91.2	91.2	91.2	91.2	91.2	91.2	91.2	91.2	91.2	91.2	91.2
Arid Sweet Bushveld Luvuvhu Catchment	CAY	0.75	0.60	0.50	0.45	0.35	0.30	0.20	0.20	0.40	0.55	0.65	0.75
	VEGINT	1.60	1.60	1.60	1.50	1.30	1.20	1.10	1.10	1.20	1.40	1.60	1.60
	ROOTA	0.80	0.80	0.80	0.85	0.90	0.95	1.00	1.00	0.95	0.90	0.80	0.80
	COAIM	0.15	0.15	0.20	0.30	0.30	0.30	0.30	0.30	0.30	0.30	0.20	0.15
	PCSUCO	82.3	82.3	82.3	82.3	82.3	82.3	82.3	82.3	82.3	82.3	82.3	82.3
Mopani Veld Luvuvhu Catchment	CAY	0.75	0.55	0.50	0.40	0.40	0.40	0.40	0.40	0.40	0.50	0.60	0.75
	VEGINT	1.80	1.60	1.50	1.50	1.50	1.40	1.30	1.30	1.30	1.50	1.70	1.80
	ROOTA	0.80	0.80	0.80	0.85	0.90	0.90	0.90	0.90	0.85	0.80	0.80	0.80
	COAIM	0.15	0.15	0.20	0.30	0.30	0.30	0.30	0.30	0.30	0.30	0.20	0.15
	PCSUCO	82.3	82.3	82.3	82.3	82.3	82.3	82.3	82.3	82.3	82.3	82.3	82.3
Mixed Bushveld Luvuvhu Catchment	CAY	0.75	0.75	0.65	0.55	0.40	0.20	0.20	0.30	0.55	0.60	0.75	0.75
	VEGINT	2.60	2.60	2.40	2.20	2.00	2.00	2.00	2.20	2.40	2.40	2.60	2.60
	ROOTA	0.80	0.80	0.80	0.85	0.90	1.00	1.00	1.00	0.90	0.80	0.80	0.80
	COAIM	0.15	0.15	0.20	0.30	0.30	0.30	0.30	0.30	0.30	0.30	0.20	0.15
	PCSUCO	82.3	82.3	82.3	82.3	82.3	82.3	82.3	82.3	82.3	82.3	82.3	82.3

North-Eastern Mountain Sourveld	CAY	0.75	0.75	0.75	0.60	0.50	0.25	0.25	0.25	0.50	0.70	0.70	0.75
Luvuvhu Catchment	VEGINT	2.60	2.60	2.60	2.40	2.20	2.00	2.00	2.00	2.20	2.60	2.60	2.60
	ROOTA	0.80	0.80	0.80	0.85	0.90	1.00	1.00	1.00	0.87	0.80	0.80	0.80
	COAIM	0.20	0.20	0.25	0.30	0.30	0.30	0.30	0.30	0.30	0.30	0.25	0.20
	PCSUCO	82.3	82.3	82.3	82.3	82.3	82.3	82.3	82.3	82.3	82.3	82.3	82.3
Lowveld Sour Bushveld	CAY	0.75	0.75	0.75	0.70	0.65	0.60	0.55	0.55	0.60	0.75	0.75	0.75
Luvuvhu Catchment	VEGINT	2.50	2.50	2.50	2.40	2.20	2.00	2.00	2.20	2.40	2.50	2.50	2.50
	ROOTA	0.80	0.80	0.80	0.85	0.85	0.90	0.90	0.90	0.85	0.80	0.80	0.80
	COAIM	0.15	0.15	0.20	0.30	0.30	0.30	0.30	0.30	0.30	0.30	0.20	0.15
	PCSUCO	82.3	82.3	82.3	82.3	82.3	82.3	82.3	82.3	82.3	82.3	82.3	82.3
Sourish Mixed Bushveld	CAY	0.75	0.75	0.75	0.60	0.45	0.20	0.20	0.20	0.55	0.70	0.75	0.75
Luvuvhu Catchment	VEGINT	2.70	2.70	2.60	2.20	2.00	2.00	2.00	2.00	2.20	2.50	2.70	2.70
	ROOTA	0.80	0.80	0.80	0.85	0.90	1.00	1.00	0.90	0.85	0.80	0.80	0.80
	COAIM	0.15	0.15	0.20	0.30	0.30	0.30	0.30	0.30	0.30	0.30	0.20	0.15
	PCSUCO	82.3	82.3	82.3	82.3	82.3	82.3	82.3	82.3	82.3	82.3	82.3	82.3
Sour Bushveld	CAY	0.75	0.75	0.75	0.60	0.45	0.20	0.20	0.20	0.55	0.70	0.75	0.75
Luvuvhu Catchment	VEGINT	2.70	2.70	2.60	2.20	2.00	2.00	2.00	2.00	2.20	2.50	2.70	2.70
	ROOTA	0.80	0.80	0.80	0.85	0.90	1.00	1.00	0.90	0.85	0.80	0.80	0.80
	COAIM	0.15	0.15	0.20	0.30	0.30	0.30	0.30	0.30	0.30	0.25	0.20	0.15
	PCSUCO	82.3	82.3	82.3	82.3	82.3	82.3	82.3	82.3	82.3	82.3	82.3	82.3

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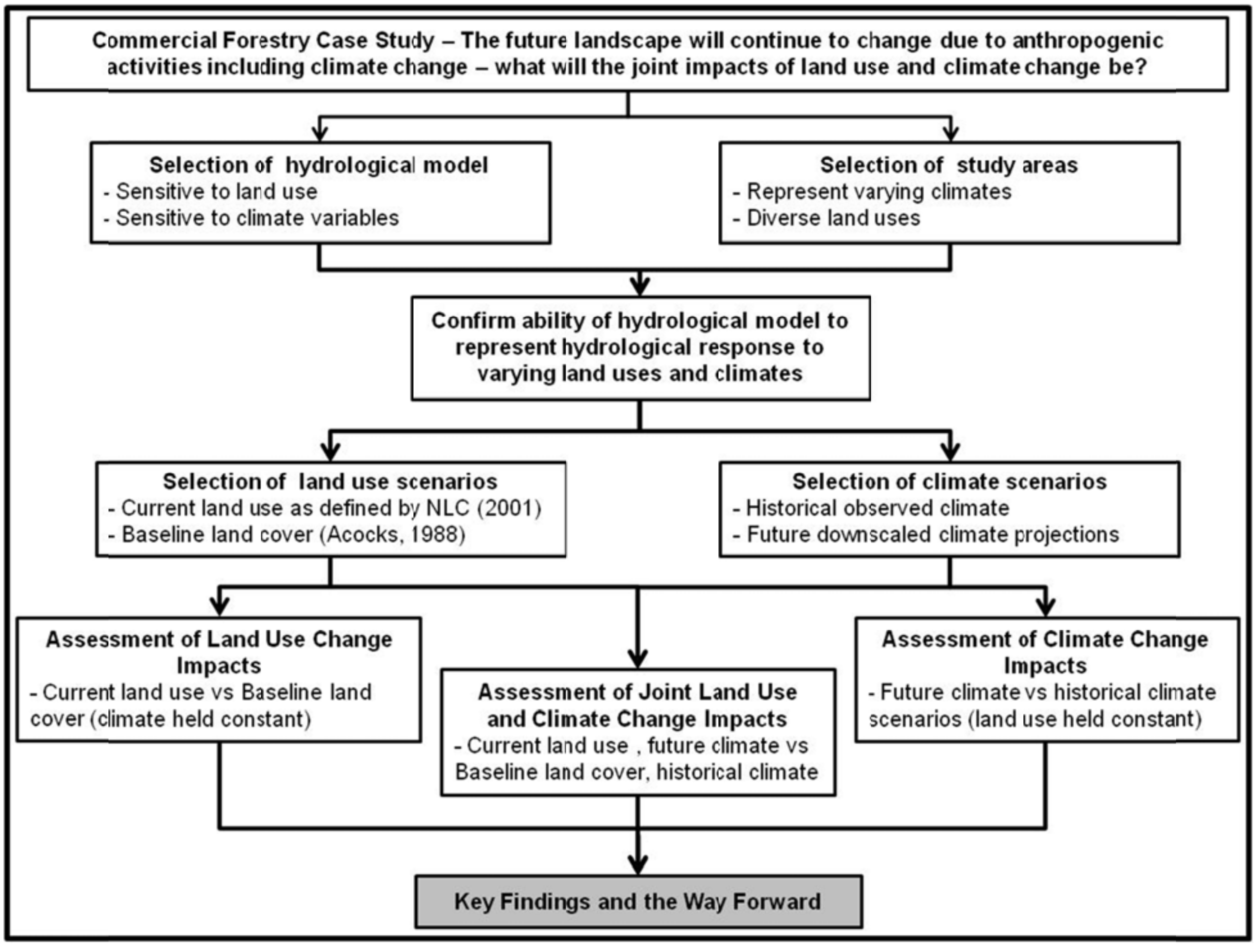
Lead in to Chapter 7

With the overall objective of the research to advance the understanding of the interactions between land use change, climate change and hydrological response to allow for improved integration of land use planning in conjunction with climate change adaptation into water resources management addressed in Chapter 6, Chapter 7 highlights key findings of the research and discusses the way forward (as highlighted in the figure below).



7. SYNTHESIS: KEY ISSUES AND THE WAY FORWARD

The research presented in this thesis displays a progression from a simple climate scenario analysis considering one land use only to a detailed study considering five downscaled GCM derived climate scenarios of present and projected future climates applied to complex, operational catchments, and in each case results were considered to be realistically simulated. From the research presented two important concepts, each with their own key findings, emerged in relation to water resources planning and management for a changing environment. The first of these concepts is **the usefulness and benefit of applying a daily time-step hydrological model** to better understand the impacts and complex interactions of separate and joint land use change and climate change on hydrological responses at different spatial and temporal scales. The key findings related to this concept were:

- that the daily time-step, physical-conceptual and process-based *ACRU* model is appropriate for use in land use change and climatic change impact studies as shown through a space for time study; and
- that when considering any hydrological impacts of land use change, climate change or combined land use and climate change, assessments need to consider the scale where the localized impacts may be evident, the progression of the impacts as the streamflow cascades through the catchment, as well as the impacts at the whole catchment scale where the accumulation of the effects through the catchment are evident

The second concept was around **the complexity of the interactions** which occur between land use change, climate change and hydrological responses. The key findings relating to this concept included:

- that the climatic variable to which plantation forestry species are most sensitive is rainfall;
- that optimum growth areas for plantation forestry will shift under changing climates, having a potentially significant impact on the landscape and thus on the hydrological responses from the landscape;
- that the contributions of different land uses to the streamflow generated from a catchment is not proportional to the relative area of that land use, and that as the mean annual

precipitation of a subcatchment decreases, so the disparities between the relative areas a land use occupies and its contribution to catchment streamflow increases;

- that specific land use changes have a greater impact on different components of the hydrological response of a catchment;
- that land uses which currently have significant impacts on catchment water resources will place proportionally greater impacts on the catchment's water resources if the climate were to become drier; thus the drier the climate becomes, the more relatively significant the role of land use becomes; and
- that each catchment is unique with its own complexities, feed forwards and feedbacks, thus each catchment will have a unique threshold of where land use change or climate change begins to have a significant influence of the hydrological response.

The key findings related to these two concepts are discussed in detail below.

7.1 Hydrological Modelling as a Tool in Impact Studies

Hydrological models are highly useful tools in assessing impacts of environmental change, including both land use and climatic change, on hydrological responses of catchments – ranging from those catchments where conditions are close to natural to more complex, highly impacted and developed catchments. However, models also have drawbacks associated with them due to inherent uncertainties related to both insufficient knowledge of the processes represented, and simplification of processes, in the model as well as uncertainties in the climate impact data in regard to data quality and the spatial representativeness of the climate stations from which daily data are available.

The usefulness and value of the hydrological model in environmental change studies for water resources planning is that it facilitates the investigation of the impacts at various spatial and temporal scales, as well as the ability to undertake scenario analyses. This usefulness and value is evident from the use of hydrological models, such as *ACRU*, by water boards such as Umgeni Water (e.g. Summerton, 2008), by consultants (e.g. Rivers-Moore *et al.*, 2007), as well as the streamflow reduction activities decision framework being based on simulation results from a hydrological model (Jewitt *et al*., 2009). When considering the impacts of environmental change on hydrological responses, assessments need to not only consider the catchment scale at which the accumulated effects of changes in the catchment are evident, but also the local scale within catchments where the localised impacts may be evident, and also the progression of the impacts through the catchment. Furthermore, hydrological models offer the benefit of extending short observed streamflow records or simulating streamflow data where rainfall data, but no observed streamflow data, are available.

However, prior to using a hydrological model for environmental change impact studies, its ability and acceptance needs be demonstrated through confirmation studies, and in particular confirmation studies at a daily time interval because diurnality is a natural time step and many hydrological processes can be represented conveniently at that temporal interval. Such confirmation studies, in which the ability of the model to simulate streamflows adequately using past and present observational data under widely ranging climatic and land use conditions is tested, increases the confidence that the model's process representations are a relatively accurate reflection of reality at a daily time step and over a range of climatic regions and land uses. Depending on the model structure, however, confirmation studies provide no guarantee that the model will continue to adequately represent hydrological processes under future conditions, especially in the case of models that require parameter calibration, neither do confirmation studies imply that the model is a truthful representation of reality. Instead, they support the likelihood that the model portrays a correct representation of reality. Thus, the greater the number and range of confirmation studies, the greater the likelihood that the model is fundamentally sound (Oreskes *et al*., 1994), especially if the model has a physical-conceptual basis.

The ability of the *ACRU* model to simulate streamflows under a wide range of climatic regimes and land uses was demonstrated in this study. Furthermore, by using national level datasets as well as either physically-based variables or experience-based default values as model inputs, the robustness and suitability of the model for use in extrapolation situations such as climate and land use change impact studies, where data beyond the readily obtainable would not be available, was shown. By demonstrating the model's suitability across a range of climates and land uses, the study further confirmed the applicability of the *ACRU* model for use in land use and climate change impact studies through a "space for time" study.

7.2 The Dynamics between Land Use, Climate Change and Hydrological Responses

Changing climates and continuing anthropogenic alteration of landscapes further complicate the already complex linkages between land use, climate and hydrological responses. As both land use and climate changes are viewed as key challenges for this century, an improved understanding of the dynamics between them and hydrological responses is crucial. The initial study in which substantial shifts were demonstrated in the climatically optimum growth areas of plantation forestry species under simple scenarios of changes in climate illustrated the significant potential shifts of land use which may occur in the future given a changing climate (Chapter 2). A changing climate is not the only influencing factor in shifting areas used for plantation forestry; economic and political factors may also result in shifting plantation forestry areas. These shifts in land use, if they were to materialize, could have considerable impacts on the water resources across a range of spatial scales. Furthermore, the potential shifts shown in Chapter 2 did not include the effect of CO_2 on growth, nor on the water efficiency of plantation forestry which could have signicant impact on water resources. Given the potential shifts in land use, the already water stressed South African situation in which certain land uses (e.g. plantation forestry) have already had significant impacts on water resources and changes in the climate are already evident, the imperative for an improved understanding of the climate-land use dynamics was heightened.

Through the application of a hydrological model, the ability of which to simulate streamflows adequately under a range of land uses and climates (Chapter 3) has been demonstrated, the dynamics between, and impacts of, land use change and climate change on hydrological responses at a range of spatial and temporal scales can be investigated.

The percentage the land cover of a catchment that has been altered is not an absolute indication of the alteration of the streamflow responses that the catchment would experience, as the nature of the land use change and the location of specific land use changes play a large role. For example, the contributions of different land uses to the streamflow generated from a catchment is not proportional to the relative area of that land use, and the relative contribution of the land use to the catchment's streamflow varies with the rainfall regime of the catchment. Added to the already complex links between water and land use is the influence of the water engineered system, such as major reservoirs, which can dampen downstream flow variability. Beyond the above, this study clearly showed that as each catchment is unique, each will have a unique threshold of where land use change begins to have a significant influence on hydrological responses (Chapter 4).

The impacts of climate change on hydrological responses are dependent on the quality and accuracy of downscaled future climate scenarios used, especially in light of uncertainties which remain with projected rainfall, which is a secondary (derived) output from the GCMs. What is, however, consistent from output of all the GCMs used in this study is the increased variability in rainfall that is projected for the future. Furthermore, this study demonstrated that any simulated changes experienced in streamflows were substantially greater than the changes in rainfall, illustrating the amplification effect of the hydrological cycle on changes in rainfall. Furthermore, the changes were shown not to be uniform across the flow regime, for example, increases in high flows may be experienced while decreases in low flows are evident (Chapter 5).

The impacts of combined land use changes and climatic changes on streamflow responses are complex. From the analyses conducted in this study no clear consensus emerged as to whether either land use change or climate change was more dominant in influencing streamflow responses. The temporal and spatial scale at which the assessment takes place, the nature of the land use change as well as the magnitude of projected climatic change all have significant influences on whether streamflow responses are influenced more by land use change or climatic change.

The results from the analyses conducted in this study (Chapter 6) indicate that as the climate becomes drier, land use will have a relatively greater impact on a catchment's water resources. Under a drier future climate the imbalance between the relative area a specific land use occupies and its contribution to the mean annual accumulated streamflow of the catchment will be enhanced. Therefore, those land uses which currently already have significant impacts on catchment water resources, such as commercial irrigated agriculture and commercial production forestry, will under a drier climate, have a proportionally greater impact on the water resources.

Through illustration of the complex relationships between land use changes, climatic changes and streamflow responses the study conducted showed the importance of the integration of land use and climate change assessments into water resources planning, for both present and future climates. These assessments, however, need to be conducted at various spatial scales and consider both the local impacts and the progression of impacts as the flows cascade downstream through the catchment. Furthermore, each catchment has unique pressing water issues and concerns, and therefore catchment specific assessments are necessary when considering joint land use and climatic change.

7.3 The Way Forward

Throughout the course of the research three key areas requiring future research came to the fore. First, in studies such as this which are concerned with the impacts of land use change and climate change on water resources, uncertainty is introduced from many sources, from the emissions scenario selected to hydrological model used. The second area of future research that was highlighted was the need to investigate the baseline (or reference) land cover against which assessments of land use impacts on hydrological responses are made. Thirdly, future research will have to assess how results from this type of study can be incorporated into water resources planning. These areas of future research are discussed in more detail below.

7.3.1 Dealing with scenario uncertainty

In a study concerned with the impacts of land use change and climate change on water resources, uncertainties are introduced relating to the hydrological model, the future climate change projections and the land use scenarios used. As plausible scenarios of hydrological responses to both land use and climatic change are required to aid in future water resources planning, this research ascribed to the philosophy that these uncertainties should be acknowledged and, where possible, constrained (Beven, 2006; Pappenfus and Beven, 2008), rather than being seen as a barrier to undertaking such impact studies. How these uncertainties were dealt with, and where possible constrained, is discussed below.

To demonstrate a hydrological model's ability and acceptance, confirmation studies comparing simulated streamflows to observed flows at a daily time step need to be undertaken. These confirmation studies do not, however, imply the model is an absolutely truthful representation of reality. Rather, they increase the confidence that the model is an acceptable representation of reality. By confirming the ability of the model to adequately represent hydrological responses across a range of climates and land uses, confidence in the use of the model under conditions of extrapolation is increased.

In this particular study, the ability of the *ACRU* model to simulate streamflow responses with past and present hydrological data across a range of climates and land uses was confirmed (Chapter 3). Although such a "space for time" study reduces the uncertainty in the use of the model for land use change and climatic change studies, it provides no guarantee that the model will continue to simulate hydrological responses adequately under extrapolated conditions. The hydrological system is dynamic, and changes in climate and land use may result in unanticipated hydrological responses, possibly beyond the ranges for which the model's ability to represent processes has been tested. However, by selecting a model such as the *ACRU* model, with a physical-conceptual structure for which individual state variables and processes have been verified across a range of climatic and physiographic conditions (Schulze, 1995), using a hydrologically sensitive method of spatial configuration in conjuction with input from national level databases, as well as applying experience-based default variables, the confidence in the model's ability to be used in extrapolation studies and to reduce possible uncertainties was increased.

When considering the future climate projections used, there are three sources of uncertainty to consider. The first relates to the emissions scenario selected. In 2000, the IPCC published the '*Special Report on Emission Scenarios*' (SRES) which developed four different "storylines", each describing the way the world population, economies, political structure and lifestyles may evolve over the next few decades. The four storylines, *viz.* A1, A2, B1 and B2 (*cf.* Chapter 5.2.4), ultimately led to the construction of six SRES marker scenarios, with the A1 storyline consisting of three sub-scenarios, *viz.* A1FI, A1B and A1T (Arnell, 2004). These scenarios are coherent, internally consistent, plausible futures which conform to sets of circumstances or constraints. However, they are not predictions of future conditions, but simply alternative images of the future, with equal likelihood of occurrence (Rounsevell *et al.*, 2005; Abildtrup *et al.*, 2006; Samaniego and Bàrdossy, 2006; Carter *et al.*, 2007). Thus, the choice of an emissions scenario influences the projections of future climate and ultimately the modelled impacts on the hydrological response. However, for the relatively near time horizon used in this study the uncertainties introduced in the selection of emissions scenario are less significant than those introduced by the structure of climate models, albeit with the proviso that, the more distant the future scenarios which are used, the greater the influence of the emissions scenario selected (Jenkins and Lowe, 2003).

The second source of uncertainty is introduced through the GCM used and the method of downscaling of the GCM output to a spatial scale relevant for hydrological impact studies (Kundzewicz *et al.*, 2007). Between the GCMs available and the downscaling method used, the simulated projections of future climate will vary. Outputs from eighteen GCMs were analysed by Covey *et al.* (2003) for the Coupled Model Intercomparison Project, with findings indicating that the simulation of precipitation from the various GCMs was varied. It was found, however, that the temperature simulations were highly similar. Even though the simulation of precipitation is less consistent than that of temperature, it is well recognised that rainfall variability will increase under a changing climate (Kundzewicz *et al.*, 2007). As rainfall is the primary driver of many of the hydrological responses, these uncertainties are of concern in water resources impact studies. This is further compounded by the streamflow output simulated by the *ACRU* agrohydrological model being more sensitive to input rainfall than other climate variables (Schulze, 1995). Therefore, the uncertainties introduced in studies such as this one which are concerned with the impacts of climatic change on water resources, are primarily due to the uncertainties in the precipitation outputs from GCMs rather than from the emissions scenario selected (Arnell, 2004; Kundzewicz *et al.*, 2007) or uncertainties in the hydrological model used. Partially owing to these uncertainties, the initial study on the shifts in climatically suitable growth areas of plantation forestry species (*cf.* Chapter 2) considered plausible rather than GCM generated scenarios of future climate, e.g. a 2°C increase in temperature and a 10% increase/decrease in precipitation. However, such scenarios are considered inadequate for the combined land use and climate change study, as they do not account for future changes in variability, nor for the spatial differences in the changes in climate. Thus, five downscaled projections of present and future climates were used in the land use and climatic change impact study (*cf.* Chapter 5). Multiple downscaled climate projections were used in order to constrain the uncertainty introduced by the future climate projection, as suggested by Kundzewicz *et al*. (2007).

The last source of uncertainty is introduced by the land use and the land cover input used. To gain a understanding of the climate interactions with streamflow responses prior to introducing the uncertainties and complexities of operational catchments, impacts of climate change on streamflow responses were assessed under a baseline land cover. Once this understanding had been gained, the compounding and interacting feedbacks between land use, climate and streamflow responses were investigated by considering the impacts of climate change on operational catchments on which substantial changes in land use had occurred. The choice to not use scenarios of potential future land use change was taken in order to reduce any further uncertainties in the study. It is recognized that socio-economic drivers such as population growth, urbanisation, national and regional economic policy and land distribution are likely to significantly alter the patterns of land use, and consequently alter catchment hydrological responses. For example, using projections of urban growth in the Mgeni catchment for the year 2050 Mauck and Warburton (2012) demonstrated the potential significant impacts urban growth on catchment water resources. The need, however, for the development of scenarios of future land use and assessment of potential hydrological responses to these future land use scenarios is recognised and highlighted as a future research need.

Viewed from a hydrological perspective and from within the scope of this study, research is required into understanding how hydrological processes may change under future environmental change scenarios and how best to parameterise hydrological models for future impacts assessments, both in regards to land use change and climatic change.

7.3.2 Resetting the land cover baseline against which land use impacts are assessed

For water resources management, protection and, in certain instances, restoration of water resources systems it is necessary to understand the magnitude of the impact of environmental changes on hydrological responses. To determine this magnitude a reference land cover or benchmark system state is required against which the response changes can be assessed. The magnitude of these assessed impacts of land use change on hydrological responses will depend on the reference which was used. Various reference land covers have been used in impact studies. For example, Niehoff *et al*. (2002) used present land use as the reference against which to assess the impacts of scenarios of future land use change, while Bewket and Sterk (2005) used the land use from an earlier point in time against which to make their assessment. On the other hand, Schulze (2003) and Costa *et al*. (2003) have used natural land cover as a reference. If these studies had used a different reference land use or cover, the results of their impacts assessments may have been different. Furthermore, the use of different reference land covers precludes direct comparisons between the various studies to be drawn.

In the South African situation the need for a relatively accurate baseline, or reference, land cover has become more important with the implementation of the National Water Act of 1998 (NWA, 1998), as the NWA (1998) requires reference flows for both the determination of the ecological reserve and the assessment of the impact of specific land uses on (especially) low flows. Currently, the South African Department of Water Affairs (DWA) supports and accepts the use of “natural vegetation” in the form of the Acocks’ (1988) Veld Types as the reasonable standard or reference land cover against which to assess land use impacts (Schulze, 2004; Jewitt *et al*., 2009). Thus, for this study the Acocks’ (1988) Veld Types were used as the reference land cover against which land use impacts on hydrological responses were assessed.

By using the Acocks (1988) Veld Types as a baseline, some uncertainties may have been introduced into the study. First, the Acocks Veld Type (1988) maps were mapped at a country-wide scale resolution with relatively little local scale detail and with only 70 Veld Types representing the country’s natural vegetation. Secondly, although the water use parameters for the Acocks Veld Types were developed on the basis of a consistent application of key climate related drivers of the cycle of vegetation water use throughout a year (Schulze, 2003) and on expert knowledge, there has to date been limited research undertaken to assess the water use of natural vegetation and thus to confirm these values (Jewitt *et al*., 2009).

More recently, Mucina and Rutherford (2006) produced a natural vegetation map which defines 435 vegetation units for improved regional and local planning, by mapping the diverse southern African geographical region in great detail using aerial photographs, satellite imagery, spatial predictive modelling and large databases in combination with traditional field-based ground-truthing. Given the improved resolution of, and the methodology used to produce, the Mucina and Rutherford (2006) natural vegetation map, a recommendation from this research, which concurs with the suggestion by Jewitt *et al*. (2009), is that it be assessed for use as the future hydrological baseline land cover in South Africa. With the additional pressure which climate change will place on South Africa's already stressed water resources and the increasing anthropogenic alterations and demands on our natural landscape, an accurate assessment of the impacts of potential shifts and changes in land use becomes crucial. By using a baseline land cover of improved resolution, the accuracy of the assessments may be increased, particularly at the subcatchment scale. However, with the difficulties around the hydrological parameterisation of different natural vegetation types remaining, the question is raised as to whether the differences between the two baselines will be significant enough to alter any assessed impacts of current land uses in that region.

Globally, with the introduction of concepts such as the water footprint concept, a baseline land cover or reference for comparative purposes is becoming an imperative. Currently, with the international acceptance of the FAO Penman-Monteith approach to estimation of evapotranspiration (Allen *et al*., 1998), green grass of uniform height 0.12 m is used as a reference against which to calculate the water use or water footprint of vegetation. Is using this grass reference to calculate the water footprint of land use hydrologically relevant? Given that the most desirable water yields and trends in flows of a specific catchment are those that occur under natural conditions, would the natural vegetation of an area not provide a more sound reference for computing vegetation water use? For example, eucalyptus trees are high water users in South Africa in comparison to most of the natural vegetation they replace and they have a negative impact on the hydrological response of that area (Gush *et al*., 2002; Jewitt *et al*., 2009). However, in Australia where they are indigenous and constitute the natural vegetation of an area their impact on hydrological responses of that area is not considered negative, but results in near-natural flow regimes for that area. By using natural vegetation as the reference, this would assist in returning flow regimes of catchments to near-natural regimes through restoration and land use change management and planning. However, the concerning factor is that our perception of what the natural state or baseline is may have shifted over generations due to the scale of influence humans have had on the environment. This shifting baseline syndrome adds to the complexity of determining the impacts of environmental change (Pauly, 1995) on hydrological response, as it accommodates a more altered environment the impacts of change over time may be masked.

A futher challenge in climate change impact studies, with regards to the baseline land cover, is that with changes in climate the spatial distribution and composition of natural vegetation will change, hence the baseline land cover will change. This shifting baseline land cover under a changing climate adds to the complexity of assessing the dynamics between land use change and climate change.

7.3.3 Moving beyond theory to application in water resources planning

Water resources management in South Africa is the responsibility of the Department of Water Affairs (DWA) at the national level, and the DWA devolves these responsibilities to the respective Catchment Management Agencies (CMAs) once these are established. The goals and priorities of the DWA align strongly with the recently announced South African Presidential outcomes (DWA, 2011). Thus, in order to integrate land use and climatic change planning into water resources management, the complexities introduced by land use and climatic change need to be placed in context of the Presidential outcomes.

To be able to achieve outputs 1 to 3 of the Presidential Outcome 10 “Environmental assets and natural resources that are well protected and continually enhanced”, the complexities introduced by land use and climatic change, need to be addressed. Output 1 speaks to enhancing both the quantity and quality of water resources of South Africa through more efficient management. Owing to the changing environmental conditions, the integration and consideration of land use and climatic change become key elements to improving the efficiency of water resources management. Output 2 aims at reducing greenhouse gas emissions, climate change impacts and improving air/atmospheric quality. Where the links to water come in, is through the target to improve the ability to cope with both unpredictable and severe climate change impacts and developing adaptation for key sectors, one of which is water. Land use management may prove to be a useful climate change adaptation strategy, particularly in the context of water resources management as shown through research presented in this thesis and in Schulze (2011). Output 3 deals with sustainable environmental management, and although water is not specifically mentioned, there is a call for "integrated planning, a clear plan that will ensure that environmental issues are integrated into land use planning and incorporated into national, provincial and municipal plans." As any land use changes may have significant impacts on water resources, water needs to be incorporated as a key issue in this integrated plan. Meeting the Presidential outcomes in terms of water resources will be a challenge, given that South Africa is currently already a highly water stressed region facing not only water quantity issues, but also water quality issues. With a changing biophysical and socio-economic environment, this challenge will become greater, thus increasing the imperative for improved understanding and integration of land use and climate change into water resources planning.

Several South African research agendas have recognised this need, particularly in regard to understanding the potential impacts of climate change on water resources and enhancing South Africa's ability to cope with environmental change. For example, the South African Department of Science and Technology (DST) in 2010 released the Global Change Research Plan for South Africa. In this context, global change refers to all aspects of a changing environment and not only a changing climate. The research plan identifies four pillars, *viz.* understanding a changing planet, reducing the human footprint, adapting the way we live, and innovation for sustainability, with eighteen research challenges across them. Land use and water are integral to each of the four pillars and to a number of the research challenges.

Although research agendas such as the DST Global Change Research Plan (DST, 2010) are an important step forward and a shift in the traditional thinking towards earth sciences research, a shift in the conventional approach to hydrological research will be required in order to enable water resources practioners to be able to deal with the challenges of environmental change, to respond appropriately, to implement adequate policies and management plans, to alleviate the potential negative impacts and to maximise the potential benefits from environmental change.

Beyond land use and climate change, catchment water resources have numerous other demands placed on them through population growth and economic development. Water quality deterioration resulting from anthropogenic activities makes meeting water demands more difficult and adds complexity in understanding and coping with environmental change.

To manage water resources adequately under a changing environment with the added social pressures and complexities, requires a holistic understanding of the dynamics and interactions between the landscape, climate and hydrological processes at scales relevant for decision making. To achieve this understanding, the conventional use of past observational data to predict the future may prove insufficient given the non-stationarity especially of observed streamflow data which already reflect upstream land use change and effects of water engineered systems. Investigation into thresholds and points of system change are required, as well as improved understanding of processes and how changes may affect these. New and innovative methods of measuring and observing may be required, as well as changes to the more conventional calibration based rainfall-runoff modelling approaches currently used by many South African water practioners to a more process-oriented, interactive modelling approach.

The uncertainty surrounding environmental change and its related impacts on hydrological responses should not be seen as a barrier to water resources planning in South Africa. Rather it should be seen as an imperative to improving our understanding of the movement of water within South African catchments, to becoming more receptive and adaptive to new concepts and information, and to developing resilient and adaptive water management strategies for the future to minimise the risks and maximise the benefits to potential impacts of climate change.

7.4 Contributions of this Research to New Knowledge

In conclusion, the contributions of this research to new knowledge may be summarised as follows:

- Confirmation of the daily time-step, physical-conceptual and process-based *ACRU* model's appropriateness for use in land use change and climatic change impact studies through a space for time study;
- Enhancement of the understanding of the dynamics between land use change and streamflow responses in complex, operational South African catchments;
- Enhancement of the understanding of the dynamics between climatic change and streamflow responses under diverse South African conditions;
- Illustration that optimum growth areas for various land uses will shift under changing climates, having a potentially significant impact on the landscape and thus on the hydrological responses from the landscape;
- Analysis of the potential shifts in plantation forestry areas under climate change for South Africa was the first study which considered the potential impacts of climate change on the South African plantation forestry sector, thus enhanced the plantation forestry sector's understanding of the potential impacts of climate change as well as aiding in strategic planning and decision making for the sector.
- Contribution to and a significant enhancement of the understanding of the impacts of combined land use and climatic change on the streamflow responses for complex, operational catchments, illustrating that with a change to a drier environment, land use would play a relatively greater role and that each catchment is unique, and thus will respond differently; and lastly
- Highlighting the crucial need for water resources planning to include land use change and climatic change.

Given the uncertainties of the future, there is an imperative to improving the understanding of the movement of water within catchments, to be receptive and adaptive to new concepts and information, and to developing resilient and adaptive water management strategies for the future in a way that minimises the risks and maximises the benefits to potential impacts of climate change. Land use change planning may be a potential adaptive strategy to reducing the impacts of climate change on hydrological responses.

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