TECHNIQUES FOR ASSESSING THE IMPACTS OF WETLANDS ON HYDROLOGICAL RESPONSES UNDER VARYING CLIMATIC CONDITIONS

Ryan Paul Gray

Submitted in partial fulfilment of the requirements
for the degree of MSc in Hydrology

School of Bioresources Engineering and Environmental Hydrology
University of KwaZulu-Natal
Pietermaritzburg

April 2011

ABSTRACT

Wetlands are considered sensitive eco-tones that provide numerous goods and services, not only to the communities which are immediately dependent upon them, but also to the many downstream stakeholders who benefit from the hydrological influences that wetlands have on a catchment.

The three main objectives of this study, the foci of which included an assessment of impacts of wetlands on catchment hydrological responses (*viz.* flood attenuation and streamflow regulation) in the Thukela catchment under varying geographical and climatic conditions, are:

- A modification and validation of the *ACRU* Model's Wetland Routine;
- Assessing impacts of wetlands on hydrological responses from catchments in varying climatic regions under historical climatic conditions; and
- Assessing impacts of wetlands on catchment hydrological responses for climate change scenarios by using outputs from a Regional Climate Model (RCM).

The *ACRU* Model was selected to undertake the daily hydrological simulations, while historical climate data and climate information derived from the C-CAM Regional Climate Model were used as inputs into the model. These varying climatic inputs, as well as the changes in water fluxes between simulations with and without the wetlands routine switched on, enabled the author to assess the impacts of wetlands on catchment hydrological responses under varying climatic conditions. The *ACRU* wetland routine initially did not produce output in line with conceptualisation of wetlands processes. As a result of this, certain modifications had to be made to the model to ensure that the results obtained mimicked wetlands hydrological processes realistically.

A validation was performed on the re-configured *ACRU* wetlands routine to show that the simulated results of impacts of wetlands on catchment hydrological responses were realistic when compared to findings from the literature review (e.g. in regard to streamflow regulation and flood attenuation). These validation results also show that the impacts of wetlands on catchment hydrological responses are dependent on the level of soil water saturation of the wetland at the

start of a streamflow event and the volume of the streamflow event in relation to the relative size of the wetland.

The results further illustrate that wetlands have a relatively small flood attenuation and streamflow regulation impact on mean annual catchment hydrology at the outlet of the 29 136 km^2 Thukela catchment. However, mean monthly results show pronounced effects (20 – 30%) of flood attenuation in the summer months and streamflow regulation throughout the year, especially in the drier winter months. The climate change scenario results illustrate that the impact of wetlands on hydrological responses are virtually entirely masked by the impact of climate change, with only minor changes shown on outflows of the Thukela between climate change scenarios without and with wetlands.

DECLARATION

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

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

Signed: …………………………… Date: ……………

R.P. Gray (Author)

Signed: …………………………… Date: ……………

Professor R.E. Schulze (Supervisor)

ACKNOWLEDGEMENTS

The author wishes to express his sincere appreciation and gratitude to the following people and institutions for the assistance rendered during this study:

- Professor Roland Schulze, for supervising this project and providing guidance and mentorship;

- Mr Mark Horan, for his assistance on the *ACRU* wetland routine, help with configuring the Thukela catchment and the *ACRU* Model in general and for the discussions, explanations and technical guidance that he provided during the course of this project;

- The School of Bioresources Engineering and Environmental Hydrology, for providing the resources and working environment required to complete this study;

- Mr Darryn Knoesen, for his support and motivation in pushing me to complete this study, while in full time employment;

- Messrs Jan Norris and Simon Johnson, for giving me the flexibility and encouragement to complete the study whilst working for Jeffares and Green;

- My parents, Paul and Carol, for always believing in me, pushing me to be the best that I can be and for providing the home and opportunities to excel in all of my endeavours, for which I will always be grateful; and

- My wife, Michelle, for all of the silent sacrifices made to help me complete this study, for her tireless motivation to push me to succeed and for her amazing patience, love and support...I will always love you!

TABLE OF CONTENTS

ABSTRACT .... **II**

DECLARATION .... **IV**

ACKNOWLEDGEMENTS .... **V**

TABLE OF CONTENTS .... **VI**

LIST OF TABLES .... **IX**

LIST OF FIGURES .... **XI**

1 INTRODUCTION **1**

2 WETLANDS: AN OVERALL REVIEW FROM A HYDROLOGICAL PERSPECTIVE **4**

2.1 WETLAND HYDROLOGICAL RESPONSES AND WETLANDS WATER BUDGETS 5
2.2 WETLAND FUNCTIONALITY 8
2.2.1 Streamflow regulation 8
2.2.2 Flood attenuation 10
2.2.3 Sediment accretion 12
2.2.4 Water purification 13
2.3 DRAINAGE OF WETLANDS 16
2.4 GOODS AND SERVICES FROM WETLANDS 18
2.5 CHAPTER SUMMARY 20

3 CLIMATE, CLIMATE CHANGE AND WATER RESOURCES: AN OVERVIEW **21**

3.1 WHAT IS CLIMATE VARIABILITY? 21
3.2 WHAT IS CLIMATE CHANGE? 22
3.3 CHANGES IN ATMOSPHERIC CO_2 CONCENTRATION 22
3.4 CHANGES IN TEMPERATURE 23
3.5 CHANGES IN PRECIPITATION 24
3.6 FIRST ORDER EFFECTS OF CLIMATE CHANGE ON WATER RESOURCES 26
3.7 SECOND ORDER EFFECTS OF CLIMATE CHANGE ON THE WATER SECTOR 29
3.8 HIGHER ORDER EFFECTS OF CLIMATE CHANGE 29
3.9 CHAPTER SUMMARY 29

4 MODELS AND MODELLING: A REVIEW RELATED TO THIS STUDY **31**

4.1 THE HYDROLOGICAL MODEL USED IN THIS STUDY: *ACRU* 32
4.1.1 Model requirements for hydrological studies under varying landscape and climatic conditions 32
4.1.2 The *ACRU* Agrohydrological Model 33
4.1.3 Concepts on which the ACRU Model is based 34

4.1.4 Suitability of the *ACRU* Model for modelling climate change impacts 37
4.1.5 The *ACRU* Wetlands Routine 39
4.2 THE REGIONAL CLIMATE MODEL USED IN THIS STUDY: C-CAM.. 43
4.2.1 General circulation models (GCMs) 43
4.2.2 Regional climate models (RCMs).. 44
4.2.3 Empirical downscaling.. 44
4.2.4 Dynamic regional downscaling.. 45
4.2.5 The Conformal-Cubic Atmospheric Regional Climate Model (C-CAM).................................... 46
4.3 LINKING RCM OUTPUT WITH THE *ACRU* MODEL.. 47
4.3.1 The general approach.. 47
4.3.2 Limitations of linking RCM outputs with the ACRU Model... 47
4.3.3 Towards an approach of modelling impacts of projected future climates.................................... 49
4.4 UNCERTAINTIES IN HYDROLOGICAL AND CLIMATE CHANGE IMPACTS MODELLING............................. 49
4.4.1 Introduction to uncertainty in modelling.. 50
4.4.2 Uncertainties in general hydrological modelling 50
4.4.3 Uncertainties in wetlands hydrological modelling... 51
4.4.4 Uncertainties in climate change modelling 52

5 CASE STUDY AREA: THE THUKELA CATCHMENT 53

5.1 PHYSIOGRAPHY OF THE THUKELA CATCHMENT.. 54
5.2 CLIMATE OF THE THUKELA CATCHMENT 55
5.3 DELINEATION OF WETLANDS IN THE THUKELA CATCHMENT.. 58

6 METHODOLOGY... 60

6.1 REVISITING OBJECTIVES AND IDENTIFYING REQUIREMENTS FOR MODELLING 60
6.1.1 Baseline (historical) climate requirements for wetlands hydrological simulations....................... 60
6.1.2 Baseline land cover information needs for wetlands hydrological simulations 60
6.1.3 Other information requirements for modelling 61
6.2 DISAGGREGATION OF THE THUKELA CATCHMENT FOR WETLANDS HYDROLOGICAL MODELLING........ 61
6.2.1 Previous catchment disaggregation... 61
6.2.2 Catchment disaggregation used in this study 63
6.3 CATCHMENT INFORMATION 66
6.3.1 Soils 67
6.3.2 Baseline land cover 69
6.4 CLIMATE INPUTS 73
6.4.1 Historical climate data.. 74
6.4.2 GCM derived climate scenarios... 75
6.5 WETLANDS INPUTS.. 76

7 VALIDATION OF WETLANDS HYDROLOGICAL PROCESSES IN THE *ACRU* MODEL 78

7.1 Validation of Processes Captured in the *ACRU* Wetlands Routine 78

7.2 Processes of Wetland Surface Water Flows Simulated with the *ACRU* Model 78

7.3 Processes of Wetland Soil Water Fluxes, Simulated with the *ACRU* Model 84

7.4 Comparison of Hydrological Responses from Catchments With and Without Wetlands, Assuming the Catchment to be Under Baseline Land Cover 87

8 RESULTS AND DISCUSSION FROM CATCHMENT-SCALE WETLAND HYDROLOGICAL REPONSES UNDER VARYING CLIMATIC CONDITIONS 103

8.1 Results Based on Historical Climatic Input 104

8.2 Impact of Climate Change on Wetland Hydrological Responses... 116

9 CONCLUSIONS AND RECOMMENDATIONS 127

9.1 Conclusions from the Study.. 127

9.2 Recommendations for Possible Future Research Based on the Findings of this Study 129

10 REFERENCES.. 131

LIST OF TABLES

Page

Table 2.1 Summary of influencing factors on wetland functions (after Barichievy, 2005) ……………………………………………………………………………………15

Table 6.1 Percentages of soil Land Types found in the Thukela Catchment (Schulze *et al.*, 2005a)……………………………………………………………………………68

Table 6.2 Acocks' (1988) Veld Types in the Thukela Catchment: Hydrological Attributes (after Schulze, 2004b)……………………………………………………………71

Table 7.1 Individual effects of a relatively large riparian wetland (9.54 km^2) on hydrological responses of a relatively small catchment (186.59 km^2) during a dry year (1968)..…………………………………………………...88

Table 7.2 Individual effects of a relatively large riparian wetland (9.54 km^2) on hydrological responses of a relatively small catchment (186.59 km^2) during a wet year (1996)..……………………………………………………..89

Table 7.3 Summary showing the averaged effects of a relatively large riparian wetland on hydrological responses of a small catchment in a wet and a dry year……………...91

Table 7.4 Individual effects of a small riparian wetland (0.68 km^2) on hydrological responses of a large catchment (4 3171.98 km^2) during a dry year (1968)………...………...92

Table 7.5 Individual effects of a riparian wetland (0.68 km^2) on hydrological responses of a large catchment (4 371.98 km^2) during a wet year (1996)..………………………..93

Table 7.6 Summary showing the averaged effects of a relatively small riparian wetland (0.68 km^2) on hydrological responses of a large catchment (4 371.98 km^2) in a wet and a dry year...95

Table 7.7 Individual effects of an upland wetland on hydrological responses of a catchment during a dry year (1968)…………………………………………………………....96

Table 7.8 Individual effects of an upland wetland on hydrological responses of a catchment during a wet year (1996)…………………………………………………………....97

Table 7.9 Summary showing the averaged effects of an upland wetland on hydrological responses in a wet and a dry year…………………………………………………..99

Table 7.10 Individual effects of an upland wetland's topsoil water content during a dry year (1968)…………………………………………………………………………...100

Table 7.11 Individual effects of an upland wetland's topsoil water content during a wet year (1996)…………………………………………………………………………...101

LIST OF FIGURES

Page

Figure 2.1: Generic non-coastal wetland water budget (after Mitsch and Gosselink, 1993)…………………………………………….…………………………6

Figure 2.2 Typical inflow and outflow hydrographs for a generic wetland (after Mitsch and Gosselink, 1986; Lymberopoulos and James, 1993)……………………..……11

Figure 2.3 Comparison of actual recorded streamflow results for a sub-catchment within the Thukela catchment with a wetland in comparison to an adjacent sub-catchment without a wetland present (after Schulze, 1979)…………..………………...…..12

Figure 3.1 Baseline values of mean annual precipitation derived from daily climate data from the Quaternary Catchments Database (QCDB) (Schulze *et al.*, 2005c)......…...…25

Figure 3.2 Sensitivity analysis of plausible changes in temperature and rainfall on mean annual accumulated streamflows in the Thukela catchment (Schulze *et al.*, 2005b)…………………………………………………………………….27

Figure 4.1 The *ACRU* Agrohydrological Modelling System: Concepts (after Schulze, 1995)………………………………………………………………………...35

Figure 4.2 The *ACRU* Agrohydrological Modelling System: General structure (after (Schulze, 1995)…………………………………………………………..….35

Figure 4.3 Concepts, processes and assumptions involved in the original *ACRU* wetlands module (after Schulze, 1987; Schulze, 2001a)……………………………...…37

Figure 4.4 Hydrological model requirements under conditions of climate change (Schulze, 2005c)……………………………………………………………………….....38

Figure 4.5 Schematic diagram showing flow routing in the *ACRU* wetland routines (after Smithers and Schulze, 1995)………………………………………………...…41

Figure 4.6 Schematic diagram showing the modified hydrological processes in the *ACRU* Wetland Routines (after Horan, 2010, pers. comm.)…………………………….42

Figure 4.7 The coverage of the 1/2° grid boxes of the RCM output from C-CAM over South Africa (Schulze *et al.*, 2005b)………………………...……………………..47

Figure 4.8 Thukela sub-catchments assigned to C-CAM derived grid boxes (Schulze *et al.*, 2005b)……………………………………………………………………..……48

Figure 5.1 Location of the Thukela catchment in South Africa in relation to KwaZulu-Natal, Water Management Areas and administrative units (Schulze *et al.*, 2005a)……………………………………………………………………….53

Figure 5.2 Altitude of the Thukela catchment (Schulze *et al.*, 2005a)…………………..…..54

Figure 5.3 Slope categories (%) in the Thukela catchment (Schulze *et al.*, 2005a)…………55

Figure 5.4 Mean annual precipitation of the Thukela catchment (after Dent *et al.*, 1989; cited by Schulze *et al.*, 2005a)…………………………………………………………56

Figure 5.5 Inter-annual coefficient of variation of rainfall across the Thukela catchment (after Schulze *et al.*, 2005a)………..........................……………………………..….56

Figure 5.6 Reference potential evaporation (A-pan equivalent) for the Thukela Catchment (after Schulze, 1997; cited by Schulze *et al.*, 2005a)……………………………57

Figure 6.1 The delineation of the Thukela catchment into 235 sub-catchments, with reasons for each specific sub-catchment (Schulze *et al.*, 2005b)…......…………………....63

Figure 6.2 Schematic of the wetlands sub-division of each of the 235 sub-catchments of the Thukela catchment into 940 sub-divisions for wetlands modelling…...….......…65

Figure 6.3 Flow linkages between the wetlands sub-divisions and the original 235 sub-catchments……………………………………………………………….….66

Figure 6.4 Distribution of soil Land Types, described as broad soil patterns, in the Thukela catchment (Land Type Survey Staff, 1986)……………………………..……..68

Figure 6.5 The distribution of certain soil characteristics found in the Thukela catchment (Schulze *et al.*, 2005a)……………………………………………………...….69

Figure 6.6 Acocks Veld Types found within the Thukela catchment (after Acocks, 1988)…...71

Figure 7.1 Time-series of daily rainfall and simulated surface water flows in a riparian wetland in a wet year (Catchment area 186.59 km^2, wetland area 9.54 km^2)....…82

Figure 7.2 Time-series of daily rainfall and simulated surface water flows in a riparian wetland in a dry year (Catchment area 186.59 km^2, wetland area 9.54 km^2)….…82

Figure 7.3 Representative Time-series of simulated streamflow contributions to a riparian wetland in a wet year (blue diamonds), in m^3/s, and channel carrying capacity (pink squares), also in m^3/s (Catchment area 186.59 km^2, wetland area 9.54 km^2)...83

Figure 7.4 Representative time-series of simulated streamflow to a riparian wetland contributions in a dry year (blue diamonds), in m^3/s, and channel carrying capacity (pink squares), also in m^3/s (Catchment area 186.59 km^2, wetland area 9.54 km^2)……………………...83

Figure 7.5 Simulated soil water movement within a riparian wetland catchment (Catchment area 186.59 km^2, wetland area 9.54 km^2)…………………………………..….86

Figure 8.1 Percentage of the area of wetlands for each of the 235 configured sub-catchments in the Thukela catchment...………………..103

Figure 8.2 Historical MAP used in hydrological simulations of the Thukela catchment, showing a range from 600 to 1 400 mm................................…………………104

Figure 8.3 Historical MMP used in hydrological simulations of the Thukela catchment, showing a range from less than 5 to over 300 mm.......…………………………105

Figure 8.4 Historical MAR, in millions of m^3, obtained from hydrological simulations with historical climate data in the Thukela catchment, without wetlands....................107

Figure 8.5 Historical MMR, in millions of m^3, obtained from hydrological simulations with historical climate data in the Thukela catchment, without wetlands.…………...108

Figure 8.6 Impacts of wetlands on mean annual accumulated streamflows under historical climatic conditions, expressed as a percentage change........…………….....…..109

Figure 8.7 Impacts of wetlands on mean monthly accumulated streamflows under historical climatic conditions, expressed as a percentage change........……………………110

Figure 8.8 Impacts of wetlands on the inter-annual CV% of accumulated streamflows under historical climatic conditions, expressed as a percentage change......…………..109

Figure 8.9 Impacts of wetlands on the CV% of monthly accumulated streamflows under historical climatic conditions, expressed as a percentage change......…….….…..111

Figure 8.10 Impacts of wetlands on mean annual total evaporation in the Thukela catchment under historical climatic conditions, expressed as a percentage change.....…….114

Figure 8.11 Impacts of wetlands on mean monthly total evaporation in the Thukela catchment under historical climatic conditions, expressed as a percentage change..………115

Figure 8.12 Percentage change of future to present mean annual precipitation for the Thukela catchment, derived from C-CAM........…………………………………….…118

Figure 8.13 Percentage change of future to present mean annual accumulated streamflows for the Thukela catchment, without wetlands, derived from C-CAM....….…...……..118

Figure 8.14 Percentage change of future to present mean annual accumulated streamflows for the Thukela catchment, with wetlands, derived from C-CAM..................….…..…119

Figure 8.15 Percentage change from future to present mean annual accumulated streamflows for the Thukela catchment as a result of the inclusion of wetlands, derived from C-CAM...119

Figure 8.16 Percentage change of future to present mean monthly precipitation for the Thukela catchment, derived from C-CAM....…………………………………………120

Figure 8.17 Percentage change of future to present mean monthly accumulated streamflows for the Thukela catchment, without wetlands, derived from C-CAM....……..…121

Figure 8.18 Percentage change between future and present mean monthly accumulated streamflows for the Thukela catchment, with wetlands, derived from C-CAM................…...122

Figure 8.19 Percentage change between future and present mean monthly accumulated streamflows for the Thukela catchment as a result of the inclusion of wetlands, derived from C-CAM……..…..123

1 INTRODUCTION

Wetlands are complex hydrological phenomena that occur in a wide variety of topographic and climatic environments, often under differing climatic and topographical conditions. While it is difficult to define what a wetland is, they are considered to be sensitive ecotones that provide numerous goods and services, not only to the communities which are immediately dependent on them, but also to the numerous downstream stakeholders who benefit from the hydrological influences that upstream wetlands have on a catchment, *viz.* flood attenuation, streamflow regulation, sediment accretion and water purification (Hammer and Bastian, 1989; Finlayson and Moser, 1991; RAMSAR, 2002; Appleton, 2003). The abundant biodiversity within the wetland is a major benefit within this ecotone. This is due to the wetland environment being wet for long periods of, if not all of, the year. Thus, the stable supply of water makes it a concentration point for fauna and flora alike. Water supplied from wetlands is highly beneficial to humans. The water, because it is often very pure, is a source of drinking water. It is also a source of water for agriculture, with the wetland potentially yielding water all year round for irrigation. The impacts of global warming and climate change on wetlands functioning and wetlands benefits are, however, not clear.

The three main objectives of this study, which focuses on assessing impacts of wetlands on catchment hydrological responses in the Thukela catchment under varying geographical and climatic conditions, include:

- A validation of the *ACRU* Model's Wetland Routine to ensure sufficiently realistic results from simulations of wetlands hydrological responses;
- Assessing the impacts of wetlands on catchment hydrological responses on a daily time-step for varying climatic regions and historical climatic conditions, i.e. impacts in a wetter region vs. a drier region, and impacts in a wetter year vs. a drier year, using daily time-step hydrological simulation modelling; and
- Assessing the impacts of wetlands on catchment hydrological responses for climate change scenarios when using output from a single Regional Climate Model (RCM) as a case study.

When considering the benefits of wetlands, as described above, it becomes evident that assessing the processes by which wetlands impact on the hydrological system is important (Mitsch and Gosselink, 1993; Donkin, 1994). To fully understand the importance of wetlands on the hydrological system, a review of wetlands from a hydrological perspective is therefore provided in **Chapter 2**.

One technique for assessing the impact of wetlands on hydrological responses of a catchment is to evaluate the impacts under various climatic conditions. Thus, an overview of climate variability and climate change, and the link between varying climatic conditions and water resources in general, is given in **Chapter 3**.

In **Chapter 4** a discussion follows on how modelling techniques can be used to assess the impacts of wetlands on selected hydrological responses, *viz.* flood attenuation and streamflow regulation, from a catchment under varying climatic conditions.

In order to undertake this assessment, a case study catchment covering a range of climatic conditions was selected, on which hydrological simulations were run to determine the impacts of wetlands on the hydrological responses. To cover a wide range of climatic conditions the Thukela catchment, which displays a range in altitude of over 3 000 m and a range of mean annual precipitation from 600 – 1 400 mm, was selected as a case study. Physiographic and climatic conditions of the Thukela catchment are described in **Chapter 5**.

The methodology used in this dissertation is outlined in **Chapter 6.** The *ACRU* Agrohydrological Model (Schulze, 1995) was selected as the model to simulate the impacts of wetlands on hydrological responses. It was selected as it is a daily time-step, conceptual-physical model with a daily water balance, which enabled the author to assess daily impacts of wetlands on hydrological responses. These impacts include changes in magnitude and seasonality of, *inter alia*, accumulated streamflows, total evaporation (both presented in **Chapter 8**) and baseflow responses (presented in the validation chapter, *viz*. **Chapter 7**). In addition, the *ACRU* model is capable of assessing the impacts of wetlands on catchment hydrological responses for a variety of climate conditions, i.e. impacts in a wet year vs. a dry year (presented in the validation chapter, *viz*. **Chapter 7**), impacts in a wetter region vs. a drier region, as well as the impacts of a General

Circulation Model's outputs for present and projected future climate scenarios. For this purpose the C-CAM model was selected with results presented in **Chapter 8**.

A validation of the *ACRU* Model's Wetlands Routine was undertaken in order to assess its efficacy in simulating hydrological responses of a wetland within a sub-catchment setup, specifically the flood attenuation and streamflow regulation impacts of wetlands on downstream sub-catchments. The validation of the simulations created confidence in the results obtained from simulations of wetlands impacts on hydrological responses under varying geographic and climatic conditions. The validation results are presented in **Chapter 7**.

The results of the hydrological simulations to assess the impacts of wetlands on mean monthly and mean annual accumulated streamflows, monthly and inter-annual coefficients of variation of accumulated streamflows and the monthly and annual changes in total evaporation, are presented and discussed in **Chapter 8**. These results are depicted as a series of maps of the Thukela catchment showing impacts of wetlands as percentages of change from simulations using baseline (i.e. historical) climatic conditions and a reference land cover. In addition, and as a case study, the impacts of climate change scenarios from a single General Circulation Model was assessed on wetlands hydrological response in **Chapter 8**.

The conclusions drawn from the results of the hydrological simulations on impacts of wetlands on catchment hydrological responses under varying climatic conditions are discussed in **Chapter 9**. Based on the experiences gained in this study, recommendations are made in the final sub-section of the Chapter on potential future research identified by the author in wetland hydrological modelling in South Africa.

2 WETLANDS: AN OVERALL REVIEW FROM A HYDROLOGICAL PERSPECTIVE

Wetlands are complex hydrological phenomena that occur in a wide variety of environments, often under differing climatic and topographical conditions (Appleton, 2003; Ellery *et al.*, 2009). As a consequence of this, it is difficult to define a wetland. Definitions found in the literature are often vague and have varying concepts on what determines a wetland to be a unique entity, and they can vary depending on the speciality of the individual defining them (i.e. botanist, soil scientist or hydrologist). The following definitions are among the most concise and widely recognised:

i. According to the US Fish and Wildlife (Cowardin *et al.*, 1979) definition a wetland must meet one, or more, of the following criteria:
   - It must be underlain by a non-soil substrate that is covered, or saturated, by water for at least part of the growing season.
   - The region must be dominated by soils that are saturated for large parts of the year, creating anaerobic conditions.
   - The wetland area must be dominated by hydrophilic vegetation, i.e. hydrophytes (cited by Cowardin *et al.*, 1979).

ii. Wetlands can be considered an ecotone or a transitional habitat between deep water and dry land. They are also classified as an environment that is not totally terrestrial or totally aquatic (Hammer and Bastian, 1989; Finlayson and Moser, 1991).

iii. The RAMSAR Convention describes wetlands as an ecological environment that can be defined by its many physical, chemical, and biological components, which their interactions (RAMSAR, 2002).

These definitions all show that a wetland is defined, if not determined, by the surrounding hydrology (Mitsch and Gosselink, 1986; RAMSAR, 2002). Wetlands generally have soils that differ from the surrounding soils types. They are often gleyed and contain a high degree of mottling. This is due to the continual wetting and drying cycles of the soils during the year.

However, the wetland soil does need to stay saturated for a long period of time (months) in order to create the anaerobic conditions found in almost all wetland soils, because the wetlands are wet for long periods, they are dominated by vegetation that can survive in inundated conditions (Mitsch and Gosselink, 1986). Donkin (1994) summarises wetlands by describing them as a hydrological continuum between upland areas forming the catchment and the open water bodies found within them.

In the following section, wetland hydrology and wetlands water budgets are described, in order to provide for a better understanding of wetlands, specifically their hydrological responses.

2.1 Wetland Hydrological Responses and Wetlands Water Budgets

Understanding the hydrological processes of wetlands implies understanding the drivers of wetland formation and maintenance (Donkin, 1994). Wetland hydrology is especially difficult to define as wetlands occur at the junction between surface and groundwater. The surface water contributions are easily defined by surface and baseflows that generally occur in hydrological catchments. The groundwater contributions are more difficult to define (Colvin *et al.*, 2005). This is due to the bi-directional flow between the wetland and the groundwater source. The groundwater source can contribute to the wetland and the wetland can contribute to the groundwater source. These different contributions can occur independently of each other. Different wetlands, determined by locality and specific circumstances, will have different levels of contributions from one, the other, or both sources, i.e. a wetland may only have the groundwater source feeding it, or it may have only the surface water derived wetland water feeding the groundwater source, or it may have different levels of contributions from both. This interaction is not yet fully understood and cannot be completely defined (Kotze *et al.*, 2005). Bearing this in mind, the wetland water budget that follows takes into account as many of the water transfers between sources and states as possible.

Wetlands may evolve due to several reasons, but are commonly formed as a result the following three factors:

- subsoil, geology and groundwater states,

- surface topographical configuration, and
- the balance between surface and groundwater inflows and outflows (Mitsch and Gosselink, 1993; Donkin, 1994).

These three factors combine to include the capacity of the wetland area to retain water and to maintain the wetland water budget, which determines the amount of water available to supply and sustain this ecosystem (Mitsch and Gosselink, 1986; Michaud, 2005). **Figure 2.1** is a systematic diagram of a generic wetland water budget for a typical inland wetland, such as those which are analysed in this dissertation (cf. **Chapters 5**, **7** and **8**).

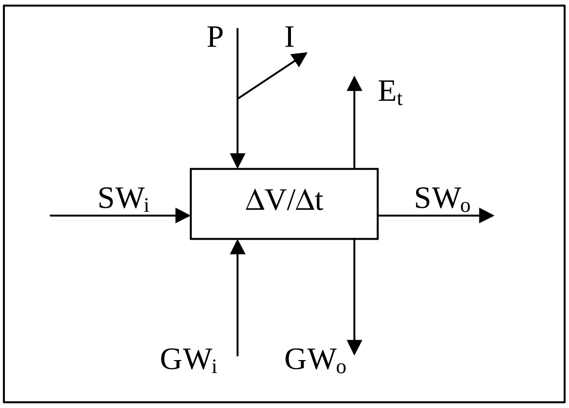


Figure 2.1: Generic non-coastal wetland water budget (after Mitsch and Gosselink, 1993)

From **Figure 2.1**, $(P - I) + SW_i + GW_i = E_t + SW_o + GW_o + \Delta V/\Delta t$ (Donkin, 1994)……...**2.1**

where,

$\Delta V/\Delta t$ = Change in storage volume per unit change in time (mm/s),

P = Gross precipitation (mm),

I = Interception losses (mm),

E_t = Total evaporation, including transpiration losses (mm),

SW_i = Surface water inflows (mm),

SW_o = Surface water outflows (mm),

GW_i = Groundwater inflows (mm), and

GW_o = Groundwater outflows (mm).

From **Figure 2.1** and **Equation 2.1** wetlands have three inputs and three outflows. The inputs are:

- surface water inflows,
- groundwater inflows, and
- net precipitation (i.e. gross precipitation minus interception losses).

The outflows are:

- surface water outflows,
- groundwater outflows, and
- total evaporation.

The surface water inflows are governed by the feeder catchment's physiography and climate. A major factor in this process is the soil characteristics. These characteristics also play an important role in the surface water outflows, as well as groundwater inflows and outflows (Colvin *et al.*, 2005). The greater the water affinity the soil has, the longer it will hold the water that has entered the wetland, thus increasing the wetland storage effect and the attenuation ability of the wetland. Wetlands typically have high organic matter content as the organic material decomposes slower in the anaerobic conditions than under the normal aerobic conditions of the remainder of the catchment. Organic matter has a high water holding capacity and will thus add to the water retention of the catchment (Chapman, 1990).

A major loss from a wetland is from total evaporation (i.e. actual evaporation from the soil surface plus actual transpiration through the wetland vegetation) and evaporation from the open water component. The open water component of the wetland is usually a shallow water body with a potentially large surface area, thus giving it a large surface area to volume ratio. The higher this ratio is, the greater the relative evaporative losses will be. The soils that are saturated for a large part of the year will also lose substantial amounts of water through evaporative processes. The losses incurred from the transpiration of unique hydrophilic wetland vegetation usually take place at high rates and will thus add significantly to the total evaporative losses.

The characteristics of the wetland water budget, which enables the wetland to influence the outflows of water, has several advantages over a run-of river reach in that it provides the wetland with functions that are beneficial to the environment, both within and downstream of its catchment area. These wetland functions are discussed in the following section.

2.2 Wetland Functionality

In the past twenty years from 1990 – 2010 the importance of wetlands to the catchment system has come to the fore. However, the hydrology and functionality of wetlands are complex (RAMSAR, 2002; Kotze *et al.*, 2005). This section outlines the broader (rather than the complex) functions of wetlands. The functions that a wetland performs not only affect the hydrological responses of the catchment in which it exists, but also include the channel environment for some distance downstream (this distance being dependent on the size of the wetland, and is not determined in this dissertation). Not only do these natural functions affect the catchment, they are a part of the everyday functionality of the wetland itself. Carter *et al.* (1978) suggests that the main functions of a wetland are governed by its hydrological interactions. Although this dissertation considers only the first two of the four main natural functions of a wetland, all four will be discussed in the following sub-sections:

- streamflow regulation,
- flood attenuation,
- water purification, and
- sediment accretion.

2.2.1 Streamflow regulation

Schulze (1995) describes streamflow as the contribution of stormflow and baseflow from upstream and localised areas. Wetlands, by acting like a sponge, have the ability to regulate downstream flow (Kotze *et al.*, 2005). They do so by absorbing water into their overall body, but at differing rates. This water then spreads through the various smaller channels which exist within many wetlands, or overtops the main wetland channel onto the surrounding area. Both of these processes, coupled with flat gradients typical of wetlands, slow the streamflow velocity (Chapman, 1990). The attenuated streamflow then reaches the wetland's outlet, which is often smaller than the inlet, thus releasing the water at a reduced and more regulated flow rate. This flow rate depends, *inter alia,* on the flow volume entering the wetland. This attenuation regulates the flows during the wet period. The flows in the dry period are regulated by the baseflow and the groundwater contribution that most wetlands receive. These two slower discharging contributions work as the regulators in the drier months due to the hydromorphic soils typically found in wetlands. These soils absorb and retain water better than most general catchment soil types found elsewhere and are furthermore usually well-vegetated, providing ample time for infiltration, and thus recharge of the baseflow store. Wetlands that are located along streams and upstream of reservoirs may release stored water directly into their respective systems (i.e. into streams and reservoirs), thereby contributing to their own preservation (Michaud, 2005).

The retention of water in times of high streamflow and its release at a slower rate provides relatively consistent flows during the wetter periods, whilst storing water internally. The store of water in wetlands also contributes to the consistent flows during the dry months, which is released from the baseflow store accumulated during the wetter months. The above conditions facilitate relatively consistent flows throughout the year, only affected by severe droughts or by large flood flows (Duever, 1988).

Although wetlands generally retain low flows at a steady rate, they have been documented to reduce low flows (Carter *et al.*, 1978; Begg, 2001). This can occur as a result of the large evaporation rates of the shallow water bodies that are found in some wetlands, accompanied by the high transpiration rates of wetland vegetation (Begg, 2001).

The wetland functioning as a large sponge taking up and retaining relatively large amounts of water only to release them gradually over time, has a marked effect on the streamflow regime (Begg, 2001). It can therefore have a positive effect by attenuating floods. The next sub-section will address the flood attenuation abilities of wetlands.

2.2.2 Flood attenuation

Probably the best known function of a wetland is its ability to attenuate flood peaks. Marble (1992) describes flood peak attenuation as the reduction and/or storage of stormflow generated upstream of the wetland. The ability of a wetland to attenuate floods, and the extent to which it can do so, are determined by several physical characteristics of the wetland (Sather and Smith, 1984; Chow, 1986; Von der Heyden, 2004). These include the following:

- *Intra-catchment position*: The location of the wetland in relation to the main channel plays an important role in how much flow can be attenuated. Wetlands that are not located on, or near to, the main channel have a significantly reduced attenuating effect. The reason for this is that the amount of water feeding such a wetland is small in comparison to the flood volumes in the main channel.
- *Topography*: The slope that the wetland is located on has an effect on flow velocity. If the slope is significantly reduced in comparison to that of the main channel, especially if it is almost flat, this will reduce flow velocities and thus have a positive attenuating effect on the flood (Kotze *et al.*, 2005). In addition to the above, if the underlying geology creates a smaller constriction at the outlet of the wetland, this will reduce the rate of flow of water from the wetland, thus decreasing the flood peak downstream of the wetland (Marble, 1992).
- *Morphology*: The morphology of a wetland is defined by its shape and the surface area available for water retention. A wetland that is large and circular in shape will have a bigger attenuation effect than a wetland that is small and elliptical in shape (Ogawa and Male, 1986).
- *Wetland soils*: The soils in a wetland are unique and play an important role in flood attenuation. The ability of the soil to allow infiltration of the floodwaters and retard the water can impact the attenuation process positively. Marble (1992) refers to this as the capillary storage capacity of the soil. The higher the capillary storage capacity the greater the attenuation ability.
- *Wetland vegetation*: A higher density of vegetation increases the degree of flow attenuated. This is due to the increase in the wetland's roughness coefficient with an increase in vegetation density (Carter *et al.*, 1978; Kadlec and Kadlec, 1978). According

to Kadlec and Kadlec (1978) the height of the vegetation also plays an important role. Short vegetation only provides limited friction when the floodwaters become deeper and pass over it. However, taller vegetation provides greater friction to the deeper floodwaters, thereby having a greater attenuation affect.

The combined effects of the above-mentioned characteristics are illustrated in **Figure 2.2**, which shows generic hydrographs of the flood peak entering a wetland and the flood peak exiting the wetland. Note that the flood peak is not only reduced, but also delayed, thereby giving downstream communities more time to prepare for the flood, should it be a large one. The peak is substantially reduced and thus is far less detrimental to the downstream environment, and the flow variability is reduced. These effects are depicted in **Figure 2.3** for actual observations made at the outlet of a vlei catchment in comparison to the outlet of a catchment without a vlei by Schulze (1979).

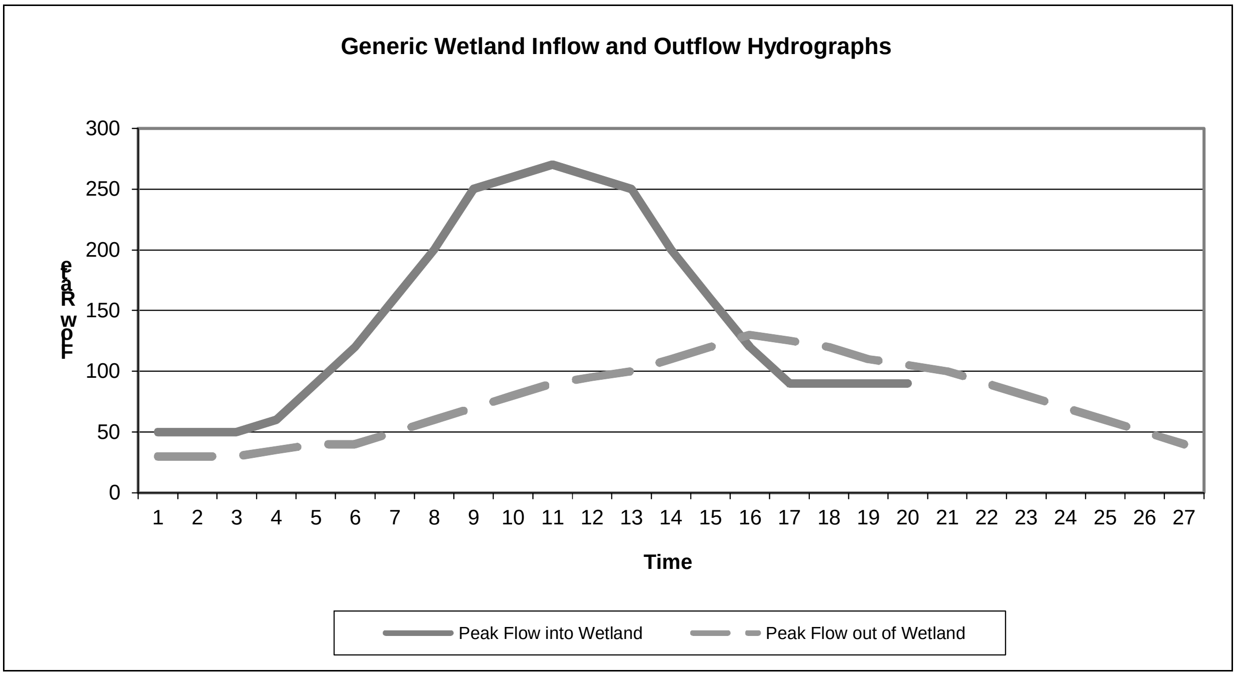


Figure 2.2 Typical inflow and outflow hydrographs for a generic wetland (after Mitsch and Gosselink, 1986; Lymberopoulos and James, 1993)

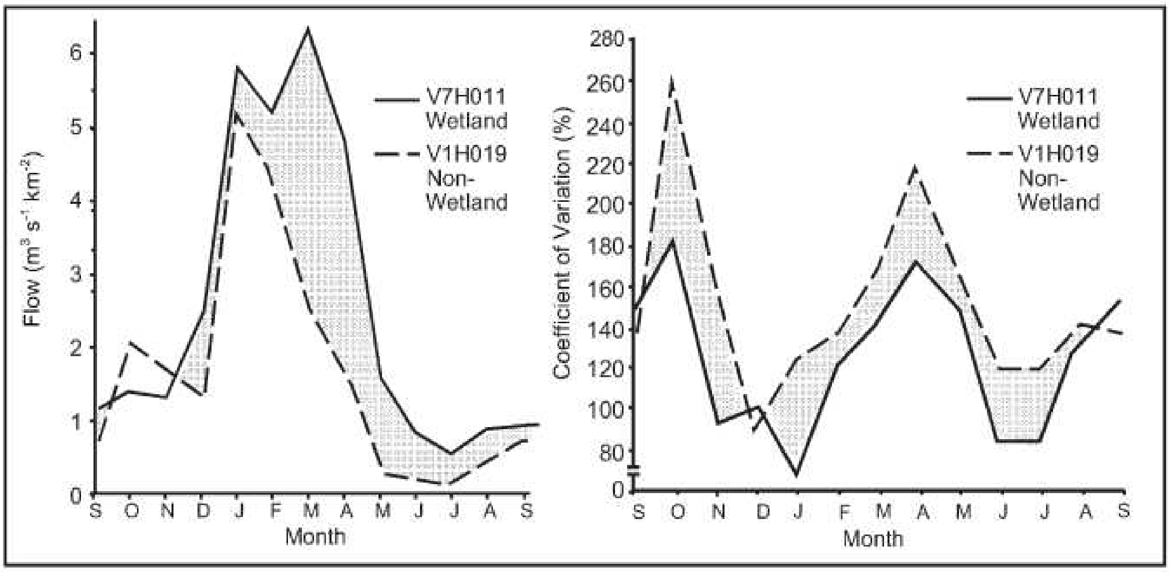


Figure 2.3 Comparison of actual recorded streamflow results for a sub-catchment within the Thukela catchment with a wetland in comparison to an adjacent sub-catchment without a wetland present (after Schulze, 1979)

2.2.3 Sediment accretion

Sediment accretion is a well-known function of wetlands. The amount of sediment a wetland may retain is dependent on physical and morphological characteristics. These characteristics include water velocity, wetland slope and vegetative cover.

The amount of sediment a specific flow volume can transport is directly proportional to water velocity (Hjulstrom, 1935 cited by Donkin, 1994). The higher the flow velocity, the greater both the particle size and quantity of sediment that can be carried by a specific volume of water. With the widening of the flow path when a channel enters a wetland, the flow velocity is reduced. This then leads to deposition of sediment, at least on a temporary basis. Wave action and turbulence can re-entrain the sediments for further transport.

The morphology of the wetland, specifically its slope, plays a major role in the deposition of sediments. A smaller gradient will facilitate slower flow velocities within the wetland, thus giving more time for sediment deposition and more opportunity of accretion, as discussed above.

The topographical position can also aid in sediment accretion. If the wetland is sheltered, specifically from wind, then less turbulence can imply less re-suspension of sediments for further transport (Hjulstrom, 1935 cited by Donkin, 1994).

Finally, the density and type of vegetation plays an important role in the deposition of sediments. A high vegetation density implies that there will be a higher coefficient of friction against the water flow, thus reducing flow velocities and presenting more opportunity for deposition. The type of vegetation also plays a role. Vegetation with an intricate root system aids in binding the sediments, thereby preventing their re-introduction into the transport system (Hjulstrom, 1935 cited by Donkin, 1994).

Sediments help bind pollutants in the water, thus improving downstream chemical and biological water quality. Suspended sediment deposition leads to cleaner and clearer water, which increases the amount of light that enters the water and penetrates to greater depths, thereby increasing vegetation growth. Sediment accretion by wetlands also has a positive effect by decreasing the siltation of downstream impoundments that may be used for recreation, agriculture and water supply. All of the above factors therefore play an important role and provide advantages for downstream users.

2.2.4 Water purification

Wetlands purify water by the removal of excess nutrients, heavy metals, pollutants and sediments, which helps aquatic systems downstream to function in a more natural and healthy manner. The reduction in flow velocity once the water has entered the wetland provides the wetland environment more opportunity to purify the water than a stream or river would. This enables various processes to occur, such as sediment trapping, nutrient immobilisation, temperature modification and heavy metal immobilisation (Carter *et al.*, 1978; Marble, 1992).

Sediments and flocculants are often clay particles which have high cation exchange capacities. This is especially the case in smectitic clays (i.e. 2:1 clays), which have greater surface area than kaolinitic clays (i.e. 1:1 clays), and thus have more scope for cation exchange (Bester, 2003).

These sediments settle, adsorbing nutrients and heavy metals that are present in the water. Once settled, the sediments form part of the anaerobic wetland bed. Wetland soils with a high proportion of smectitic clays have a low hydraulic conductivity and a high porosity (Faulkner and Richardson, 1989). In combination these two characteristics allow for little movement of water once it is in the soil pore space. This feature of the soil not allowing water to move freely is due to the considerable adhesive and cohesive bonds between the water and soil particles. These trapped minerals and heavy metals are immobile in their anaerobic, or reduced, state (Bester, 2003). The immobilisation of the heavy metals and excess nutrients is achieved through cation exchange with the sediment, or via microbial action. The higher the microbial activity, the healthier the wetland is (Breen *et al.*, 1994). Wetlands with high microbial activity are vital for nitrogen fixation and the immobilisation of other nutrients such as phosphorus (P), potassium (K), sulphur (S) and sodium (Na) which could have been derived from fertilizer application of upstream farming activities. These conditions are also responsible for ammonium volatilisation, by removing some of the nitrogen from the system (Bester, 2003).

Over time the wetland vegetation adsorbs these trapped nutrients and heavy metal pollutants. The vegetation assimilates the pollutants, having a naturally high tolerance to the toxins. When the vegetation senesces, it biodegrades at the bottom of the wetland. In this anaerobic environment the decomposition is a slow process, thus releasing the heavy metals and inorganic toxins back into the system gradually and in an immobile state (Bester, 2003).

Certain wetland vegetation types play another role in the water purification process. These types of wetland vegetation, in association with a specific type of bacteria (nitro-bacter, which is a nitrogen fixing bacteria), can convert inorganic chemicals into useful organic nutrients through their general functioning, e.g. legumes converting dissolved inorganic nitrogen (N_2) to nitrate (NO_3). Nitrates are the favoured form of nitrogen for plant uptake (Bester, 2003).

When a wetland is drained, and thus oxidised, all the heavy metals and toxins are mobilised creating pollution problems downstream. This is discussed further in the next sub-section.

In summary, the major wetland functions and their influencing factors are shown in **Table 2.1**. The influencing factors are shaded against the corresponding function. It is evident from **Table 2.1** that the functionality of a wetland is affected by many factors, the most prominent being its morphology.

Table 2.1 Summary of influencing factors on wetland functions (after Barichievy, 2005)

INFLUENCING FACTORS		**PRIMARY FUNCTIONS**			
Main Factors	**Contributing Factors**	**Streamflow Regulation**	**Flood Attenuation**	**Sediment Accretion**	**Water Purification**
Wetland Morphology	Size	■	■	■	■
	Shape	■	■	■	■
	Slope	■	■	■	■
	Groundwater Depth	■	■		
	Surface Water Depth	■	■	■	■
	Outlet Size	■	■	■	■
Soil Characteristics	Depth	■	■		■
	Type	■	■		■
	Texture	■	■		■
Vegetation Characteristics	Density	■	■	■	
	Height	■	■	■	
	Type	■	■	■	■
	Roughness	■	■	■	
Other Influences	Intra-catchment Position, i.e. off-channel	■	■	■	■
	Shelter			■	■
	Organisms				■

2.3 Drainage of Wetlands

The drainage of wetlands has been a common practice in the past. Most drained wetlands can provide advantages when used for agriculture (RAMSAR, 2002; Von der Heyden, 2004). Drained wetland soils are generally nutrient rich and their location is perceived to have access to sufficient water (Von der Heyden, 2004). These two factors will increase the chance of obtaining good crop yields by supplying the crop with vital nutrients, especially nitrogen in the form of previously trapped nitrate, and enough water so that the plant is not water stressed, which is a major crop yield reducing factor. Wetlands have also been drained to facilitate rapidly expanding economies, such as South Africa's, which need more industrial and urban land (RAMSAR, 2002).

Although the above paragraph highlights advantages in draining wetlands, (i.e. both agricultural benefits and other spatial benefits), there are numerous negative impacts to this practice, especially when perceived from hydro-ecological and climate change perspectives.

Section 2.2 outlined the functionality of wetlands. However, when wetlands are drained, many of these functionalities are lost. Some examples follow.

- When a wetland is drained the water that normally flows through it, and is thus attenuated, is diverted through or around the reclaimed area by canals and furrows. This allows the water to move through less-impeded, thereby negating any attenuation benefits the wetland once provided (Von der Heyden, 2004). The effects of this will be discussed later.
- In much the same manner, the ability of flood attenuation is lost, thus creating potentially severe problems for downstream ecosystems and communities. The flood proceeds through the reclaimed area unrestricted and the full magnitude is felt both on site and downstream. This can result in loss of life, major infrastructural damage and damage to ecosystems fauna and flora (RAMSAR, 2002).
- Siltation of downstream catchments and storage structures can become problematic with the draining of wetlands. This will reduce the life of downstream storage structures and

could have substantial financial repercussions relating to the costs of removing the sediment or constructing new dams and weirs.

- The loss of wetland goods and services must also be considered. The reeds, trees, fish and other useful fauna and flora will be lost to communities who benefit from them. Losses would also include less tangible benefits such as recreation and ecotourism.
- The final major impact when a wetland is drained may be perceived as a double-edged sword. First, the drained wetland can no longer purify water. This implies that heavy metals, carbon, nitrogen and other pollutants are no longer immobilised in the wetland anaerobic conditions and are free to move downstream and pollute other catchments and ecosystems. Secondly, the pollutants that were trapped and immobilized due to the anaerobic reducing environment at the base of wetlands are now mobilised. This is caused by the introduction of oxygen to the system through the drainage process, which oxidises the heavy metals, converts carbon into carbon dioxde (CO_2 – a greenhouse gas), nitrates into nitrous oxide (N_2O – another greenhouse gas) and other organic and inorganic pollutants (Bester, 2003). This oxidation releases large quantities of previously stored toxins into the system, either for direct uptake by the crops planted there, or for volatilisation into the atmosphere to potentially create a greater impact on global warming (Bester, 2003).

The impacts of global warming and climate change on wetlands drainage mentioned above are not clear cut. There is an increase in CO_2 emission due to the increase in carbon released from the carbon sink and there is also an increase in certain other greenhouse gases, although in lesser quantities, e.g. N_2O (RAMSAR, 2002). However, drainage of wetlands would decrease methane (NH_4 – a further greenhouse gas) emissions because the microbial anaerobic consumption of carbon has ceased (RAMSAR, 2002). It has not yet been determined which has the greater influence, increased CO_2 or decreased NH_4 emissions (RAMSAR, 2002).

In more recent times, there has been a concerted effort to restrict the drainage of wetlands through legislation. This is considered to be a step in the right direction because wetlands provide many advantages to ecosystems and humans alike.

2.4 Goods and Services from Wetlands

In the past, many wetlands were generally considered to have little intrinsic value, except for the provision of recreational activities (e.g. the Okavango Delta in Botswana). Recent experience shows that this is definitely not the case. Cowan (1995) highlights the importance of wetlands and the goods and services they supply. They can be considered a substantial resource for arid to semi-arid areas as they are a constant site of life and activity and, considering that wetlands cover 6 % of the earth’s surface, there should be no shortage of the goods on offer (Cowan, 1995). This section addresses the potential goods and services that a wetland could supply. The specific goods and services supplied vary due to locality, topographical position and wetland size.

The abundant biodiversity within the wetland is a major benefit within this ecotone (Kotze *et al.*, 2005). This is due to the wetland environment being wet for long periods of, if not all of, the year. Thus, the stable supply of water makes it a concentration point for fauna and flora alike. This is not limited to the specific fauna and flora that have adapted to live in the wetland environment. The wetland environment also attracts bird and wildlife to it because of the abundance of potential food and water.

Water supplied from wetlands is highly beneficial to humans (Von der Heyden, 2004). The water, because it is often very pure, is a source of drinking water (Kotze *et al.*, 2005). It is also a source of water for agriculture (Von der Heyden, 2004), with the wetland potentially yielding water all year round for irrigation. The potential use of wetlands derived from draining specific parts of the wetlands for agriculture, such as pastures for grazing, has societal and economic benefit (Kotze *et al.*, 2005). These areas are well suited to livestock farming with the supply of water and grazing of both pastures and natural reeds and grasses, thus making it easy to maintain healthy stock.

Wetlands contain harvestable resources that have been used by indigenous communities for decades (Kotze *et al.*, 2005), such as

- sedges and reeds for crafts (i.e. mats);
- reeds and wood for construction;
- wood for fuel;

- traditional medicinal plants;
- grazing for livestock; and
- fish, birds and game for hunting.

These harvestable resources provide a stable source of products that enable communities to live sustainably off the wetland environment (Kotze *et al.*, 2005).

Certain parts of the wetland can be drained for agriculture. Pastures are not the only crops planted in these regions. As the wetland soil contain nutrients and are high in water content, harvestable crops can also be planted there, adding to the food supply for local communities and even for selling the product at markets for income.

When communities have lived near to, and utilised, wetland habitats for a prolonged period of time, a cultural significance is often placed on them (Kotze *et al.*, 2005). Resources for crafts, traditional medicines, food and religious ceremonies have been used in the past, placing importance on these sites.

Finally, wetlands are an important site from an education and research perspective (Kotze *et al.*, 2005). There is a diversity of wildlife and vegetation, with hydrological, geological and groundwater factors that can only be found in and around wetlands. The potential for research and learning is considerable, and this important fact should not be neglected when considering the good and services of wetlands.

In summary, wetlands have many functions, goods and services that cannot be ignored. They are an important part of the natural hydrological environment as well as the human environment, so much so that an economic value can be placed on the goods and services provided.

Knowing how a wetland functions does not imply that it is easy to assess how changes in the wetland hydrology will impact the fragile network that exists in these habitats. To fully assess many of these impacts, hydrological modelling is required.

2.5 Chapter Summary

To summarise the above-mentioned impacts of wetlands in relation to this dissertation, not all of the wetlands hydrological responses will be assessed. The two main streamflow based hydrological responses are assessed, *viz.* flood attenuation and streamflow regulation. The flood attenuation response will be assessed in terms of daily accumulated streamflow and not in terms of flood peak flow as this is outside the scope of this research.

The hydrological responses discussed in this Chapter that are not assessed as a part of this dissertation are the sediment accretion and water quality functions that a wetland has on a hydrological system, nor are potential impacts on socio-economic factors, such as the goods and services provided by wetlands.

Out of the overall review on wetlands from a hydrological perspective, wetlands surface water flows and the ability of a wetland to regulate streamflows and attenuate floods will be assessed using hydrological modelling. **Chapter 4** deals with hydrological modelling in general, with a specific focus on wetlands. As a prelude to the modelling, the following Chapter addresses the general relationships between varying climatic conditions and water resources.

3 CLIMATE, CLIMATE CHANGE AND WATER RESOURCES: AN OVERVIEW

In order to understand the effects of climate and climate change on water resources, *per se*, and specifically on wetlands, there is a need to first distinguish clearly between climate variability and climate change.

3.1 What is Climate Variability?

Owing to uncertainties surrounding the causes of changes in climate, i.e. whether the changes are natural climate variability or anthropogenically induced climate change, both climate variability and climate change need to be defined. In this sub-section, climate variability is briefly discussed.

Climate variability can occur both spatially and temporally. An example of spatial variation is the range of gauged mean annual precipitation (MAP) across South Africa, ranging from < 50 mm to > 3000 mm (Lynch, 2004). Schulze (2005d) confirms that South Africa is a high risk hydroclimatic region due to its low percentage conversion of MAP to mean annual runoff (MAR), which is exacerbated not only by the spatial variability of rainfall across South Africa, but also the intra-annual and inter-annual rainfall variability within South Africa. These natural variances in climate make South Africa's individual sub-catchments susceptible to changes in climate, although the impacts due to the change in climate are attenuated in larger river systems (Schulze, 2005d).

The natural climate variability within a catchment is observed in two main ways, i.e. comparisons between wetter areas and drier areas, and comparisons between wetter years and drier years. These climate variances have been the natural climatic state that society is used to, and thus humans have developed ways to cope with present-day climate variability (Kabat *et al.*, 2003). These coping mechanisms are providing a strong base for dealing with climate change which is imposed on the natural climate variability, namely adaptation for future water-related impacts caused by climate change (Kabat *et al.*, 2003). Climate change differs from the natural variability of climate in as much as climate variability generally is experienced over a shorter time frame, *viz.* diurnal to decades (Schulze, 2003b). Climate variability is reversible and thus not permanent. The next sub-section addresses issues of climate change.

3.2 What is Climate Change?

Climate change is the positive or negative trend in climate when superimposed over natural climate variability in the long-term, caused by anthropogenic influences. Climate change spans time scales of decades to centuries. Within lifetimes and up to centuries, it is permanent and irreversible (Schulze, 2003b). The rest of this Chapter will focus exclusively on climate change, which could have significant effects on water resources in the long term.

Climate change, in the context of this dissertation, is hypothesised to be caused by increased levels of atmospheric greenhouse gases which cause global warming (Arnell, 1996; Jones *et al.*, 1996; Rowlands, 1998; van Dam, 1999; Smith *et al.*, 2004). Enhanced greenhouse gas concentrations in the atmosphere may lead to different responses in climate-related variables. Each of these responses has an individual and combined effect on the local environment. The main responses of the hydrological system include changes in atmospheric carbon dioxide (CO_2) levels, changes in temperature and changes in precipitation (Rowlands, 1998; Schulze, 2003b).

The remainder of the Chapter will outline how these factors can influence the local climate and affect water resources both positively and/or negatively, starting with enhanced CO_2 concentrations, as these are considered the primary driver of climate change.

3.3 Changes in atmospheric CO_2 concentration

Greenhouse gases are commonly understood to be one of the leading causes of global warming, which contributes to climate change (IPCC, 2007b; Raupach *et al.*, 2007). Thus, an increase in atmospheric CO_2 concentration, and that of other greenhouse gases, contributes directly to the accelerated effects of climate change, such as increases in temperature and change in precipitation, which are discussed in the sub-sections which follow.

An increase in atmospheric CO_2 concentrations results in *enhanced* rates of photosynthesis, and thus more rapid development of vegetative matter, with the rate depending on whether the plant has a C_3 or C_4 photosynthetic pathway (Hulme, 1996). By itself, and under conditions of no plant stress, higher photosynthesis rates would increase rates of transpiration (Rosenzweig and Hillel, 1995; Schulze, 2003b), and thus dry the soil profile more rapidly, potentially resulting in a lower runoff response to a given magnitude rainfall. This is, however, counteracted by transpiration losses being *reduced* by higher CO_2 concentrations through decreased stomatal conductance. This reduction varies between plants with C_3 and C_4 pathways, and the hydrological effects of this reduction depend also on the plants' above-ground biomass and on levels of soil water stress. Schulze and Perks (2000b) have shown with simulations using the *ACRU* Model, which can account for the above processes and feedbacks, that for a doubling of pre-industrial revolution CO_2 levels to 560 ppmv, the mean annual runoff in the Thukela catchment would be decreased by 2 – 4 % for C_3 plants if all other variables remained unchanged.

3.4 Changes in temperature

A change in temperature can have many impacts on water resources, both direct and indirect. An increase in temperature will increase the potential evaporation (Rosenzweig and Hillel, 1995; IPCC, 2001; Rowlston, 2003; Schulze, 2003b). This will increase the amount of water that can evaporate from open water bodies and from the available soil water. Furthermore, it will increase the potential for increased transpiration which could, in turn, result in a reduction in antecedent soil water conditions before rainfall events, thereby reducing runoff. This drying of the soil will also have a direct impact on agriculture in terms of areas that are currently climatically suitable for dryland farming, as well as the amount of irrigation required to sustain a crop at maximum transpiration rates. Both of these impacts on the soil water balance and hence runoff to downstream users. Increased warming could thus lead to a shift in habitable ecosystems for fauna and flora (Kurukulasuria and Rosenthal, 2003) which, again, could be especially detrimental to agriculture, as susceptible crops may have to be moved to more temperate regions, which could change the partitioning of rainfall into stormflows, baseflows and evaporative losses. There may also be an increase in the incidence, severity and duration of temperature related extreme events, *viz.* droughts and heat waves (Rowlston, 2003; Schulze, 2003b). Conversely, an increase in temperature can affect agriculture positively by increasing the length of the growing season. However, this could have a negative impact on water resources because there would then be an increase in soil and irrigation water usage from an earlier beginning in the season to a later end of the season, as has been illustrated by Schulze and Perks (2000b). Of the recorded temperature records starting in the 1850s, 13 of the 14 warmest years up to 2008 had occurred from 1995 onwards (Jones, 2009). In addition, the IPCC (2007) has shown that the rate of temperature increase for the 50 years up to 2006 was almost double that of the 100 years up to that point in time. This recorded increase in temperature is suggested to be as a result of climate change, and thus a cause for concern based on the potential negative impacts discussed above. In a sensitivity study with the *ACRU* Model, Schulze and Perks (2000b) have shown that an increase in temperature by 2 ^{o}C, while keeping all other variables constant, could reduce mean annual runoff in the Thukela catchment by an average of approximately 5 %, but with reductions of up to 20 % in the ecological sensitive high Drakensburg areas of the catchment.

3.5 Changes in precipitation

The main driver of streamflow response in the hydrological cycle is precipitation. Changes in precipitation characteristics can have wide-reaching implications over space and time (IPCC, 2001). There can be changes, either positive or negative, in the total amount of precipitation an area may receive throughout the year. Changes can also be experienced in the reduction in raindays (days in the year that receive greater than 1mm of precipitation), or the change in mean annual precipitation (MAP). Lynch (2004) found that the MAP at rainfall stations in South Africa ranges from < 50 mm to > 3000 mm. This spatial range in rainfall across a country shows a high susceptibility to climate change in the more arid western regions (**Figure 3.1**). If there was to be a decrease in MAP then there are various cascading effects on the hydrological cycle. The first, and most important, would be the reduction in runoff leading to a decrease in available water resources (Rosenzweig and Hillel, 1995; Rowlston, 2003), both in that area and downstream. Other effects can be in regard to changes in:

- seasonal runoff (e.g. Schulze *et al.*, 2005c),
- antecedent soil water conditions (e.g. Schulze *et al.*, 2005c),
- groundwater recharge (e.g. Cave *et al.*, 2003),

- irrigation requirements (e.g. Schulze *et al.*, 2005c), and
- the number and severity of extreme events, which may affect hydrological design (Schulze, 2003b; Schulze *et al.*, 2005c; Knoesen *et al.*, 2009).

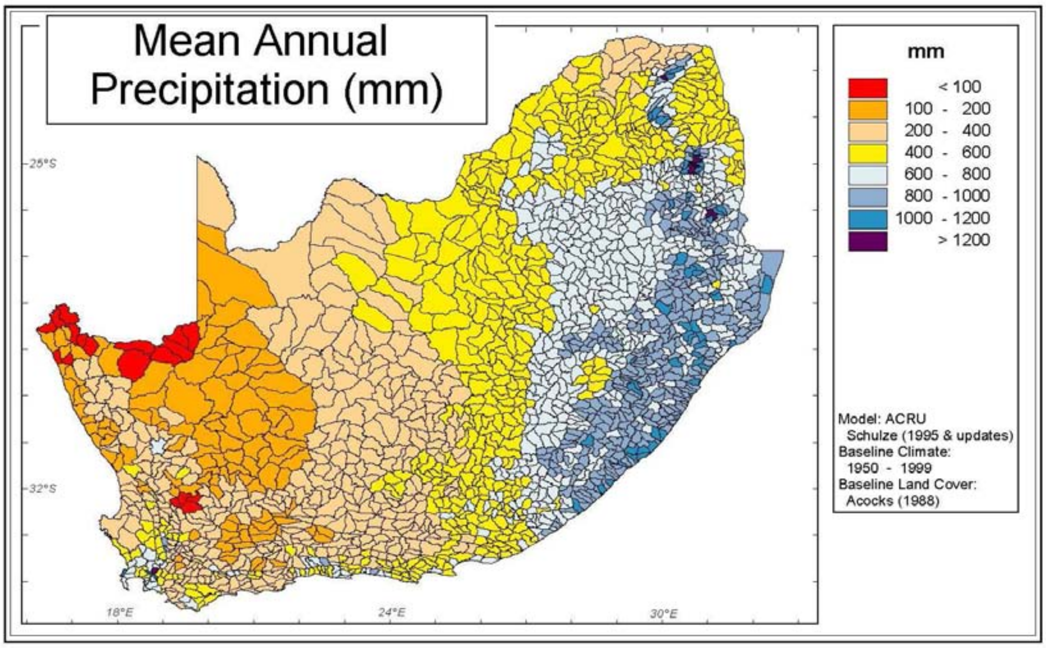


Figure 3.1 Baseline values of mean annual precipitation derived from daily climate data from the Quaternary Catchments Database (Lynch, 2004)

It is hypothesised that there could be a change in the number, and type, of rainfall events. Sediment yields and stormflows are initiated by single rainfall events, thus if there is an increase in days without rainfall and days with < 10 mm of rainfall there would be an effect on the number of stormflow-causing events (Schulze *et al.*, 2005c). However, Schulze *et al.* (2005c) also states that there could be an increase in raindays that receive greater than 25 mm/day, which would increase sediment transportation. The increase in sediment transportation could increase the rate of sedimentation of impounded water (Newson, 2009). The potential impacts of a change in precipitation could then have follow-on impacts on terrestrial systems, such as aquatic and semi-aquatic habitats through increases in water temperature (Barichievy and Schulze, 2010) and land use (IPCC, 2007).

*****

Some of the major factors that affect water resources as a result of climate change have been outlined above. Their individual influences are significant. However, the interactions are occurring simultaneously, thereby compounding the potential effects of a change in precipitation, temperature and atmospheric CO_2 concentrations. An increase in temperature combined with a decrease in precipitation will have the largest negative impact on water resources. The increase in CO_2 levels can have a positive effect on water resources by the reduction of vegetative water losses (Schulze and Perks, 2000; Schulze, 2003b). The balance between these three factors will determine to what extent water resources are impacted.

In the following section, more details of first order effects of climate change on water resources will be addressed.

3.6 First Order Effects of Climate Change on Water Resources

First order impacts are those resulting directly from changes in rainfall, temperature and CO_2. Hypothetically, they affect mainly runoff. Runoff from a catchment is made up predominantly of stormflows and baseflows, and it has a significant effect on the amount of water available to the various sectors, including the Human Reserve and the Ecological Reserve (NWA, 1998), industry, domestic use, agriculture and recreation. Small changes in precipitation have an amplified effect on runoff. In the western regions of South Africa, less than 5% of annual precipitation is converted to runoff (Segius *et al.*, 2004; Schulze *et al.*, 2005b), whereas the eastern region has approximately a 15% conversion of rainfall to runoff (Schulze, 2005d). Thus, it can be argued that a small decrease in rainfall in the western regions is, in relative terms, far more significant than in the eastern region, although not in absolute terms. Temperature also plays a major role in the low conversion rate from precipitation to runoff. An increase in temperature can lead to significant decreases in runoff due to higher soil water evaporation and transpiration rates, which both result in lower antecedent soil water conditions, higher infiltration rates, and subsequently less runoff. An example of effects of first order impacts on streamflows is depicted in **Figure 3.2,** in which it is shown how a plausible change in temperature and rainfall is simulated to affect the hydrological response from the Thukela catchment.

Taken from a WRC report to which the author was a contributor (Schulze *et al.*, 2005b), **Figure 3.2** shows how a 2 ^{o}C increase in temperature in combination with a 10 % reduction in rainfall could decrease accumulated streamflow in the Thukela catchment by up to 30% of their current levels under baseline land cover conditions (Acocks, 1988) and with hydrological responses simulated with the *ACRU* Model. Such a change in streamflow could lead to a redistribution of water resources both spatially and temporally (van Dam, 1999). If there were a large enough spatial shift, the major reservoirs could fall out of the main runoff generating areas, thus having a significant effect on meeting water demands. This could be amplified by the increased demand from population growth.

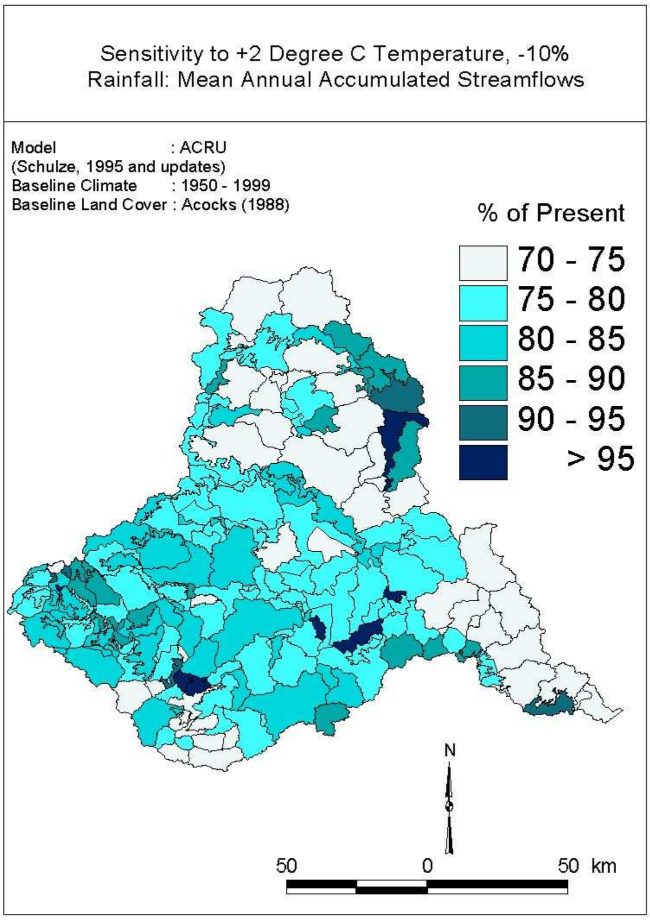


Figure 3.2 Sensitivity analysis of plausible changes in temperature and rainfall on mean annual accumulated streamflows in the Thukela catchment (Schulze *et al.*, 2005b)

Because South Africa is a semi-arid country with an uneven spatial distribution of precipitation (cf. **Figure 3.1**), and it is classified as a water-scarce country (Otieno and Ochieng, 2004), it is more vulnerable to first order climate change impacts than countries with a more even rainfall distribution. Vulnerability in the context of this study may be defined as the level of exposure to damage that will be incurred from climate change, both for social and natural systems (IPCC, 2001). As a result of this vulnerability, there needs to be various plans for adapting to these potential changes, in order to keep water resources sustainable. While adaptation is not an integral component of this dissertation, three relatively simple examples of adaptation to sustain South Africa's water resources into the future are nevertheless summarised from Schulze and Perks (2000a):

- *Improved management of supply and demand*: This can be undertaken simply by being able to move resources between different catchments, whereby the water resources of an area that has excess water can be used in a catchment that is in deficit.
- *Increase water supply*: This would imply construction or modification of infrastructure and implementation of improved operating rules to make better use of the available runoff; including the use of additional and less common sources of water resources such as desalinated water from the ocean.
- *Reduce water demand*: This could include water pricing and more efficient application of irrigation water.

Similarly, the IPCC (2001) suggested that system optimisation for the physical water supply should be looked into. In South Africa large volumes of water are lost due to under-maintained pipes and facilities (e.g. Falkenmark and Lannerstad, 2004). As much as 15 – 20 % of the water being allocated to urban use in South Africa is lost from the system through leakage (Mukheibir and Sparks, 2003), which is considered high by international standards.

The following section moves away from the basic effects of climate change on runoff, and focuses on secondary effects, which include ecological concerns, groundwater vulnerability and the role of water in agriculture.

3.7 Second Order Effects of Climate Change on the Water Sector

Second order effects of climate change assess how a potential change in climatic conditions may impact on various sectors such as agriculture, stream ecology, wetlands and groundwater. The effects incurred by these may then cascade detrimentally or positively to available water resources, thereby indirectly or directly affecting humans.

3.8 Higher Order Effects of Climate Change

Third order impacts can be defined as impacts that climate change have directly on human society, such as water poverty, water quality and loss of life and infrastructure through extreme events.

3.9 Chapter Summary

Some of the major factors that affect water resources as a result of climate change have been outlined in this section. Their individual influences are noteworthy. However, they all operate simultaneously, and that potentially compounds individual effects. An increase in temperature and a decrease in precipitation have the largest negative impacts on water resources at varying levels of significance. This is due to both these factors potentially decreasing runoff and streamflow and, in a water scarce country such as South Africa, this poses increasing problems to vulnerable sectors. The increase in CO_2 levels can have a positive effect on water resources by improving *green* water efficiency. The balance between these three factors will determine the extent to which water resources are threatened.

The reduction of runoff is a first order effect of climate change. This reduction of runoff flowing into reservoirs will place a strain on water supply in South Africa. This, coupled with population growth, indicates a potential water supply problem in the future. Increasing infrastructure is not the only answer. To overcome this problem, improving efficiency, recycling water, and the ability to transfer water between areas easily will be vital to maintain future sustainability. The effects on water resources are not the only problems that may occur. Impacts, especially on agriculture and groundwater, need to be assessed as they will be vital for future water supply and food production. Communities experiencing water poverty could be among the most vulnerable to changes in climate as the communities it affects have no defence against it. All the above factors point to the need to improve modelling techniques to identify potential ‘Hot-Spots’ of climate change impacts.

There is thus a great need for the improvement of modelling techniques in order to better understand the potential impacts of climate change. As technology improves and computing power increases, it becomes easier to create models such as RCM’s that have a higher horizontal spatial scale than at present. This will allow hydrological modelling of possible future changes in the climate with more accuracy, which will help in the identification of areas that will be most affected and creating possible adaptation and mitigation strategies for specific regions. Thus Chapter 4 will discuss models and modelling in more detail.

4 MODELS AND MODELLING: A REVIEW RELATED TO THIS STUDY

If it is considered that a variety of natural influences will dominate hydrological responses differently at a range temporal and spatial scales, and this is then coupled with anthropogenic influences, which again influence hydrological responses at different time and space scales, then then an understanding can be gained of the complexity and demands of a simulation model that can adequately represent the hydrological cycle (Schulze, 2003a). Many reasons can be argued for hydrological modelling. However, the main reasons are a result of limitations of hydrological measurement techniques (Beven, 2001) and the fact that hydroclimatic observations cannot be made at every location where water related decisions are required. Arnell (2002) makes reference to this in regard to streamflow gauge networks, stating that gauges are either non-existent or poorly maintained and neglected, especially in developing countries such as South Africa. In addition, streamflow records are likely to include inhomogeneities, by way of incorrect calibration of recording equipment, weir overtopping, misinterpretation of data and inadequate record length (Warburton, 2005). The potential limitations in the examples given above bring to the fore the need to model across space and over time, in particular with the use of a physical conceptual model (Beven, 2001; Warburton, 2005). The above can be related to the study of wetlands hydrological responses, with the lack of flow gauging stations situated upstream and downstream of wetlands limiting the quantity of recorded hydrological data at these sites.

In order to effectively model the impacts of wetlands across a range of climatic conditions which may be found in a catchment, or for a change in climate, one must first be able to model the catchment's hydrology adequately. To do this accurately, the model used must be able to link two major components of the hydrological system within its structure, *viz.* modelling hydrological processes which occur on the *landscape* component of a catchment and modelling *channel* related processes. Anthropogenic influences on the landscape (e.g. urban and crops) and the channel (e.g. dams and weirs) components will affect, and can even compound, any effects of climate regimes when modelling impacts of wetlands on hydrological responses. A distinction therefore has to be made between anthropogenic influences on the landscape and in the channel which affects wetlands and the impacts of climate change. In order to isolate the effects of wetlands on hydrological responses, or effects of different climate regimes on wetland responses, one therefore requires a reference point, which is a catchment with baseline land cover and a model configuration in which influences of wetlands (and their characteristics) can be "switched on" or "switched off". Such a "baseline" approach is taken in this dissertation as it will allow for the identification of wetlands impacts independently, or for climate change impacts alone, or a combination of the two.

As will be elaborated upon later, for the purpose of this dissertation, the following models were selected: for wetlands hydrological modelling the *ACRU* Agrohydrological Model (Schulze, 1995) was chosen, while for the climate change modelling (both with and without wetlands), the Conformal-Cubic Atmospheric Regional Climate Model (C-CAM; Engelbrecht, 2005) was selected. *ACRU* was selected as it is considered to give realistic and representative hydrological results (cf. verification studies, including those for wetlands, given in Schulze, 1995), and C-CAM was the only suitably downscaled Regional Climate Model (RCM) from which daily climate output was readily available in the School of Bioresources Engineering and Environmental Hydrology at the time that this dissertation commenced.

In light of the above, issues of hydrological modelling (including model requirements and some emphasis on wetlands modelling), as well as issues of climate change modelling (including sub-sections on general circulation models, regional climate models and downscaling of the C-CAM Model) will be discussed below.

4.1 The Hydrological Model Used in This Study: *ACRU*

In this section the requirements of a suitable hydrological model will be outlined, and then the model selected for this dissertation is discussed.

4.1.1 Model requirements for hydrological studies under varying landscape and climatic conditions

Beven (2001) outlines the various choices when selecting a hydrological model. Models can be

- lumped or distributed,
- physically based or calibrated, or
- deterministic or stochastic.

Selecting a deterministic model allows one to make projections in space and, coupling this with a process-based system allows one to accurately account for the soil water budget (Beven, 2001). A deterministic model provides the user with a specific output, as opposed to allowing for uncertainty, as in stochastic models (Beven, 2001).

Thus, a suitable model to simulate wetlands hydrological processes/ impacts within a broader catchment context needs to meet the following requirements (Bevan, 2001):

- Differentiate between channel and landscape based processes;
- Explicitly model the dynamics of different runoff generation processes;
- Simulate on a relatively short (daily) time-step;
- Have the ability to model different levels of land management practices;
- Address management conflicts on varying spatial scales;
- Model various dominant processes over a wide range of climatic conditions;
- Model hillslope processes; and, in regard to this study;
- Contain specific wetland routines.

Thus, in order to perform hydrological simulations across a range of climatic conditions (including climate change), both with and without wetlands, a model was required that was deterministically based and conceptual-physical in its process representations. A model which meets most of the above requirements is the *ACRU* Agrohydrological Model (Schulze, 1995; Schulze and Smithers, 2003; Smithers and Schulze, 2003 and updates).

4.1.2 The *ACRU* Agrohydrological Model

ACRU is a daily time step, conceptual-physical and multi-purpose agrohydrological model, with the capability of simulating, *inter alia*, streamflow, impacts of climate change and impacts of changes in land cover, and all of the above across a range of spatial scales (Schulze, 1995). The model revolves around multi-layer soil water budgeting and is structured to be hydrologically sensitive to catchment characteristics (Schulze, 1995). It is a conceptual-physical model, i.e. it is conceptual given that it creates a system in which critical processes and dynamics are idealised, and physical in that there is explicit representation of physical processes (Eagleson, 1983; Schulze and Smithers, 2003; Schulze, 2005c). These attributes are vital in order to undertake the necessary scenario analyses required for this dissertation (Schulze, 2009).

4.1.3 Concepts on which the ACRU Model is based

The *ACRU* Agrohydrological Model (Schulze, 1995) is centred around the following aims, also presented graphically in **Figures 4.1** and **4.2**:

- Variables are generally estimated from physically based characteristics of the catchment. Thus, *ACRU* is not a parameter fitting model (Schulze, 1995).
- It is a *multi-purpose* model which integrates the various runoff production and water budgeting components of the surface water hydrological system (Schulze and Smithers, 2003). The daily multi-layer soil water budget forms the basis of the model, as depicted in **Figure 4.2**. The water budgeting can be applied as a versatile model for applications in hydrology (e.g. climate change impacts, land use impacts, ecological requirements and water resource assessments) as it is sensitive to both climatic and land use changes on the soil water and runoff regimes (Schulze, 1995). As such, it can be considered a versatile total evaporation model (Schulze and Smithers, 2003).
- *ACRU* is a daily time-step model using daily climate input data, thereby optimising the available climate data (Schulze, 2001b). Using Fourier analysis, the less sensitive variables, such as crop coefficients, are transformed internally within the model from basic monthly inputs to the required daily level (Schulze, 1995). If more sensitive intra-daily climate variables are required, *ACRU* synthetically disaggregates daily values into shorter time steps, for example, when intra-day rainfall distributions are required for flow routing (Schulze and Smithers, 2003).

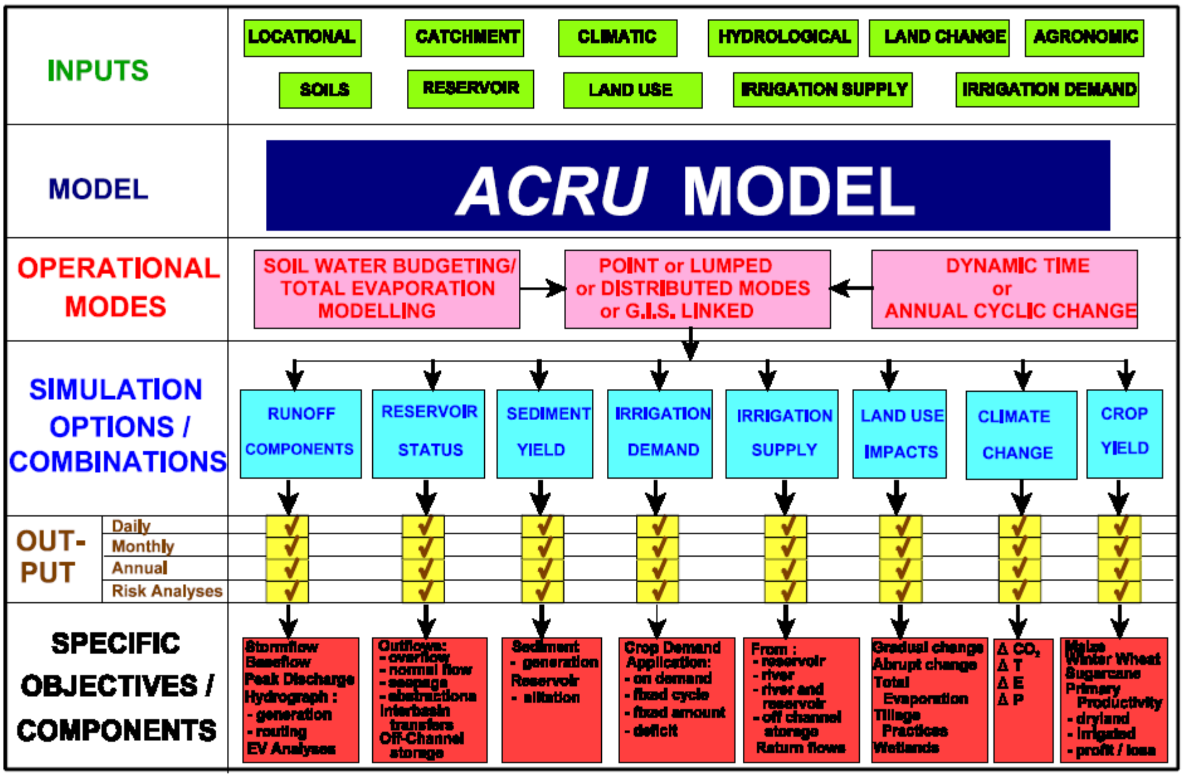


Figure 4.1 The *ACRU* Agrohydrological Modelling System: Concepts (Schulze, 1995)

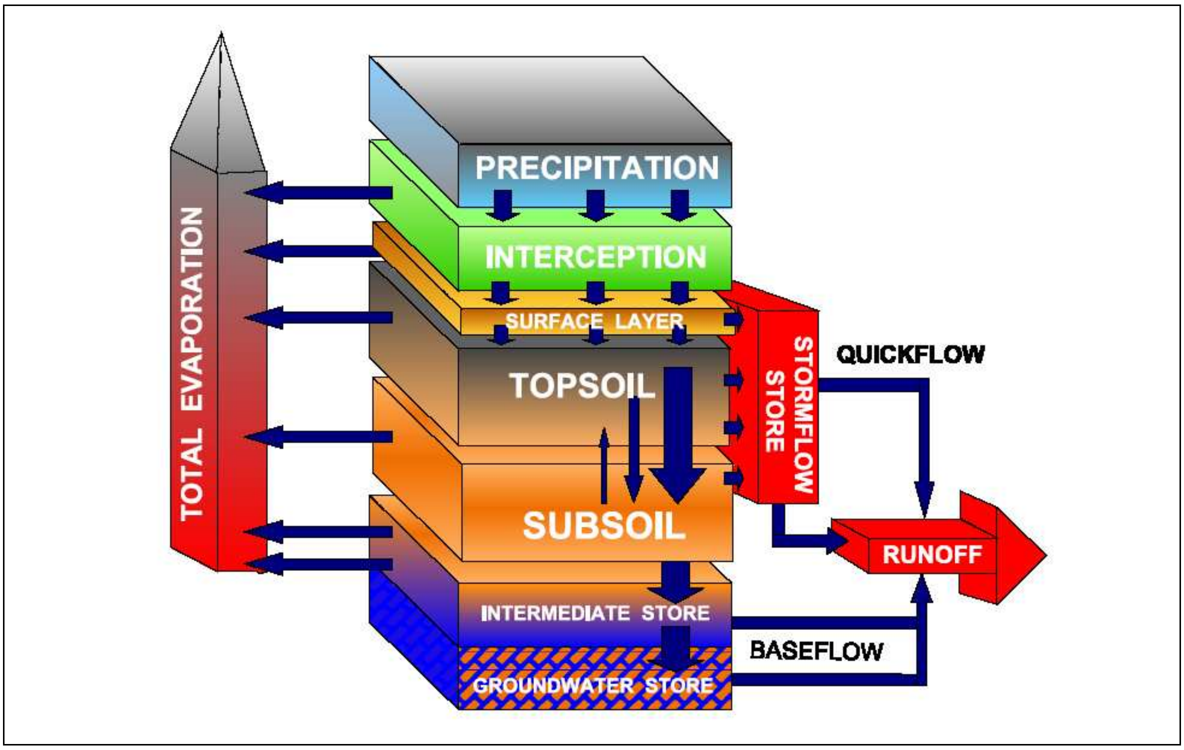


Figure 4.2 The *ACRU* Agrohydrological Modelling System: General structure (Schulze, 1995)

- Owing to the various levels of input data that can be entered, or the detail of output required, there are multiple options, or alternate pathways, available in many of *ACRU*'s routines (Schulze and Smithers, 2003). It can thus be considered a *multi-level* model. In general, the greater the detail of the input parameters, the higher the accuracy in the model outputs.
- *ACRU* can operate as a *point* model, as a *lumped* small catchments model, on large catchments or at national scale. In areas that have varying land uses and soils, over large catchments or at national scale *ACRU* operates as a *distributed* cell-type model (Schulze, 1995). In distributed mode individual sub-catchments, which ideally should not exceed 50 km^2 in area, but which are often at the level of Quaternary or sub-Quaternary (Quinary) Catchments in South Africa, are identified. Once discretised into sub-catchments, flows translocate from 'exterior' through 'interior' cells according to a defined layout, with the ability to generate individual results sets for each sub-catchment, which may be different to those of other sub-catchments. This can also apply to sub-catchments with different levels of input (Schulze and Smithers, 2003).
- Schulze and Perks (2001) outline some modifications to the *ACRU* model in order to enhance climate change impact studies, *viz.*,
  - ➢ A new thermally driven biomass indicator which can account for simulating effects of seasonal climatic condition on water use, interception and rooting coefficients;
  - ➢ A plant-water stress routine with a declining water use coefficient (K_d), leading to sustained wilting, and for the full, or partial, recovery of K_d upon the soil wetting up again; and
  - ➢ New values for the magnitude of maximum transpiration suppression for C_3 and C_4 plants under conditions of enhanced CO_2 concentrations.
- Included in the *ACRU* Model is a wetland routine more detail on which, and new modifications, are described in detail in **Section 4.1.5**. This routine is founded on a hydrological (i.e. water balance) basis (as opposed to a hydraulic basis), as shown in **Figure 4.3**. The routine has an open water and a wetlands vegetation component which can vary in area. In its original form, if there is more water entering from upstream (which includes all upstream baseflows) than the wetland's channel capacity can carry,

the excess water will spill over onto the wetlands topsoil which, in turn, will feed the subsoil via seepage once the topsoil has exceeded its drained upper limit (field capacity). If there is insufficient water in the channel, then no water spills onto the wetland topsoil. The soil water that percolates down through the wetland's soil profile is released slowly from the baseflow store in the form of baseflow. More details on the *ACRU* Wetland Routine are given in **Section 4.2.5**.

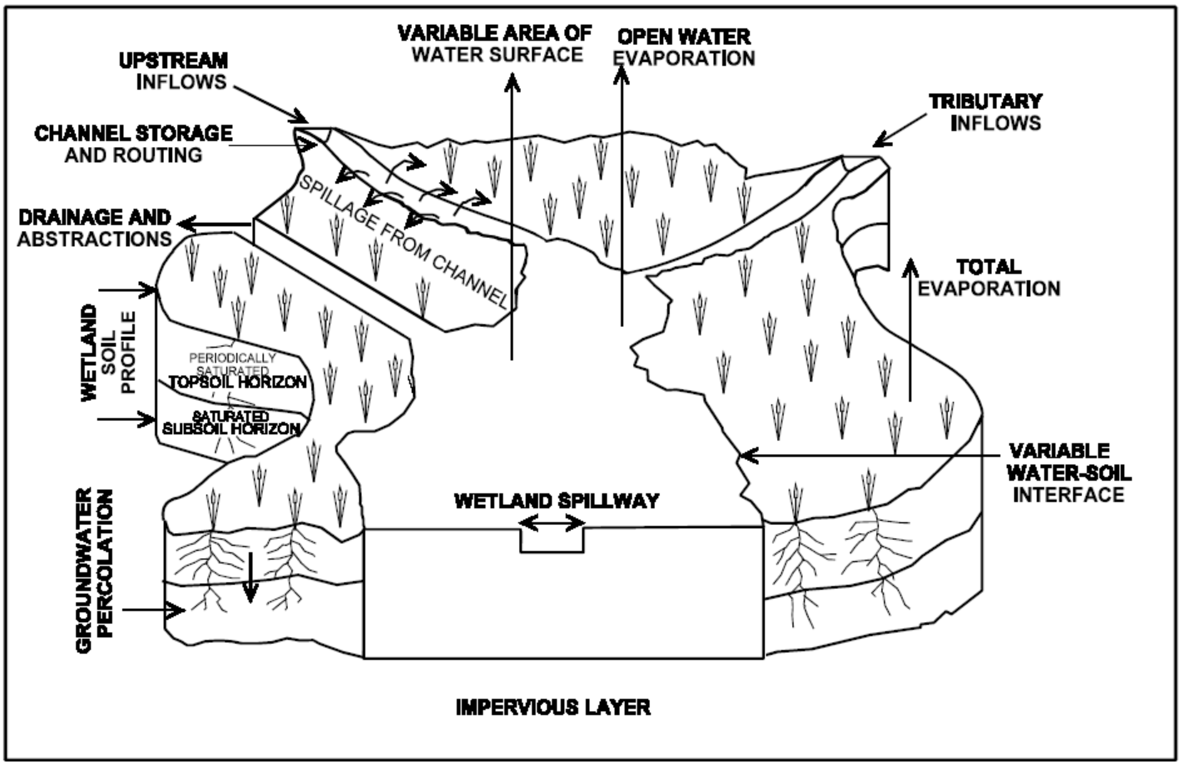


Figure 4.3 Concepts, processes and assumptions involved in the original *ACRU* wetlands module (after Schulze, 1987; Schulze, 2001a)

4.1.4 *S*uitability of the *ACRU* Model for modelling climate change impacts

A component, although a relatively small one, of this dissertation considers potential impacts of climate change on wetlands hydrological responses. Schulze (2005c) describes how modelling the impacts of climate change can be represented when *hydrological processes* are combined with *water resource management*, as outlined in **Figure 4.4**.

In order to avoid response changes that would occur on the landscape component of the catchment, namely evaporative demand and rainfall partitioning, a distributed model must be used. This, accompanied with a fresh approach to modelling the drivers of the *hydrological processes*, is vital to reduce perturbations in the modelling process (Schulze, 2009b). Management of water resources ideally takes the form of Integrated Water Resources Management (IWRM). This involves the sustainable supply of water to meet the local requirements from the available water resources (i.e. rivers, dams, groundwater, etc). Manipulation and control of the available flows and storages within the catchment are management strategies undertaken to supply water to various user sectors. A potential problem when modelling this type of system coupled with climate change concerns the changing dynamics between supply and demand (Schulze, 2005c). An often neglected aspect of modelling the landscape and channel components of a catchment are what Schulze (2005c) terms the *transitional components,* such as riparian zones, estuaries and wetlands. The latter is particularly relevant to this study.

The modelling requirements summarised in **Figure 4.4** essentially require a multi-purpose, conceptual-physical model with a detailed soils water budget (Schulze, 2005c). The *ACRU* Model includes many of the above requirements and was thus used for the simulations undertaken as a part of this dissertation.

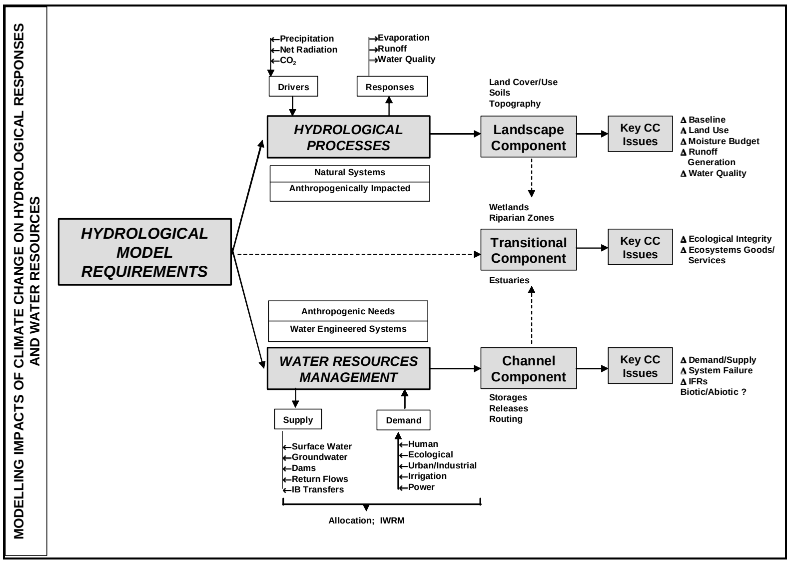


Figure 4.4 Hydrological model requirements under conditions of climate change (Schulze, 2005c)

4.1.5 The *ACRU* Wetlands Routine

Wetlands are highly diverse and occur in many different forms (cf. **Chapter 2**). Most wetlands classifications are therefore of a general nature, as are descriptions of the wetland functions. The process of modelling wetlands integrates both general theoretical knowledge of wetlands and the use of measured data from actual wetlands (Smithers and Schulze, 1995). A hydrologically based wetlands model should be able to confidently determine the relative importance of wetland characteristics on the hydrological responses. In so doing, the model should be able to simulate different types and/or characteristics of wetlands and changes in wetland responses under different climatic conditions.

Wetlands can be found in a variety of hydrological, topographical and geological settings. The original *ACRU* Wetlands Routine is based on a definition proposed by O'Brien and Motts (1980), *viz.* that wetlands are areas that are typically flooded periodically, and which have groundwater at, or near, the surface for the majority of the year.

In order to effectively model hydrological responses from wetlands, their hydrological role must be appreciated. As reviewed in **Chapter 2**, the four main hydrological wetlands characteristics to consider are:

- Streamflow regulation,
- Flood attenuation,
- Water purification, and
- Sediment accretion.

The ability of wetlands to temporarily store transient water makes them important hydrological modifiers. Thus, confirmation that the model simulates the various hydrological influences a wetland has on a catchment is important. The *ACRU* Wetland Routine has been verified through a study by Smithers (1991) on the Ntabamhlope wetland in KwaZulu-Natal, South Africa, and more recently on the Mvoti vlei, also in KwaZulu-Natal (Horan, 2006, pers. comm.). These verifications showed trends in flow attenuation, increases in dry season flows and lower monthly coefficients of variation of flows. These findings concur with those of Schulze's (1979) study at

Ntabamhlope in which observed streamflows from a wetland were compared with observed streamflows from an adjacent catchment with no wetland (cf. **Figure 2.3**).

In regard to the four main hydrological wetlands characteristics listed above, the *ACRU* Wetland Routine does not, however, account for the water quality aspects of wetland functioning, i.e. it does not account for chemical adsorption, i.e. water purification, and sediment deposition that would normally occur in the wetland. The *ACRU* Model only accounts for water quantity, i.e. the wetland's streamflow regulation and flood attenuation functions.

The *ACRU* Model simulates wetlands by utilising the hydrological balance equation outlined by Smithers and Schulze (Schulze, 1995). The equation used is as follows:

$$\Delta \mathbf{S_w} = \mathbf{P_g} + \mathbf{I_{su}} + \mathbf{I_{gw}} - \mathbf{E} - \mathbf{O_s} - \mathbf{O_{gw}} \qquad \ldots\textbf{Equation 4.1}$$

where

$\Delta \mathbf{S_w}$	=	change in storage (mm),
$\mathbf{P_g}$	=	gross rainfall (mm),
$\mathbf{I_{su}}$	=	surface inflow (mm),
$\mathbf{I_{gw}}$	=	groundwater inflow (mm),
$\mathbf{E}$	=	total evaporation (mm),
$\mathbf{O_s}$	=	surface outflow (mm), and
$\mathbf{O_{gw}}$	=	groundwater outflow (mm).

These and other concepts used in the *ACRU* Wetlands Routine are depicted in **Figure 4.3**. Similarly **Figure 4.5** gives a representation of the flow routing used in the original *ACRU* Wetlands Routine. However, the reservoir storage component of the wetland was found not to function as expected and the wetlands routine was therefore modified with assistance from Horan (2010, pers com), as depicted in **Figure 4.6**. The following is a description of how the model was configured for this study to simulate responses from wetlands:

- The wetland is modelled as its own sub-catchment, with fixed boundaries.

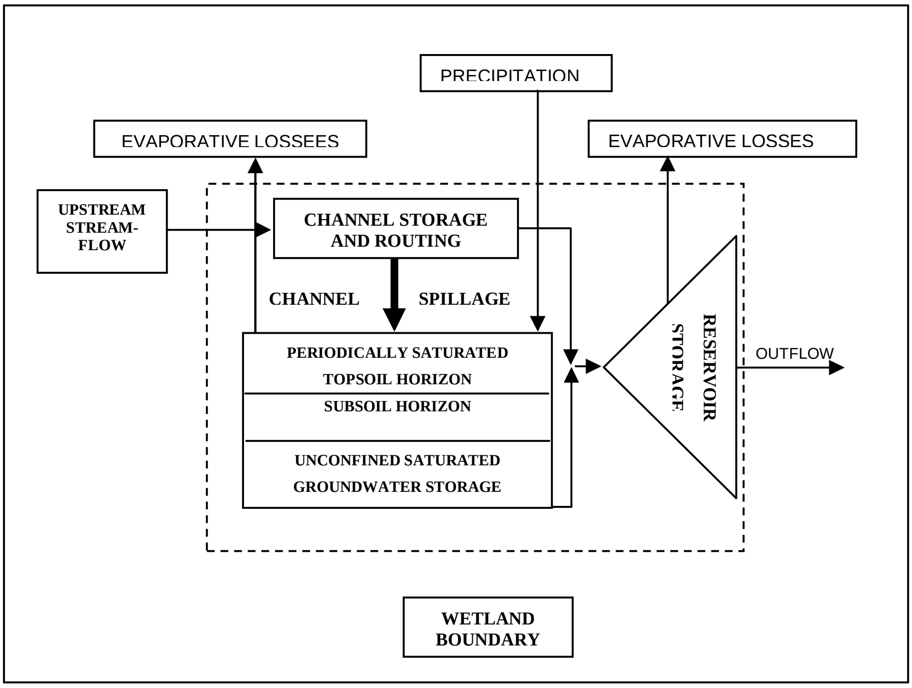


Figure 4.5 Schematic diagram showing flow routing in the original *ACRU* wetland routines (after Smithers and Schulze, 1995)

- An impervious layer is assumed to underlie the base of the wetland (see later bullet points).
- Spills from the channel onto the wetland's topsoil only occur when the channel capacity is exceeded. In this study the channel capacity was defined as the 50th percentile annual flow volume in mm, converted to a daily flow expressed in m^3/s, plus any releases of water out of the wetland catchment (simulated as an independent sub-catchment) as baseflow.
- When the wetland's soil is totally saturated from the above two sources of water, the excess water then exits the wetland as stormflow.
- When the wetland's topsoil is at, or above, field capacity, percolation of soil water moves water down the soil profile to the subsoil. This process is repeated from the subsoil to the baseflow store.
- The baseflow store below the subsoil horizon is considered to be unlimited in volume and has an impervious base, therefore only releasing water out of the wetland in the form of baseflow. There is thus no deep percolation or groundwater recharge from the wetland in this model.

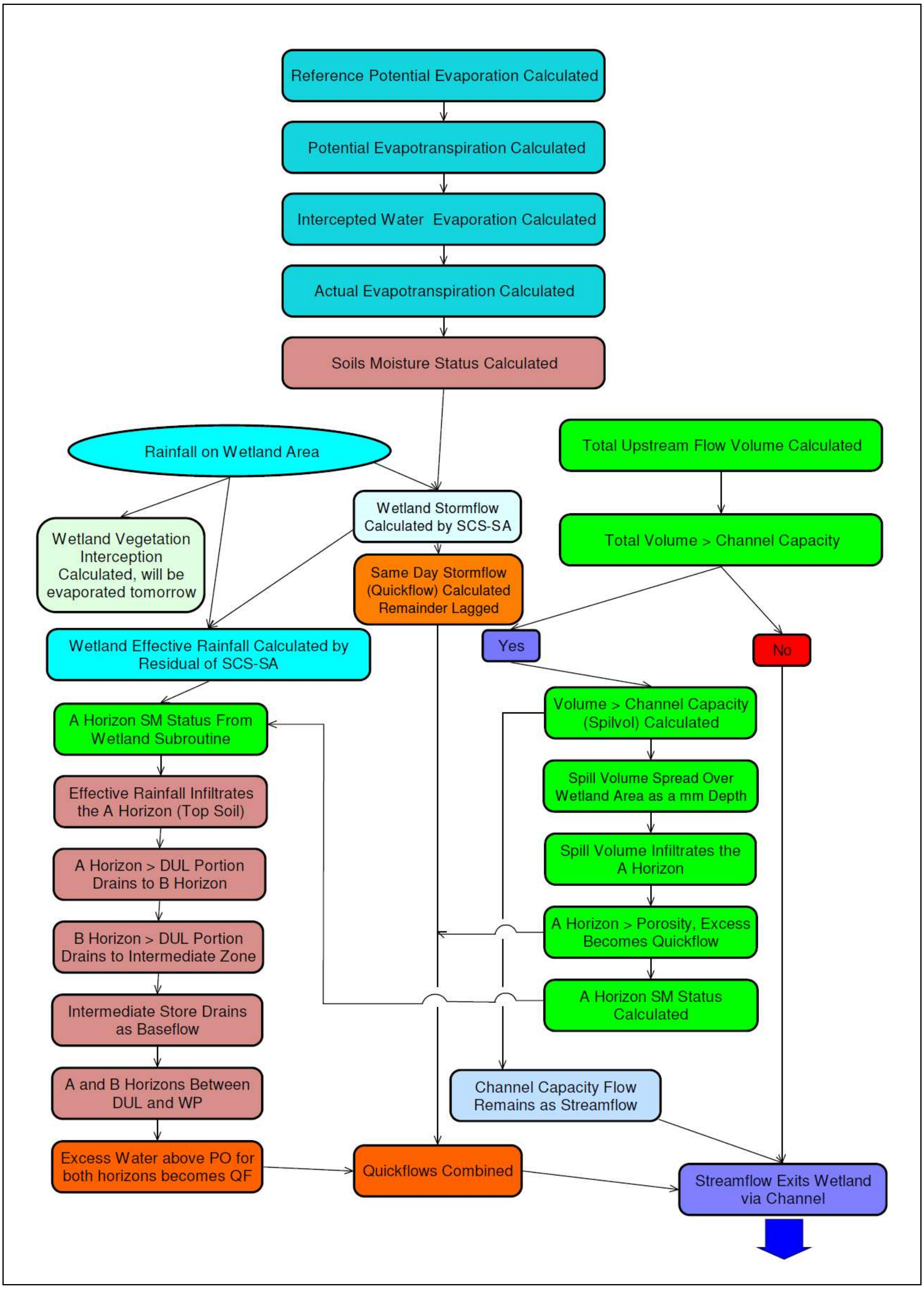


Figure 4.6 Schematic diagram showing the modified hydrological processes in the *ACRU* Wetland Routines (after Horan, 2010, pers. comm.)

- The baseflow release from the baseflow store is based on a decay function that is dependent on the volume of water contained in the baseflow store, i.e. the greater the volume of water stored in the baseflow store, the higher the rate of baseflow released from the store on a daily basis.
- Based on the above, the wetland system losses are made up of total evaporation and outflows in the form of stormflow and baseflow.

* * * * *

Following on the description of the wetlands routine, the next section addresses climate change modelling as used in this study.

4.2 The Regional Climate Model Used in This Study: C-CAM

By way of introducing the C-CAM Regional Climate Model, a brief overview of General Circulation Models (GCMs), Regional Climate Models (RCMs) and downscaling issues in climate change is given in this Section. Climate modelling is a very complex method of simulating global atmospheric conditions coupled with sea-surface temperatures (SSTs) to obtain projections of a plausible future climate. This global model output can then be downscaled to a regional level in order to perform impact studies. The initial step in climate modelling is the use of general circulation models, which will be briefly outlined in the following sub-section.

4.2.1 General circulation models (GCMs)

In order to obtain regional scenarios, one must have a basic understanding of what a General Circulation Model is. A GCM simulates climate processes at detailed temporal scales with numerous layers in the atmosphere, but at a large spatial scale, commonly 200 - 300 km^2 (Hewitson *et al.*, 2005). It will primarily model sea-surface temperature, plus regional feedbacks and dynamics coupled with the major far-field winds, and incorporate large scale responses to greenhouse gas forcing superimposed on these simulations, in order to obtain a plausible change in climate (Engelbrecht, 2005; Hewitson *et al.*, 2005). Outputs between different GCMs show common trends and directions, however, the magnitudes of change may vary due to incomplete process representations in GCMs and local topographical influences. GCMs can credibly simulate the dynamics of the synoptic scale fields of high and low pressure systems that govern the regional climates (Beven, 2001; Engelbrecht, 2005; Hewitson *et al.*, 2005). They do, however, have a certain level of uncertainty attached to them as they are not as efficient at simulating finer scale climatic processes, such as convective rainfall and rainfall intensity (IPCC, 2007; Giorgi *et al.*, 2008). In order to account for these climatic processes, GCM outputs need to be downscaled to a catchment representative level. One method of achieving this is using Regional Climate Models (RCMs), which are discussed in the following sub-section.

4.2.2 Regional climate models (RCMs)

The synoptic forcing performed by GCMs takes into account only broad topography and land-water boundaries. The climate is predominantly influenced by two important land-surface parameters, namely albedo (surface reflectance to incoming solar radiation) and soil moisture (Hewitson *et al.*, 2005). Soil moisture affects evaporation and hence latent heat fluxes at the surface, while albedo influences surface temperature and hence specific heat fluxes. These outputs need to be downscaled to a finer spatial scale that can be used for impact assessments (Hewitson *et al.*, 2005; Bergant *et al.*, 2006; Giorgi *et al.*, 2008).

There are two methods commonly used to downscale the results from a GCM to a regional scenario, *viz.* Empirical Downscaling and Dynamic Regional Downscaling using RCMs (Engelbrecht, 2005). Downscaling is important in order to achieve relevant results from impact studies (Engelbrecht, 2005). The two types of downscaling are outlined in the sub-sections to follow.

4.2.3 Empirical downscaling

Empirical (or statistical) downscaling is a commonly used technique for providing the regional-scale responses to global climate change as simulated by comparatively low spatial resolution GCMs (Hewitson *et al.*, 2005). This form of downscaling is directly representative of the circulation that is simulated by the GCM. Statistical models are usually developed using present-day climate, thus making them inherently dependent on the dynamics and physics of current conditions (Engelbrecht, 2005). Renwick *et al.* (1999) cautions against their use when extrapolating to future climates as conditions may fall outside the current observations used. Empirical downscaling is implemented with Self Organising Maps (SOMs), which provide a data description and visually depict the major characteristics of the multi-dimensional data distribution function (Hewitson *et al.,* 2005).

4.2.4 Dynamic regional downscaling

Renwick *et al.* (1999) state that because dynamic modelling is explicitly physically based, it will more likely give reliable results for an atmosphere of increased greenhouse gas concentrations. Cloud parameterisations and the propagation of other biases in downscaling GCM output to RCMs can create problems in dynamic downscaling. However, since the physical laws that oversee atmospheric motion are valid universally, a well-formulated and carefully chosen parameterisation scheme based on physical laws should produce adequate rainfall simulations irrespective of the location (Engelbrecht, 2005). Engelbrecht (2005) believes that using a high resolution dynamic model with a universally appropriate cloud parameterisation is a sound solution for simulating both present and future climates at the regional scale.

There are two methods of dynamic downscaling from GCM outputs:

- *Nested limited-area modelling*: This is considered the more traditional of the two approaches (McGregor, 1997). In this case the RCM receives atmospheric information, at regular time intervals, for the lateral boundaries of the limited domain (area of earth being modelled) in question (Engelbrecht, 2005). This is a computationally efficient way to obtain high resolution simulations of the area in question.
- *Variable-resolution global modelling*: This newer method provides far more flexibility for dynamic downscaling from any GCM, needing only far-field winds and sea-surface temperature from the GCM (McGregor and Dix, 2001). It integrates the GCM with high horizontal resolution over a specific area (i.e. the area to be simulated). This method

limits problems that may be encountered in nested limited-area modelling, such as reflections at lateral boundaries (Engelbrecht, 2005).

In this dissertation, outputs from a variable-resolution global model were used for the present and future climate variables needed to run hydrological simulation (with the *ACRU* Model) for impact studies on a regional scale. The RCM outputs used in this study are derived from the *Conformal-Cubic Atmospheric Model* (C-CAM; Engelbrecht, 2005). The next sub-section gives an outline of C-CAM.

4.2.5 The Conformal-Cubic Atmospheric Regional Climate Model (C-CAM)

C-CAM is derived by projecting panels of a cube onto the earth surface and the model is formulated on a quasi-uniform grid (Engelbrecht, 2005). The various physical parameterisations used, enable the model to simulate the atmospheric conditions, a canopy scheme and six layers of soil temperatures and soil moisture (Engelbrecht, 2005). A higher resolution for specific areas can be attained when the model is run in stretched-grid mode (Engelbrecht, 2005).

Southern Africa's climate was simulated with C-CAM for a present period 1975 – 2005 and a future period 2070 – 2100 (Engelbrecht, 2005). The spatial resolution over southern Africa was half a degree, i.e. 50 - 60 km. Sea surface temperatures (SSTs) and other initial conditions were provided by the CSIRO Mk3 AOGCM, which was used to provide data from 1961 – 2100, using observed greenhouse gases from 1961 – 2000 and obtaining predicted emissions from 2001 – 2100 from the A2 SRES scenario (Engelbrecht, 2005; Schulze, 2005a).

The outputs from C-CAM, such as daily minimum and maximum screen height air temperatures and daily precipitation amounts, were qualitatively verified against the corresponding observed averages from the University of East Anglia's Climate Research Unit (CRU) for the period 1961 – 1990. C-CAM was considered by Engelbrecht (2005) to generally simulate both temperatures and rainfall parameters well across southern Africa.

4.3 Linking RCM Output with the *ACRU* Model

The link between the outputs from a RCM as the inputs for a hydrological model is an important one. The following section briefly outlines the link, its limitations and approaches used in this study.

4.3.1 The general approach

A general approach to applying RCM output data in climate change impact studies would be to use the daily output from both present and future climate scenarios as input into a daily time-step hydrological model, such as the one used in this study (*ACRU*) in order to model hydrological responses, and then to evaluate the differences in hydrological responses between the two climate scenarios (Schulze *et al.*, 2005c). The daily precipitation, maximum and minimum temperatures from the C-CAM RCM were used as input into *ACRU* for the climate change component of this study.

4.3.2 Limitations of linking RCM outputs with the ACRU Model

There are two major limitations to linking RCM outputs with the *ACRU* Model. The first is the coarse spatial resolution of the RCM output. The RCM outputs are area-weighted, spatially averaged daily rainfall/temperature values for the entire grid box under consideration, which is ½^o × ½^o, i.e. 50 – 60 km × 50 – 60 km or 2 500 – 3 600 km^2 (Schulze *et al.*, 2005c). These are shown for South Africa in **Figure 4.7**.

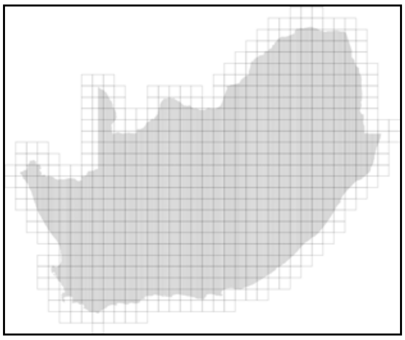


Figure 4.7 The coverage of the 1/2° grid boxes of the RCM output from C-CAM over South Africa (Schulze *et al.*, 2005b)

Hydrological responses such as stormflows and "pulses" of deep percolation beyond the subsoil are triggered by individual, episodic rainfall events which, in convective form (typical of much of southern Africa), may occur only in cells of 10s to ~100s km^2, which is a much smaller scale than the 2 500 km^2 – 3 600 km^2 grid boxes of C-CAM. This difference in scale would lead to:

- too few days with no rainfall;
- too few large, runoff-producing events; and
- too many days of low rainfall, i.e. < 1 mm

in comparison to actual station data from within the study area (Schulze *et al.*, 2005c). Owing to runoff having a highly non-linear relationship with rainfall, the runoff generated from anything but large scale general and uniformly distributed rains would be most likely under-estimated. The second limitation is that actual sub-catchments, with irregular watershed boundaries and areas, have to be assigned to a unique grid box of the RCM. For this study in the Thukela catchment the following procedures were adopted (refer to **Figure 4.8**):

- The MAPs of individual sub-catchments that fall within, or predominantly within, a C-CAM grid box were area averaged.
- The averaged MAP was used in conjunction with the C-CAM-derived "Present" MAP scenario to develop an adjustment factor per sub-catchment.
- Each individually derived sub-catchment adjustment factor was then applied to the daily rainfalls produced by C-CAM for the climate change component of this study (Schulze *et al.*, 2005b).

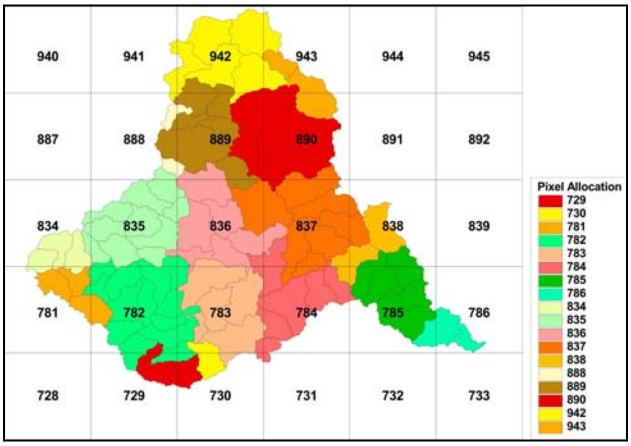


Figure 4.8 Thukela sub-catchments assigned to C-CAM-derived grid boxes (Schulze *et al.*, 2005b)

4.3.3 Towards an approach of modelling impacts of projected future climates

The answer to the first limitation of the RCMs (i.e. coarse spatial scale) was therefore simply to compute a ratio of RCM-derived future climate occurrences and statistics to RCM-derived present climate occurrences and statistics for each sub-catchment within the study area, i.e. the Thukela catchment. Any potential impacts of climate change using the C-CAM RCM (and other RCMs based on spatial averaging) could then be assessed in *relative terms* by evaluating whether the ratio was > 1 or < 1, while in more *absolute terms* one could multiply this ratio by the value derived for a sub-catchment from the baseline current climate simulations (cf. Schulze *et al.*, 2005c).

The reasoning behind using the ratio approach is based on two suppositions, *viz*.

- that any "errors" in spatial averaging by RCMs would be the same for both their present and future climates, and these "errors" would thus be cancelled by use of a ratio (Schulze *et al.*, 2005c); and
- that hydrological inputs and model responses from the Thukela catchment's baseline simulations are more realistic at the sub-catchment spatial scale than those derived from RCMs for actual present-day and baseline hydrology.

In most of the analyses which follow in **Chapter 8**, ratio maps of future: present statistics of hydrological input and/or output variables are presented, together with maps of the corresponding baseline condition derived from daily climate values for 50 years of historical data.

4.4 Uncertainties in Hydrological and Climate Change Impacts Modelling

This section on uncertainty is divided into four sub-sections which largely reflect the different modelling techniques used in this study, *viz*.:

- introduction;
- uncertainties in general hydrological modelling;
- uncertainties in wetlands hydrological modelling; and
- uncertainty in climate change model.

4.4.1 Introduction to uncertainty in modelling

Brugnach *et al.* (2009) define uncertainty as the lack of complete knowledge and understanding of a specific management system. There are many uncertainties in hydrological and climate change modelling, and one needs to consider in what areas these uncertainties predominantly lie. Due to the multiple the modelling of hydrological responses, namely hydrological, wetlands and climate change modelling, used in this study, the uncertainty associated with each need to be considered.

4.4.2 Uncertainties in general hydrological modelling

In hydrological modelling, uncertainties include:

- Uncertainties in the data used input to hydrological models;
- Uncertainties in the links between components of the hydrological system (feedforwards and feedbacks); and
- Uncertainties in the conceptualisation of hydrological processes by the model (McColl *et al.*, 2000; Yen, 2002; Schulze, 2005a).

The data recorded and used as input into the hydrological model are subject to human error in both measurement and interpretation, coupled with measurement anomalies (e.g. weir overtopping) and missing data. All of these lead to uncertainty (Arnell, 2002). The network density of rainfall and streamflow gauging stations and record length add to these uncertainties. Two sources of uncertainty in the components of a system that should be identified are catchment conditions and climate drivers (Warburton, 2005). The uncertainty surrounding catchment conditions stems from the non-stationary nature of hydrology within a catchment, i.e. erosive processes changing the landscape, land use change affecting runoff, and antecedent soil moisture conditions determining the magnitude of stormflow responses (Schulze, 2005a). Uncertainty created by climate drivers arises from a lack of knowledge on the intensity and duration of daily rainfall (Schulze, 2005a). Uncertainties introduced by the conceptualisation of hydrological processes include parameterisation of catchment inputs and the degree of detail of process representation (Schulze, 2005a). Schulze (2005a) also notes that both the point uncertainties and the degree of spatial randomness needs to be considered for the above points.

Previously, Suter (1993) identified four main sources of uncertainty in hydrological modelling, which can also be taken as sources for uncertainty in regional climate modelling. These are: Up- and down-scaling, human error in observation, an imperfect knowledge of every component of every process, and the natural randomness (stochasticity) of the entire hydrological system. In summary, Beven (2001) states that data, understanding and modelling ability are needed to create the perfect hydrological model for a real catchment.

4.4.3 Uncertainties in wetlands hydrological modelling

There are numerous uncertainties in wetlands hydrological modelling resulting from a lack of complete understanding of the way in which different wetlands function from a hydrological perspective. There are unknowns and complexities in wetlands hydrological functioning that may not be represented adequately by the hydrological model. These include:

- Identifying all of the hydrological processes that occur in wetlands, and appreciating their different sensitivities;
- Accounting for different hydrological processes between the different types of wetlands;
- Adequately accounting for the potential of an open water body component within a wetland;
- In the context of this specific study, making certain assumptions on upland versus riparian wetlands and their functioning, which can introduce uncertainty should these assumptions not be representative of real world wetlands;
- Considering the implementation of water use relationships between the various wetlands vegetation types (such as sedges, grasses and trees) and how they impact on the wetlands hydrological responses; and
- Defining and simulating the groundwater-surface water interface that is often present in wetlands, with its highly complex set of processes that are difficult to conceptualise and implement as a routine within a hydrological model.

The final sub-section briefly discusses uncertainties in climate change modelling.

4.4.4 Uncertainties in climate change modelling

In regard to climate modelling with GCMs, there is considerable uncertainty emanating from their limited predictive accuracy of rainfall as a result of the highly complex nature of the global climate system the GCMs attempt to simulate (McColl *et al.*, 2000; Yen, 2002). In addition, the subjective nature in which the model algorithms are created, as a result of the specific perspectives of a model developer, increases the uncertainty of model outputs (Giorgi *et al.*, 2008). Giorgi *et al.* (2008) suggest that reviewing outputs from several GCMs in conjunction with each other is likely to increase the certainty of the results, and thus increase the confidence level for decision making purposes. In this study, however, outputs of only one GCM was used as a scenario of varying climatic conditions in order to assess the impacts of a climate change scenario on wetland hydrological responses. The outputs from a single GCM were used as an additional technique for assessing potential impacts, and not intended for use as a full climate change impact assessment.

The uncertainties alluded to above are appreciated, but are not addressed in this dissertation as they do not form a core objective if this research.

* * * * *

The next Chapter provides a brief description of the catchment used as a case study to apply the modelling techniques discussed in this Chapter.

5 CASE STUDY AREA: THE THUKELA CATCHMENT

The Thukela was selected as the case study catchment for a detailed evaluation of wetlands hydrological responses because of its diversity. The catchment has diverse physiography, climate, soils and land cover, as well as being socio-economically diverse. Furthermore in a previous project (Schulze *et al*., 2005c) the author had assisted in configuring the catchment for general climate change modelling.

The Thukela catchment is one of 19 Water Management Areas (WMAs) delineated in South Africa. It is located on the east coast of the country in the province of KwaZulu-Natal, as show in **Figure 5.1**. It covers an area of 29 036 km^2 and is located between the following geographic co-ordinates:

27^o 25' – 29^o 24' S

28^o 58' – 31^o 26' E

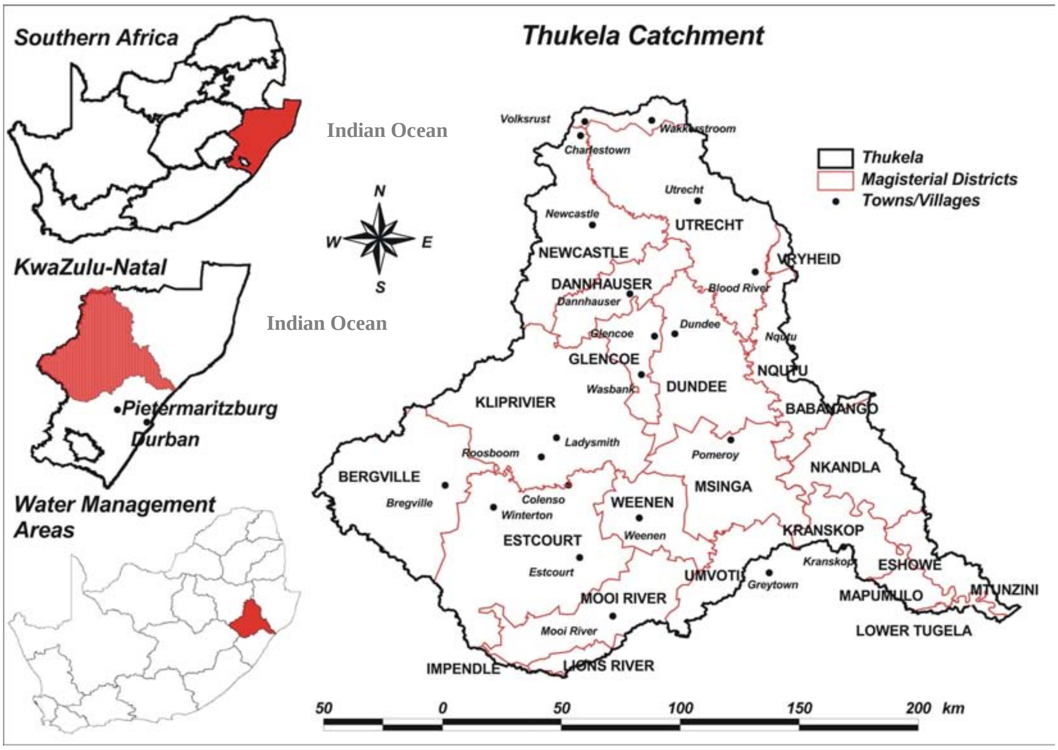


Figure 5.1 Location of the Thukela catchment in South Africa in relation to KwaZulu-Natal, Water Management Areas and administrative units (Schulze *et al*., 2005a)

5.1 Physiography of the Thukela Catchment

The Thukela catchment spans a large area, and contains a wide range and variety of topography. The catchment includes the high lying Drakensberg Mountains at over 3 300 m altitude in the west, and this source area of the Thukela River is characterised by mountains with high relief. The mountains then give way to the lowlands towards the east, which lead into deeply incised valleys in which the Thukela flows into the Indian Ocean (Schulze *et al.*, 2005a).

With this landscape the major tributaries to the Thukela River are the Little Thukela, Mooi, Bushman's, Klip, Sundays and Buffalo Rivers.

In association to this varied landscape, there is a wide range of altitudes and slopes, illustrated in **Figures 5.2** and **5.3** respectively. These two figures show the Drakensburg Mountain range in the north and west, with its high relief and steep slopes shown in **Figure 5.3**. As the altitude decreases towards the centre of the catchment, so do the slopes, which then again become steeper towards the east leading to the Indian Ocean.

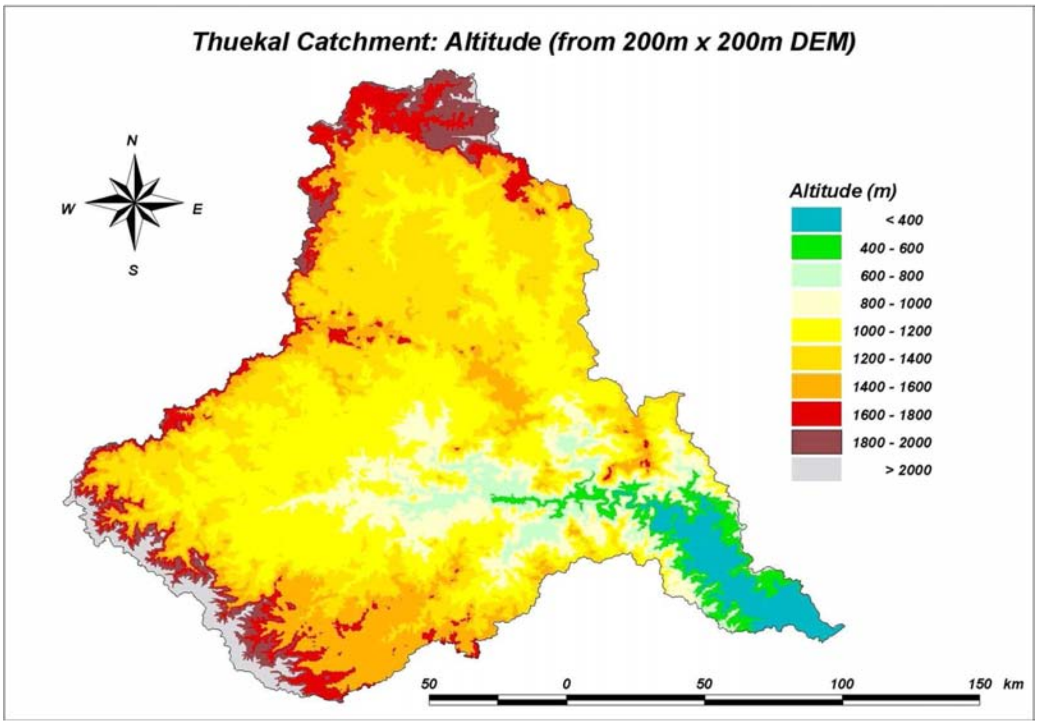


Figure 5.2 Altitude of the Thukela catchment (Schulze *et al.*, 2005a)

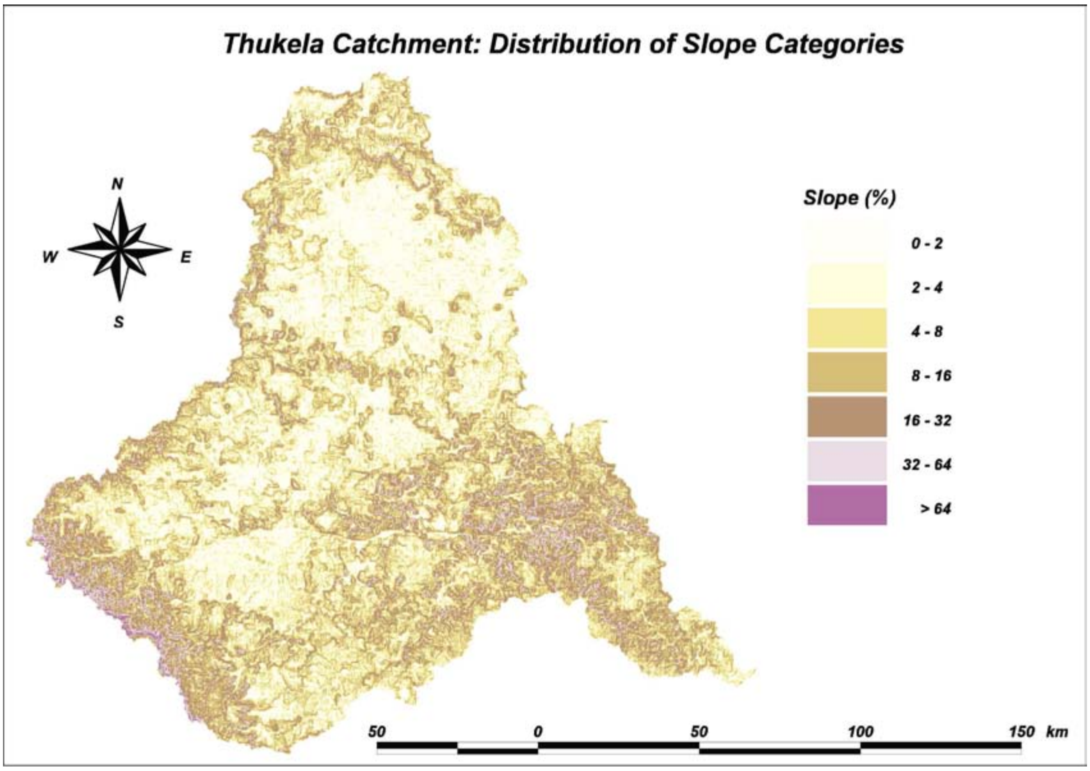


Figure 5.3 Slope categories (%) in the Thukela catchment (Schulze *et al.*, 2005a)

5.2 Climate of the Thukela Catchment

A catchment of this size and physiographic variability contains many different climatic regions. The Indian Ocean in the east experiences both frontal rainfall and precipitation from coastal low pressure systems, the Drakensberg escarpment to the west is characterised by frontal, convective and orographic rainfall and the lowlands in between are exposed mainly to frontal and convective rainfall, but with lower rainfall than the eastern and western peripheries. These differing landscapes, with their differing climatic drivers each have their distinctive mean annual precipitation (MAP), rainfall variability and potential evaporation. These are shown in **Figures 5.4**, **5.5** and **5.6** respectively.

The differences in altitudes and climatic conditions lead to variability in other characteristics. For example, the types of soils are not only dependent on the geology they are formed from, but are also modulated by temperature, slope and rainfall characteristics, which all play an important role in their pedogenesis.

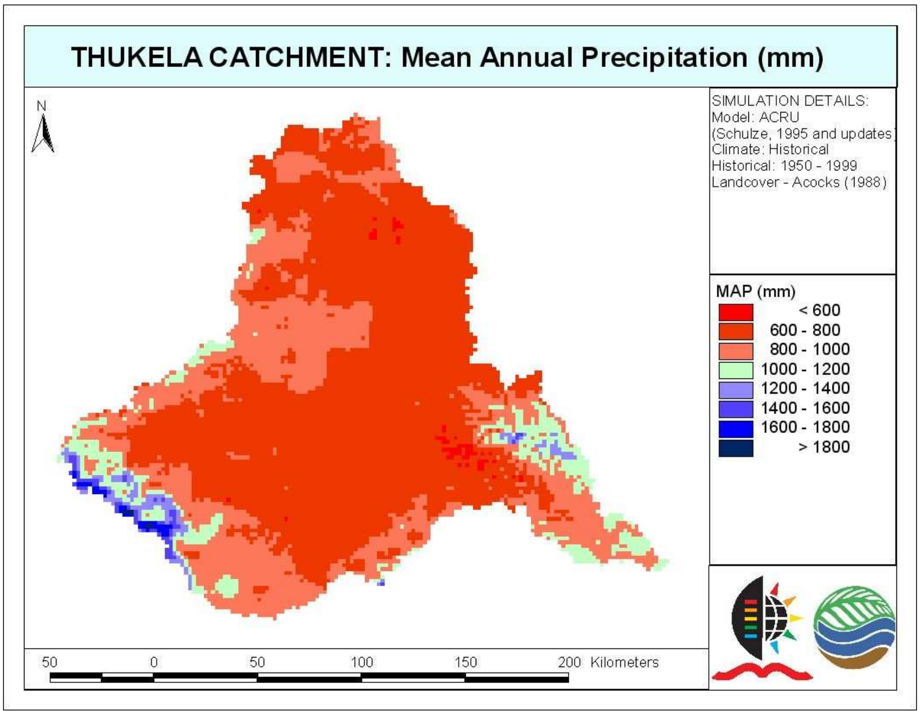


Figure 5.4 Mean annual precipitation of the Thukela catchment (after Dent *et al.*, 1989; cited by Schulze *et al.*, 2005a)

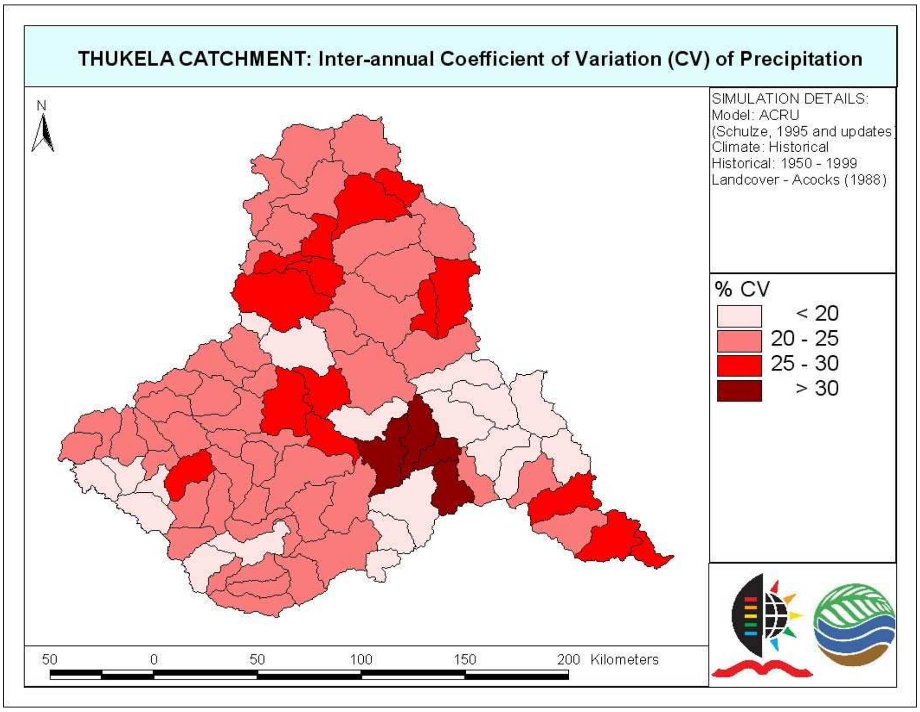


Figure 5.5 Inter-annual coefficient of variation of rainfall across the Thukela catchment (after Schulze *et al.*, 2005a)

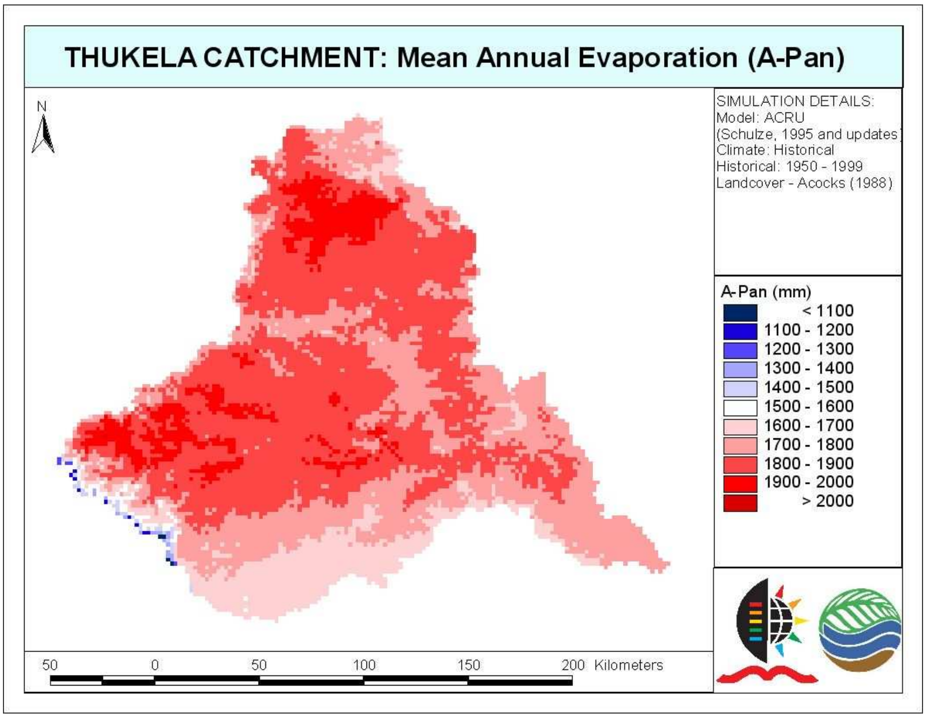


Figure 5.6 Reference potential evaporation (A-pan equivalent) for the Thukela Catchment (after Schulze, 1997; cited by Schulze *et al.*, 2005a)

The Thukela catchment also contains an abundance of wetlands. These wetlands differ not only in topographical position, size and shape, but also in the hydrological regimes in which they are located. Two types of wetlands are considered in this dissertation:

- The *upland wetlands* are found in areas that are relatively flat in relation to the surrounding topography, are often underlain by an impermeable medium and are not directly linked to a main river channel; and
- The *riparian wetlands*, or channel wetlands, which are found along the main river channels, often where they are underlain by impermeable media, and these wetlands are fed by the overtopping of water from the channel of a river, which is supplied by streamflow and baseflow contributions from upstream catchments, that flows through the wetland (cf. **Chapter 8**).

The wetland delineation, for the purpose of this study, is discussed in the following sub-section.

5.3 Delineation of Wetlands in the Thukela Catchment

The entire Thukela catchment was set up in GIS software, *viz*. Arcview 3.2 (Applegate, 1991). This enabled the input of various GIS coverages, such as Acocks' Veld Types (Acocks, 1988) or the coverages containing delineated wetlands. Various other factors could be used simultaneously in GIS in order to review different aspects of the research.

Four sources of information were used in determining the location and area of a wetland in this study, *viz.*

- the National Land Cover database coverage of 1996 (NLC, 1996), which identifies wetlands;
- the National Land Cover database coverage of 2000 (NLC, 2000), which also identifies wetlands;
- defined hydromorphic soil types, such as Arcadias and other soil forms with gleyed horizons, as identified within the Thukela catchment by Van der Eyk *et al.* (1969); and
- defined wetlands within the catchment as identified on electronic versions of 1:50 000 topographic maps (Surveyor General, 2004).

The following four criteria were run as queries in ArcGIS software (ESRI; Applegate, 1991) to identify wetland areas for this study, *viz.*

- areas where all four sources identified wetlands and their areas coincided;
- areas where three sources coincided;
- areas where two sources coincided; and
- in cases where only one source showed a wetland present, this wetland was not considered for further analysis.

From the outputs of the above queries those areas where all four sources coincided were accepted, while the areas with three and two sources coinciding were viewed on the respective 1:10 000 Orthophoto maps to determine whether it was a wetland or a coincidence of characteristics, after which a decision to accept or reject the area as a wetland was then made.

Once the final decisions had been made, the wetland areas that were accepted were used to create a wetlands shape file.

From this new shape file an additional refined query was undertaken. This query was used to determine which wetlands were upland wetlands and which wetlands were riparian wetlands. The rivers throughout the catchment were created into their own coverage and used to cross-reference against the wetlands shape file. All the wetlands that were located along the rivers and streams within the catchment were considered to be riparian wetlands; conversely all the wetlands located away from channels and streams were considered to be upland wetlands.

* * * * *

A fuller understanding of the methodologies used in modelling wetlands hydrological processes in this study, and with the *ACRU* Model, is provided in the following Chapter.

6 METHODOLOGY

In this Chapter the methodology used, the steps followed and the assumptions made in this dissertation are outlined. By way of introduction, objectives of this research will be revisited briefly and then elaborated upon.

6.1 Revisiting Objectives and Identifying Requirements for Modelling

There are three main objectives of this research. The first is on validating that the *ACRU* Model can simulate wetlands hydrological responses in a realistic manner, the second objective is to assess impacts that wetlands have on hydrological responses and the third, and final, objective aims at identifying any effects that climate change may have on wetlands responses.

These objectives are addressed by a simulation modelling approach, the components of which are discussed in the following sub-sections.

6.1.1 Baseline (historical) climate requirements for wetlands hydrological simulations

Baseline climate is very important to establish as a benchmark from which to determine changes in hydrological responses, in this instance specifically the impacts which climate has on steamflows, both with and without wetlands. The 50 year period 1950 – 1999 was selected to represent the baseline climate for this dissertation for reasons outlined in **Section 6.4.1**.

6.1.2 Baseline land cover information needs for wetlands hydrological simulations

Similarly, a baseline land cover is necessary to establish as a benchmark from which to determine changes in hydrological responses, in this instance specifically the impacts which wetlands have on streamflows. The Acocks (1988) Veld Types were selected as the baseline land cover for this dissertation for reasons outlined in **Section 6.3.2**.

6.1.3 Other information requirements for modelling

In addition to the baseline climate and land cover is the climate information on climate change (discussion in **Section 6.4.2**) and other important catchment attributes that are utilised by the *ACRU* Model for the Thukela catchment. These include:

- vegetation information (from a hydrological perspective; **Section 6.4.2**),
- soils information (from a hydrological perspective; **Section 6.3.1**),
- the disaggregation of the Thukela catchment for wetlands hydrological modelling (**Section 6.2.1 – 6.2.2**), and
- wetland information (**Section 6.5**).

All of these inputs, both climatic and in relation to the catchment, are discussed in more detail in the sections to follow.

6.2 Disaggregation of the Thukela Catchment for Wetlands Hydrological Modelling

6.2.1 Previous catchment disaggregation

The Thukela catchment is a designated Water Management Area (WMA) that consists of 86 Quaternary Catchments. A Quaternary Catchment is a fourth level of catchment disaggregation, i.e. South Africa has been disaggregated into Primary Catchments, these being subdivided into Secondary, again into Tertiary and finally into Quaternary Catchments. This disaggregation of the Thukela catchment into 86 sub-catchments was performed by the Department of Water Affairs.

This spatial scale was considered not fine enough to realistically evaluate the hydrological responses of the Thukela catchment (Schulze *et al.*, 2005b). The Quaternary Catchments therefore needed to be further sub-divided. The sub-divisions would then be for general use (i.e. for other research opportunities in the Thukela catchment in the future). The sub-divisions were thus based on various characteristics (not only wetlands specific). The final sub-division for wetlands (**Section 6.2.2**) was undertaken after the disaggregation of the 86 Quaternaries into a finer spatial resolution. The factors on which the initial further sub-divisions of Quaternaries were based are listed below, and briefly explained:

- **Altitude –** based on known altitude-rainfall and altitude-temperature relationships, especially over a topographically diverse catchment such as the Thukela;
- **Soils –** based on the premise that the depth of soils and their texture will determine the proportion of infiltrated precipitation that is partitioned into stormflow, baseflow and evaporation;
- **Vegetation –** based upon the integral role vegetation plays on the hydrological cycle through varying root depth, biomass indices, plant water use and interception values;
- **Ecological considerations –** sites identified as critical reaches where it would be advantageous to have estimates for the ecological reserve or other important environmental flows;
- **Gauging sites –** sites where streamflow gauging weirs are found and that do not coincide with the original 86 Quaternaries, and where these sites can be used for model verification;
- **Dams –** based on the fact that dams play a major role in modulating the hydrology of a catchment, and thus have far reaching downstream effects;
- **Political History –** areas of the former "Homelands" under the previous government, which could have wide-ranging effects on the hydrology of a catchment as they functioned under non-natural patterns of land use and were frequently degraded by overgrazing (Schulze *et al.*, 2005b).

Based on the above premises, the author was part of a team that configured the Thukela into 235 sub-catchments (Schulze *et al.*, 2005b). These 235 sub-catchments are shown, together with the specific reason for their sub-divisions, in **Figure 6.1**.

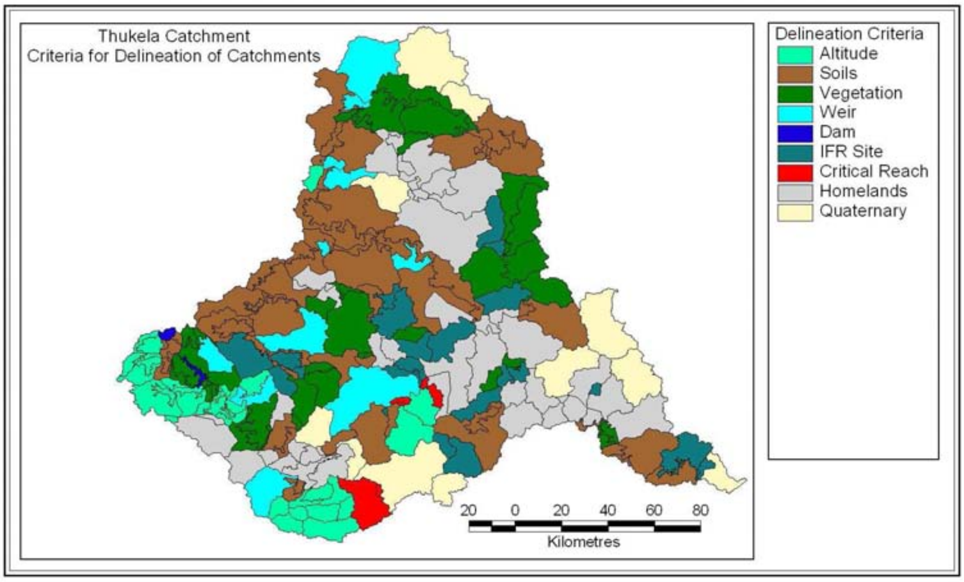


Figure 6.1 The delineation of the Thukela catchment into 235 sub-catchments, with reasons for each specific sub-catchment (Schulze *et al.*, 2005b)

6.2.2 Catchment disaggregation used in this study

The above catchment configuration needed to be further divided to incorporate an adequate set-up to allow for wetland and climate change modelling. In order to do this, some assumptions were made by the author and his supervisors.

Assumption 1: Only two types of wetlands were distinguished in this study for purposes of hydrological modelling, namely riparian wetlands and upland wetlands. Riparian wetlands, as their name suggests, are located on the main riparian channel. Upland wetlands are found in areas away from the main channel (but still on a small hypothetical channel representative of the relative contributing catchment) and result from a depression or impervious layer beneath the hydrologically defined subsoil leading to water accumulating for an indeterminate period of time.

Assumption 2: All the riparian wetlands found in a specific sub-catchment were grouped into a single wetland. In the same way, all the upland wetlands in a given sub-catchment were also grouped as a single upland wetland. Thus, each of the 235 sub-catchments, where they contain either type of wetland, was modelled with an area of upland wetland and an area of riparian wetland.

Assumption 3: The *ACRU* Model requires an upland wetland to have a feeder sub-catchment in order to simulate its functioning properly. The simulated upland wetland would be fed by an area equal to its own area, and would contain the same natural vegetation as the surrounding area. This would be similar to conditions which were observed in the field in which only a small area contributes to an upland wetland.

Assumption 4: In *ACRU*, the wetlands area is considered to be mainly land area rather than an open water body.

Assumption 5: When modelling with *ACRU* there is no loss of water from the baseflow store beneath the subsoil to the groundwater store (as they are defined to be the same thing in the wetlands routine) as it is assumed that the wetlands are underlain by an impervious layer (in the Thukela catchment often a dolerite sill).

Assumption 6: When a large rainfall event occurs, the saturated overland flow will exit a wetland catchment on the same day as the rainfall event.

Bearing in mind the above assumptions, the final delineation of sub-catchments could be completed. Each of the 235 sub-catchments was split into four smaller units, as in **Figure 6.2**:

- The first is the *Feeder catchment*, which area feeds its runoff into the upland wetland. It has an area equal to that of the upland wetland to which it is contributing water. It contains the original Acocks (1988) land cover of that particular sub-catchment.
- The second unit is the *Upland Wetland catchment*.
- The third is the sub-catchment that functions as it would if there were no wetlands. Its land cover is considered in this study to be natural vegetation represented by Acocks' (1988) Veld Types and is termed the *Baseline catchment*.
- The fourth sub-catchment is the area making up the *Riparian Wetland catchment*.

The four new sub-divisions contribute to each other in sequence, with the Feeder catchment contributing to the Upland Wetland catchment, the Upland Wetland catchment feeding the Baseline catchment and that feeding the Riparian Wetland. The outflow from the *Riparian Wetland catchment* then feeds into the following downstream sub-catchment. However, it does not feed into the *Feeder catchment*, but rather into the *Baseline catchment*. In this way the upland wetland does not receive any flow it would not normally have received in reality, and the upland water is still routed through the catchment as a whole before it reaches the next riparian wetland and ultimately the outlet. **Figures 6.2** and **6.3** depict the sub-division and linkages between the sub-catchments. The 235 original sub-catchments of the Thukela catchment therefore now become 940 sub-divisions.

In the case where there is no upland or riparian wetland in the 235 configuration sub-catchment, a nominal area of 0.01 km^2 (the smallest possible input to the *ACRU* Model) had to be assigned to the non-existent wetlands (either *Upland Wetland catchment* or *Riparian Wetland catchment* or both) for purposes of consistency in the configuration for modelling.

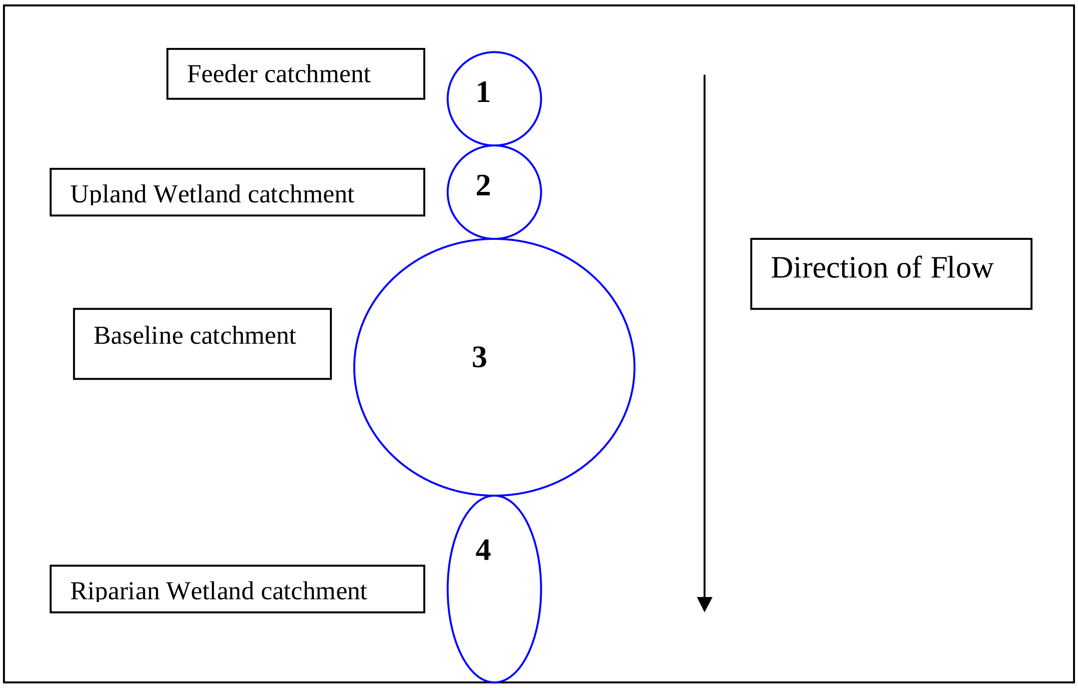


Figure 6.2 Schematic of the wetlands sub-division of each of the 235 sub-catchments of the Thukela catchment into 940 sub-divisions for wetlands modelling

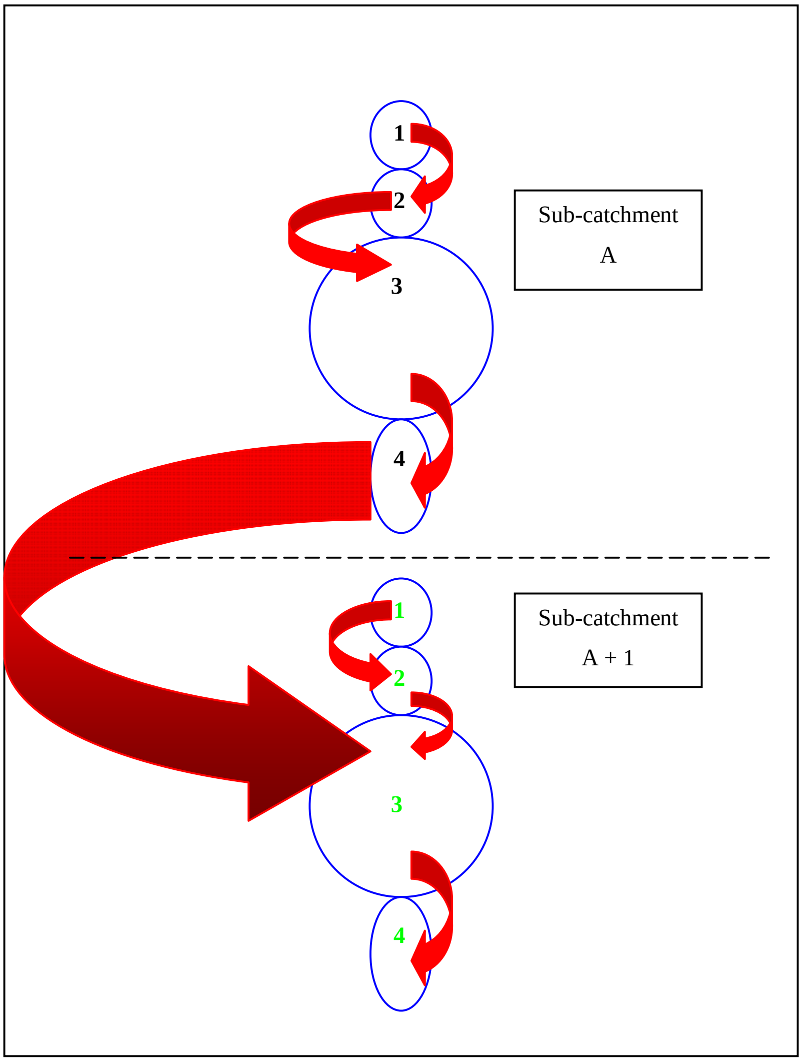


Figure 6.3 Flow linkages between the wetlands sub-divisions and the original 235 sub-catchments

In the above sub-section a description has been given on how the sub-catchment configuration for wetlands was derived for the hydrological modelling. In the following section the main catchment input information required for hydrological simulations is outlined.

6.3 Catchment Information

The two main catchment characteristics that will be addressed in this section are the soils and baseline land cover that are found in the Thukela catchment.

6.3.1 Soils

Soil characteristics play a major buffering role in the conversion of rainfall to runoff. Seven of the nine soil Land Types, defined as broad soil patterns, which have been identified in South Africa are found within the Thukela catchment (**Figure 6.4**). Of these seven, the catchment is dominated by two Land Types, accounting for over half the area. These are the Glenrosa and/or Mispah soil forms, which are shallow soils often less than 0.5 m in total depth and the red-yellow apedal soils, which are commonly deep and well-drained. The percentages of soil Land Types making up the Thukela catchment are given in **Table 6.1.**

The soils information needed for the *ACRU* model was derived from the soils databases of the Land Type Survey Memoirs. The information was extracted using a computer program called AUTOSOIL (Pike and Schulze, 1995 and updates), which extracted the relevant information that the *ACRU* Model requires as input from the Land Type database, *viz.*

- thicknesses of the topsoil and subsoil,
- soil water content at saturation, field capacity and the permanent wilting point for both topsoil and subsoil, from which plant water availability can be calculated,
- saturated drainage rates from the topsoil to the subsoil and the subsoil to the baseflow store, and
- the soil erodibility factor (not used in this study).

Some key hydrological characteristics of soils in the Thukela catchment are mapped in **Figure 6.5**.

Table 6.1 Percentages of soil Land Types found in the Thukela Catchment (Schulze *et al.*, 2005a)

Land Type	**%**
Red-yellow apedal, freely drained soils	23.1
Plinthic catena: upland duplex and margalitic soils rare	13.5
Plinthic catena: upland duplex and/or margalitic soil common	12.8
Prismacutamic and/or pedocutanic diagnostic horizons dominant	7.7
One or more of vertic, melanic, red structured diagnostic horizons	3.9
Glenrosa and/or Mispah forms (other soils may occur)	37.4
Miscellaneous land classes	1.6

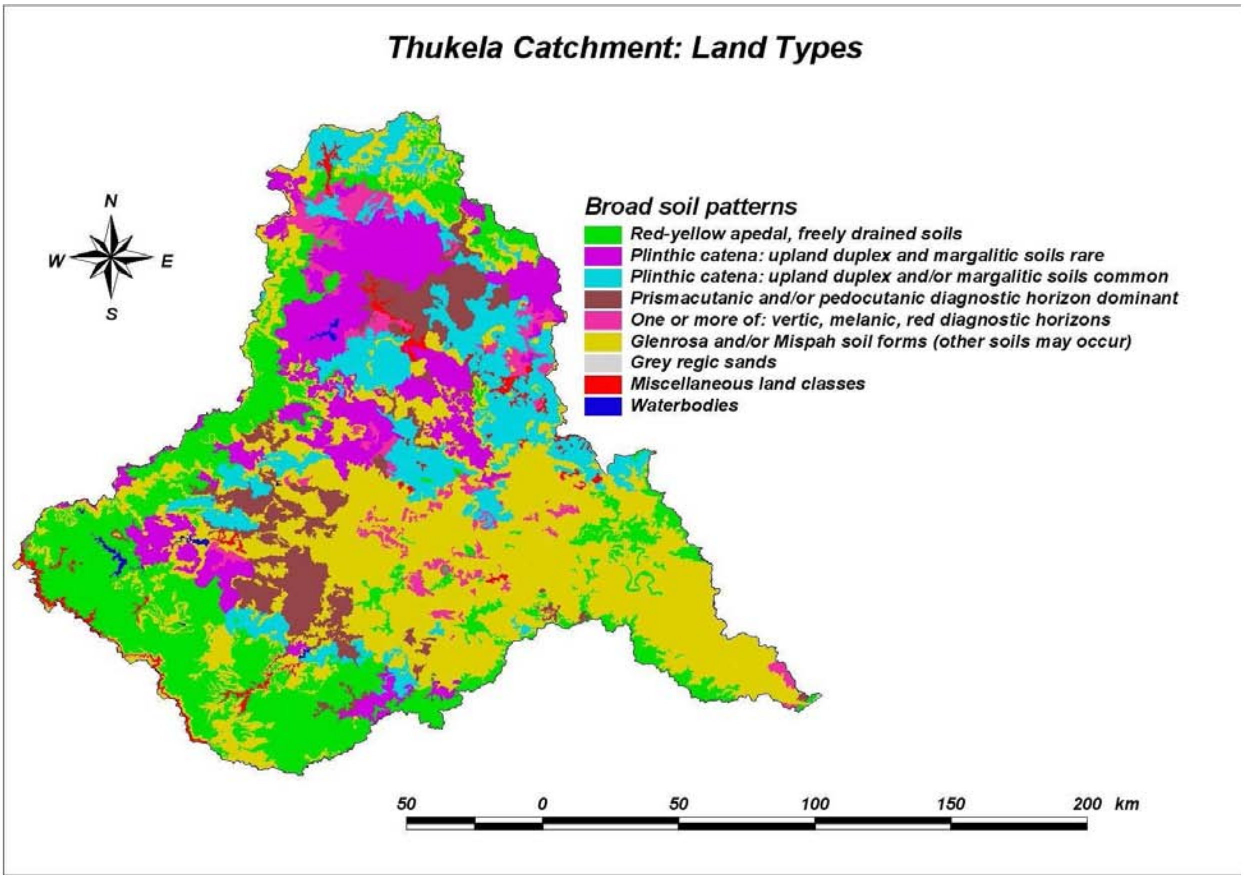


Figure 6.4 Distribution of soil Land Types, described as broad soil patterns, in the Thukela catchment (Land Type Survey Staff, 1986)

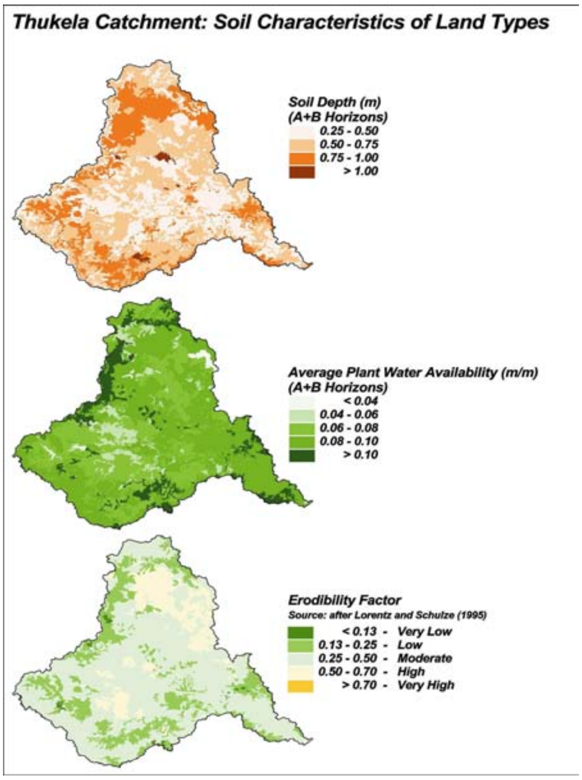


Figure 6.5 The distribution of certain soil characteristics found in the Thukela catchment (Schulze *et al.*, 2005a)

6.3.2 Baseline land cover

The significance of land cover in hydrological modelling is in its impact on the evapotranspiration and interception processes and as a protection from surface erosion. In order to determine hydrological responses under natural conditions, both with and without wetlands considered, it is important to first define the catchment's baseline land cover. It is also important to note that in order to assess the impacts of climate change on hydrological responses, the same baseline land cover should be used as a reference, in order to isolate effects of climate change by themselves (Schulze, 1997; Schulze *et al.*, 2005c).

Several classifications of mapping natural vegetation and biomass in southern Africa have been made in the recent past (Acocks, 1988). A vegetation classification that is still respected and has become scientifically accepted in South African hydrological circles as the *de facto* indicator of baseline land cover is that by Acocks (1988). Acocks (1988) delineated South Africa, Lesotho and Swaziland into so-called "Veld Types". Although the Mucina and Rutherford (2006) natural vegetation classification is more recent, it was not used for the following reasons:

- The specific vegetation characteristics needed for hydrological modelling (root distribution, water use coefficients, canopy interception, surface cover, etc) have not yet been determined.
- For this reason, it was decided to use the well respected Acocks (1988) classification for hydrological modelling.
- Furthermore, if any discrepancies were to result from using a different baseline land cover, these are likely to be negligible, as the hydrological outputs are compared as ratios, and land cover attributes remain constant for all simulations undertaken.

Figure 6.6 shows the spatial distribution of the 14 Acocks Veld Types found within the Thukela catchment. Schulze (2004b) provides scientific background on assigning hydrological attributes on a month by month basis to the Acocks Veld Types (1988) used in this study. There are four main hydrological characteristics of vegetation which are relevant to this dissertation, and they are as follows:

- K_{cm}, - the water use (i.e. crop) coefficient, which expresses the fraction of water evapotranspired by the Veld Type in comparison with a reference potential evaporation, assuming the plant is not under any soil water stress (*ACRU* variable name: CAY);
- R_A, - the fraction of root mass distribution in the topsoil (ROOTA);
- I_l, - the interception loss of rainfall (mm) by a plant on a rainday (VEGINT); and
- c, - the coefficient of initial abstraction, which is an index of infiltrability and is dependent, *inter alia*, on ground cover characteristics and rainfall intensity (COIAM).

The Thukela catchment is dominated by the following Veld Types: Valley Bushveld, Southern Tall Grassveld, Natal Sourveld and the Highveld Sourveld/ Döhne Sourveld. The catchment also contains the following other important Veld Types, which occur to a lesser extent: Ngongoni Veld, the Coastal Forest and Thornveld found in the coastal region of the catchment. The above-mentioned vegetation characteristics needed for hydrological modelling can be found in **Table 6.2**.

Using the Acocks Veld Types as a reference land cover for the land use in the catchments, i.e. wetlands, and when assessing impacts of climate change scenarios, the wetlands can now be superimposed onto this same coverage. With these two sets of simulations, *viz.* baseline land cover without explicitly modelling wetlands out the wetlands and baseline land cover including the wetlands, the effects of wetlands on the natural catchment can be determined.

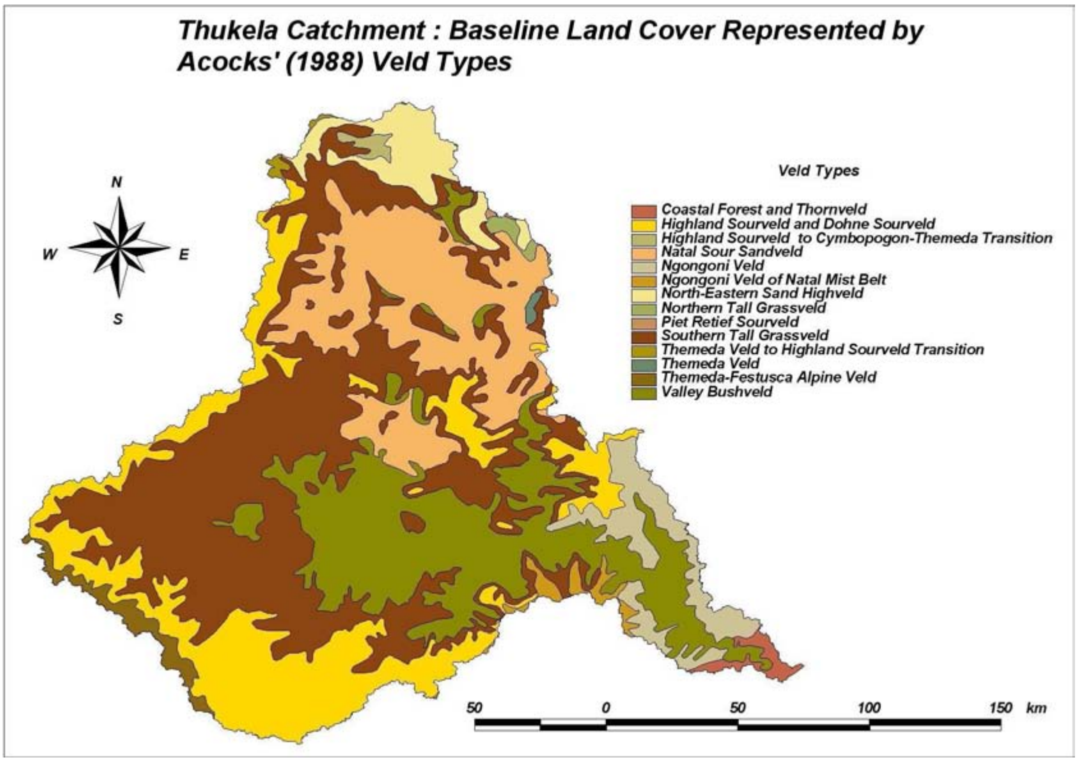


Figure 6.6 Acocks Veld Types found within the Thukela catchment (after Acocks, 1988)

Table 6.2 Acocks' (1988) Veld Types in the Thukela Catchment: Hydrological Attributes (after Schulze, 2004b)

CAY : Water Use (Crop) Coefficient (A-pan equivalent) COIAM : Coefficient of Initial Abstractions (Infiltrability)
VEGINT : Interception (mm) per Rainday ROOTA : Root Fraction in Topsoil

Acocks' Veld Type	% Surface Cover	Varia-ble	Jan	Feb	Mar	Apr	May	Jun	Jul	Aug	Sep	Oct	Nov	Dec

Table 6.2 Acocks' (1988) Veld Types in the Thukela Catchment: Hydrological Attributes (after Schulze, 2004b)

CAY : Water Use (Crop) Coefficient (A-pan equivalent) COIAM : Coefficient of Initial Abstractions (Infiltrability)
VEGINT : Interception (mm) per Rainday ROOTA : Root Fraction in Topsoil

Coastal Forest and Thornveld	100.0	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
		COIAM	0.30	0.30	0.30	0.30	0.30	0.30	0.30	0.30	0.30	0.30	0.30	0.30
Highland Sourveld And Döhne Sourveld	73.40	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
		VEGENT	1.60	1.60	1.60	1.40	1.20	1.00	1.00	1.00	1.30	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
		COIAM	0.15	0.15	0.25	0.30	0.30	0.30	0.30	0.30	0.30	0.30	0.20	0.15
Highland Sourveld to Cymbopogen-Themeda Veld Transition	59.16	CAY	0.62	0.62	0.62	0.50	0.30	0.20	0.20	0.20	0.25	0.50	0.62	0.62
		VEGINT	1.10	1.10	1.10	1.10	1.00	0.90	0.90	0.90	1.00	1.10	1.10	1.10
		ROOTA	0.90	0.90	0.90	0.90	0.95	1.00	1.00	1.00	0.95	0.90	0.90	0.90
		COIAM	0.15	0.15	0.25	0.30	0.30	0.30	0.30	0.30	0.30	0.30	0.25	0.15
Natal Sour Sandveld	82.30	CAY	0.75	0.75	0.70	0.50	0.35	0.20	0.20	0.20	0.50	0.65	0.70	0.75
		VEGINT	1.80	1.80	1.80	7.80	1.60	1.40	1.40	1.40	1.50	1.70	1.80	1.80
		ROOTA	0.90	0.80	0.90	0.95	0.95	1.00	1.00	1.00	0.95	0.90	0.90	0.90
		COIAM	0.15	0.15	0.20	0.30	0.30	0.30	0.30	0.30	0.30	0.30	0.25	0.15
Ngongoni Veld	73.4	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
		COIAM	0.20	0.20	0.25	0.30	0.30	0.30	0.30	0.30	0.30	0.30	0.25	0.20
Natal Mist Belt Ngongoni Veld	73.40	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
		VEGENT	1.50	1.50	1.50	1.30	1.10	1.10	1.10	1.10	1.40	1.50	1.50	1.50
		ROOA	0.90	0.90	0.90	0.94	0.96	1.00	1.00	1.00	0.95	0.90	0.90	0.90
		COIAM	0.15	0.15	0.20	0.30	0.30	0.30	0.30	0.30	0.30	0.30	0.20	0.15
North-Eastern Sandy Highveld	59.16	CAY	0.62	0.62	0.60	0.50	0.35	0.20	0.20	0.20	0.35	0.50	0.62	0.62
		VEGINT	1.30	1.30	1.30	1.20	1.00	1.00	1.00	1.10	1.20	1.30	1.30	1.30
		ROOTA	0.90	0.90	0.90	0.90	0.95	1.00	1.00	1.00	0.95	0.90	0.90	0.90
		COIAM	0.15	0.15	0.25	0.30	0.30	0.30	0.30	0.30	0.30	0.30	0.25	0.15
Northern Tall Grassveld	82.30	CAY	0.75	0.75	0.75	0.50	0.40	0.30	0.20	0.20	0.55	0.70	0.75	0.75
		VEGINT	1.70	1.70	1.70	1.60	1.50	1.40	1.40	1.50	1.60	1.70	1.70	1.70
		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
		COIAM	0.15	0.15	0.20	0.30	0.30	0.30	0.30	0.30	0.30	0.30	0.25	0.15
Piet Retief Sourveld	73.40	CAY	0.70	0.70	0.70	0.55	0.45	0.20	0.20	0.20	0.50	0.60	0.70	0.70
		VEGINT	1.30	1.30	1.30	1.30	1.10	1.00	1.00	1.00	1.20	1.30	1.30	1.30
		ROOTA	0.90	0.90	0.90	0.90	0.95	1.00	1.00	1.00	0.95	0.90	0.90	0.90
		COIAM	0.15	0.15	0.25	0.30	0.30	0.30	0.30	0.30	0.30	0.30	0.20	0.15

Table 6.2 Acocks' (1988) Veld Types in the Thukela Catchment: Hydrological Attributes (after Schulze, 2004b)

CAY : Water Use (Crop) Coefficient (A-pan equivalent) COIAM : Coefficient of Initial Abstractions (Infiltrability)
VEGINT : Interception (mm) per Rainday ROOTA : Root Fraction in Topsoil

Southern Tall Grassveld	82.30	CAY	0.75	0.75	0.75	0.50	0.40	0.20	0.20	0.20	0.55	0.70	0.75	0.75
		VEGINT	1.60	1.60	1.60	4.60	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
		COIAM	0.15	0.15	0.20	0.30	0.30	0.30	0.30	0.30	0.30	0.30	0.20	0.15
Highland Sourveld to Themeda Veld Transition	59.16	CAY	0.62	0.62	0.62	0.50	0.30	0.20	0.20	0.20	0.25	0.50	0.62	0.62
		VEGINT	1.10	1.10	1.10	1.10	1.00	0.90	0.90	0.90	1.00	1.10	1.10	1.10
		ROOTA	0.90	0.90	0.90	0.90	0.95	1.00	1.00	1.00	0.95	0.90	0.90	0.90
		COIAM	0.15	0.15	0.25	0.30	0.30	0.30	0.30	0.30	0.30	0.30	0.25	0.15
Themeda Veld	64.50	CAY	0.65	0.65	0.65	0.50	0.40	0.20	0.20	0.20	0.35	0.55	0.65	0.65
		VEGINT	1.20	1.20	1.20	1.10	1.00	0.90	0.90	0.90	1.10	1.20	1.20	1.20
		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
		COIAM	0.15	0.15	0.25	0.30	0.30	0.30	0.30	0.30	0.30	0.30	0.25	0.15
Themeda-Festuca Alpine Veld	37.80	CAY	0.50	0.50	0.45	0.35	0.20	0.20	0.20	0.20	0.30	0.35	0.45	0.50
		VEGENT	1.30	1.30	1.30	1.10	0.90	0.90	0.90	0.90	1.10	1.20	1.30	1.30
		ROOTA	0.90	0.90	0.90	0.95	1.00	1.00	1.00	1.00	1.00	0.95	0.90	0.90
		COIAM	0.15	0.15	0.25	0.30	0.30	0.30	0.30	0.30	0.30	0.30	0.25	0.15
Valley Bushveld	82.30	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
		COIAM	0.20	0.20	0.25	0.30	0.30	0.30	0.30	0.30	0.30	0.25	0.20	0.20
Wetlands		CAY	0.80	0.8	0.80	0.70	0.60	0.50	0.40	0.40	0.40	0.50	0.60	0.70
		VEGINT	0.60	0.6	0.60	0.60	0.60	0.60	0.60	0.60	0.60	0.60	0.60	0.60
		ROOTA	1.00	1.00	1.00	1.00	1.00	1.00	1.00	1.00	1.00	1.00	1.00	1.00
		COIAM	0.20	0.20	0.20	0.20	0.20	0.20	0.20	0.20	0.20	0.20	0.20	0.20

The above section has provided detail on the hydrological land cover inputs used in this study, with the section to follow providing the climatic inputs required for hydrological modelling, both with and without wetlands, in this study.

6.4 Climate Inputs

For this project two climatic inputs were required. The *Historical* climate data were used to determine the effects of wetlands on a catchment under baseline climate conditions. The *climate* *change* information, for both present and future climate scenarios, was generated by the C-CAM RCM (Engelbrecht, 2005). These two climate input sources are discussed below.

6.4.1 Historical climate data

The daily historical climate data for temperature (maximum and minimum) and precipitation were derived, respectively, by Schulze and Maharaj (2004) and Lynch (2004) from reliable climate station data found within the Thukela catchment. The input data used for the *ACRU* Model were obtained from the Quaternary Catchment Database, QCDB (Schulze *et al.*, 2007).

The QCDB contains daily climate data for every Quaternary catchment in South Africa for the 50 year period 1950 – 1999 (Schulze *et al.*, 2007). The QCDB rainfall data were derived by Lynch (2004) using in-filled data from 12 153 rainfall gauges, which were all extensively checked for errors using a range of techniques. The following paragraph describes briefly how rainfall data were selected from the QCDB for use in the historical simulations undertaken in this study.

The input data used from climate stations were decided upon based on their location, the duration of the record, the quality of record and their altitude with respect to each sub-catchment. An adjustment to the station data was then calculated for each month of the year by the techniques described in Smithers and Schulze (2004) to render the station data more representative of that of the sub-catchments they represent.

The adjustment factors were limited to being between 0.7 and 1.3 so as not to make unrealistically high or low adjustments. The closer the adjustment factor is to 1, the more representative the raingauge data are of the sub-catchment's rainfall. The month-by-month adjustment factors were input into the model's input file/menu for each sub-catchment. This process was considered to provide relatively accurate daily rainfalls for all the sub-catchments throughout the Thukela.

The daily temperature inputs to the *ACRU* Model for this project were also obtained from the QCDB. Temperature play an important role in the hydrological simulations as the daily maximum and minimum temperature values are used in the calculation of reference potential evaporation, in this study using the Hargreaves and Samani (1985) equation. In the Hargreaves and Samani (1985) equation potential evaporation is calculated using a conceptually-based temperature driven equation that both explicitly and implicitly takes into account important evaporation factors such as vapour pressure deficit, extra-terrestrial radiation and net radiation. It has been found to provide more realistic daily values for South Africa than other methods of similar sophistication (Pike, 1988; Bezuidenhout, 2005).

Time-series of daily maximum and minimum temperatures from the qualifying temperature stations within the Thukela catchment were generated from quality controlled data for a common 50 year period, *viz.* 1950 – 1999, using techniques developed by Schulze and Maharaj (2004). The station temperature values were then converted to a one arc minute raster coverage using regional and seasonal temperature lapse rates, with the full details of this process given in Schulze and Maharaj (2004).

6.4.2 GCM derived climate scenarios

In this section the discussion focuses on the dynamically downscaled climate values generated from the C-CAM General Circulation Model (Engelbrecht, 2005; cf. **Chapter 4**). There are other Regional Climate Models (RCMs) and GCMs, output from which could presently (2011) be used. However, at the time of this project's inception, C-CAM was the only GCM available to the University of KwaZulu-Natal with suitably downscaled *daily* climate values for South Africa. For the climate change component of this study the daily rainfall and temperature files from C-CAM were therefore used as the climate input to the daily time-step *ACRU* model.

There is, however, a problem when using RCM output as input in a daily model. The RCM output values are in an area-weighted, spatially averaged grid format and not at irregular points representing sub-catchments. This could potentially create problems for applications with the *ACRU* model which relies on point climatic inputs at "driver" climate stations representative of the defined sub-catchments. The gridded C-CAM output is therefore not ideal for catchments hydrological modelling because certain hydrological responses are triggered by localised rainfall events generated by convective storms, which make up a substantial portion of the Thukela catchment's rainfall. Certain differences were thus found to occur between C-CAM rainfall output and observed point rainfall values, as already alluded to in **Chapter 4**.

However, the above problem was largely overcome by analysing the RCM-derived *ACRU* Model outputs as ratios of '*Future'* to '*Present'* when assessing impacts of climate change. Therefore, any potential impacts of climate change using C-CAM output could be assessed using *relative changes* by evaluation whether the simulated output ratios are less than (<) or greater than (>) one (Schulze *et al.*, 2005c). This was based on the simple supposition that:

> "Possible spatial averaging 'errors' created by C-CAM RCM would be the same for both the present and future simulations, thus negating them through the use of a ratio" (Schulze *et al.*, 2005c, page 149).

The downscaled RCM outputs, used in conjunction with the hydrological model, enabled the simulation of hydrological responses within the Thukela catchment. Additional input was required in order to assess the impacts of wetlands on catchment hydrological responses. These wetlands inputs are discussed in the following section.

6.5 Wetlands Inputs

Three main sets of wetlands input were required for the *ACRU* Model for this study. The first two have been discussed previously in **Section 5.3** of this document, and what follows is a summary thereof.

These inputs are:

- *Wetland area* – This was determined for each of the wetlands within the 235 sub-catchments. The determination was based on a review and collation of wetland areas from different data sources into a comprehensive wetlands coverage for the Thukela catchment (cf. **Section 5.3**). Once the wetland areas had been selected, the areas of all the upland wetlands per sub-catchment were summed and their final accumulated area was entered into *ACRU* as the upland wetland area for each sub-catchment. The same process was followed for the riparian wetlands.

- *Volume of open water body* **–** For the purpose of this dissertation, the wetland was assumed to have no actual open water component as this component is usually very small in natural wetlands, be they upland or riparian.
- *Vegetation type* **–** The type of vegetation ranges in wetlands. This is dependent on their location, topographical position and overall moisture levels. Owing to the large variability in the wetlands vegetation of the Thukela catchment, a generic wetlands vegetation was assumed. The relevant vegetation details are contained in the database imbedded within the *ACRU* Model under the land use called “WETLANDS 5100102” (Smithers and Schulze, 1995). These values were based on detailed studies by Chapman (1990) and Donkin (1994).

In this Chapter the methodologies used to derive climate, land cover, soils, catchments and wetlands inputs were described. This information was then used in simulations of hydrological responses of wetlands, the results from which are presented in **Chapters 7** and **8**. The wetlands were simulated as an independent sub-catchment, with the channel carrying capacity defined as the 50th percentile annual flow volume in mm, converted to a daily flow rate expressed as m^3/s.

7 VALIDATION OF WETLANDS HYDROLOGICAL PROCESSES IN THE *ACRU* MODEL

7.1 Validation of Processes Captured in the *ACRU* Wetlands Routine

In **Chapter 4** of this dissertation the *ACRU* Agrohydrological Model's Wetlands Routine was discussed. This Chapter provides validation of the wetlands processes, using results from wetlands in the Thukela catchment. Both upland wetlands and riparian wetlands are simulated in *ACRU* using the same routine. The different results obtained from the two types of wetlands (i.e. upland and riparian wetlands) that are simulated in this study are brought about by their respective upstream contributing areas and the manner in which the wetland system is configured. The wetlands' hydrological responses are assessed by analysing surface water flows and soil water flows to show how a wetland attenuates and regulates streamflows. Below is a series of validations of the processes by which the *ACRU* Wetlands Routine simulates the various hydrological responses of a typical wetland. This type of detailed validation of the *ACRU* Wetlands Routine has not been performed before. In light of this dissertation's assessing wetlands hydrological responses under varying climatic conditions, the validations were undertaken with model outputs from the wettest and driest year of the 50 year historical record used.

7.2 Processes of Wetland Surface Water Flows Simulated with the *ACRU* Model

The main processes of the wetlands routine within the *ACRU* Model can be described by three scenarios.

Scenario 1: The model is structured such that if the accumulated streamflow entering the wetland from the upstream catchment is smaller than, or equal to, the carrying capacity of the channel (i.e. bankful discharge) defined for the wetland, then the entire contributing streamflow volume will flow through the channel and exit the wetland without spillage onto the wetland *per se*.

Based on **Scenario 1**, the following hypotheses can be postulated:

Hypothesis 1: Accumulated streamflow entering the wetland from the upstream contributing catchment will leave the wetland on the same day if it is equal to, or less than, the channel carrying capacity of the wetland.

Hypothesis 2: If there is no spillage from the wetland channel onto the wetland topsoil, the topsoil moisture content will only increase if rain falls onto the wetland soil surface.

Scenario 2: If the accumulated streamflow entering the wetland from its contributing catchment is greater than the carrying capacity of the channel defined for the wetland, then the difference will spill on to the adjacent wetland topsoil. As the topsoil store increases to beyond its field capacity, so soil water will translocate down the soil profile into the subsoil and ultimately into the baseflow store. This scenario results in Hypothesis 3.

Hypothesis 3: Accumulated streamflow entering the wetland from the upstream contributing catchment will spill onto the wetland topsoil if the streamflow has a volume greater than the wetland's channel carrying capacity, thus increasing the soil water content of the topsoil. Once the topsoil's water content exceeds its field capacity, it will move down the soil profile and increase the soil water content of the subsoil, and when the subsoil's field capacity is exceeded it percolates into the baseflow store from which it is released into the downstream catchment.

Scenario 3: When the wetland's topsoil and subsoil stores are both at saturation, and additional streamflow continues to spill onto the topsoil due to the contributing accumulated streamflow being greater than the channel carrying capacity, then the additional streamflow that spills onto the topsoil will exit the catchment in the form of quickflow on the same day as the spill occurs. From this scenario Hypotheses 4 to 7 have been formulated.

Hypothesis 4: Because a relatively shallower topsoil is set to hold less water than the relatively thicker subsoil, which in turn is set to hold less water than the baseflow store which can hold an unlimited amount of water, the relative movement of soil water, in relation to the specific soil water stores (topsoil, subsoil or baseflow store), will decrease down the soil profile.

Hypothesis 5: When the wetland topsoil is saturated and the water from the wetland channel spills onto the adjacent topsoil, or if rainfall falls onto a saturated topsoil, the overland flow component, i.e. quickflow, will leave the wetland on the same day.

Hypothesis 6: Of the total streamflow volume entering the wetland, not all will exit on the same day, unless the entire soil profile is saturated or the volume of streamflow entering the wetland is less than its channel's carrying capacity.

Hypothesis 7: The baseflow generated within a wetland will, when leaving the wetland, extend for a period after the rainfall event has occurred and the stormflow has been generated.

Based on the flow chart in **Figure 4.6**, **Figures 7.1** and **7.2** show the model's output for representative time-series from wet and dry years depicting the process of surface water movement through the wetland.

Figures 7.1 and **7.2** display four sets of results, *viz.*:

- daily rainfall – in light blue bars;
- the accumulated streamflow contributing to the wetland from upstream catchments – labelled as Accumulated Inflow (dark blue diamonds);
- the volume of streamflow that spills onto the wetland topsoil when the accumulated streamflow from the upstream contributing catchment is larger than the wetland channel's carrying capacity – Channel Spills (pink squares); and
- the quickflow responses leaving the wetland when the channel spills onto saturated topsoil – Quickflow (red triangles).

Figure 7.1 shows the four results for the wettest year in the historical record used in this study, *viz.* 1996. The wetland under study here is a riparian wetland of 9.54 km^2 in a catchment of 186.59 km^2. The results illustrate that when the wetland's soil is saturated due to continual spillage from the channel, rainfall events (light blue bars) result in spikes of quickflow (red triangles), as discussed in **Hypothesis 5**, while a decrease in upstream contributions (dark blue diamonds) results in an equivalent reduction in overtopping (pink squares).

When, from **Figure 7.1**, the topsoil and subsoil are already at saturation due to the wetland's channel spilling for an extended time, and the streamflow contribution from the upstream catchment that enters the wetland is greater than the channel carrying capacity, spillage takes place onto the surrounding wetland area, as referred to in **Hypothesis 3**. This keeps the soil at saturation (**Figures 7.3** and **7.4** respectively). When additional rain falls onto the wetland, it exceeds the volume of water which the soil can hold. Hence, there is a quickflow response from the wetland (**Hypothesis 5**). If the soil water content is below saturation, some infiltration from the spillage will occur. If the spilling rate is greater than the infiltration rate, then a quickflow response will occur (**Hypothesis 3** and **4**).

Figure 7.2 shows the same four simulated processes, but for the driest year in the historical record used in this study, *viz.* 1968). The results in **Figure 7.2** illustrate that overtopping only occurs following significant rainfall events and upstream contributions (pink squares), but with insufficient overtopping to saturate the soil. This results in no quickflow being generated off the wetland (**Hypotheses 1** and **6**; red triangles at zero level).

Figure 7.3, again for a wet year, and for the same riparian wetland, illustrates continual overtopping due to significant upstream contributions (i.e. blue diamonds are larger than pink squares), as postulated in **Hypothesis 3**. For a dry year, however, **Figure 7.4** illustrates that only intermittent overtopping occurs when the soil is saturated after significant storms have occurred (cf. **Figure 7.2**), and not on every day (**Hypothesis 5**).

The dry year results from the same riparian wetland show that there is infrequent inflow from the upstream contributing catchments. Rainfall occurs periodically during the representative time-

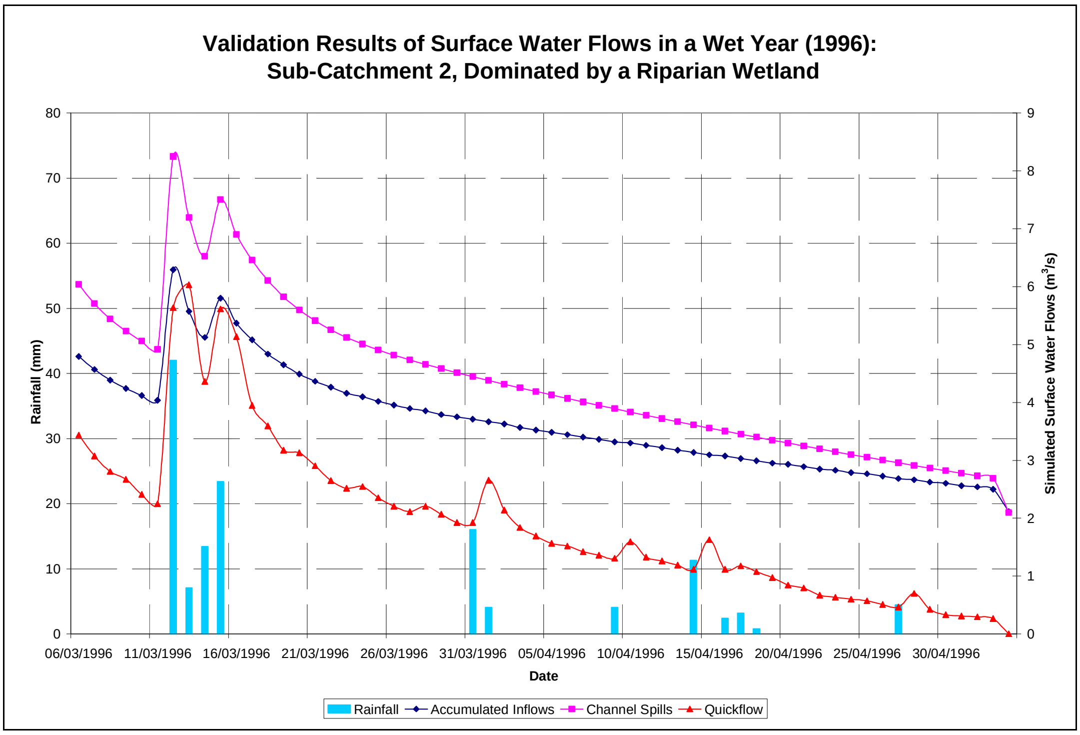


Figure 7.1 Time-series of daily rainfall and simulated surface water flows in a riparian wetland in a wet year (Catchment area 186.59 km^2, wetland area 9.54 km^2)

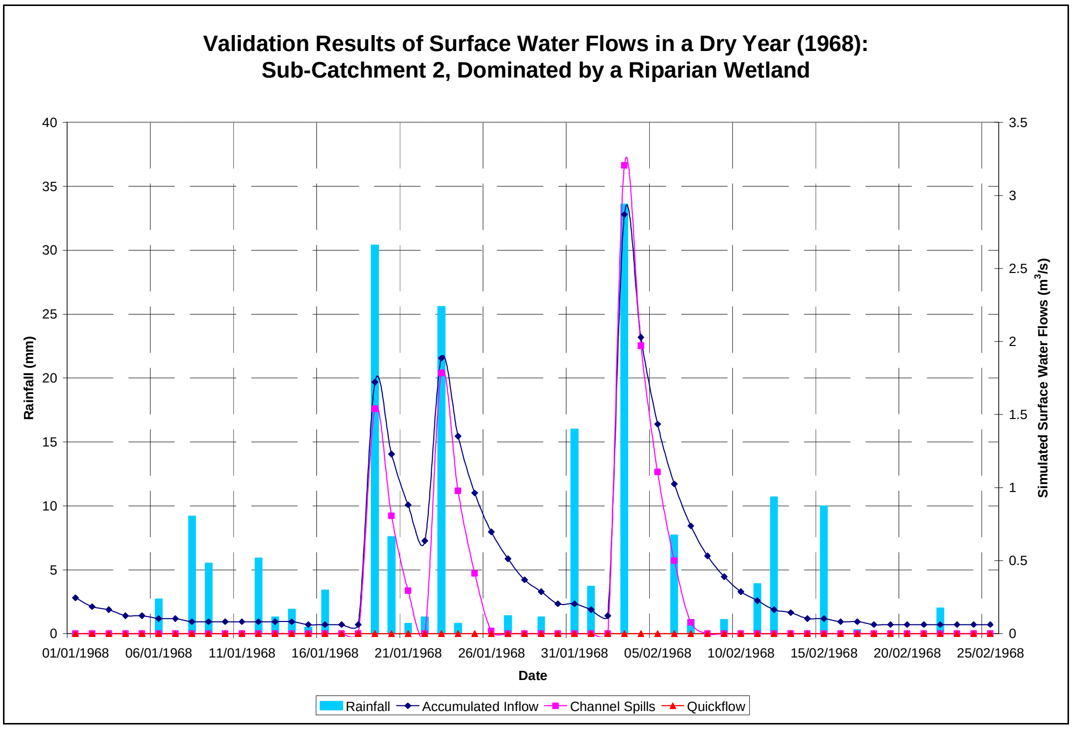


Figure 7.2 Time-series of daily rainfall and simulated surface water flows in a riparian wetland in a dry year (Catchment area 186.59 km^2, wetland area 9.54 km^2)

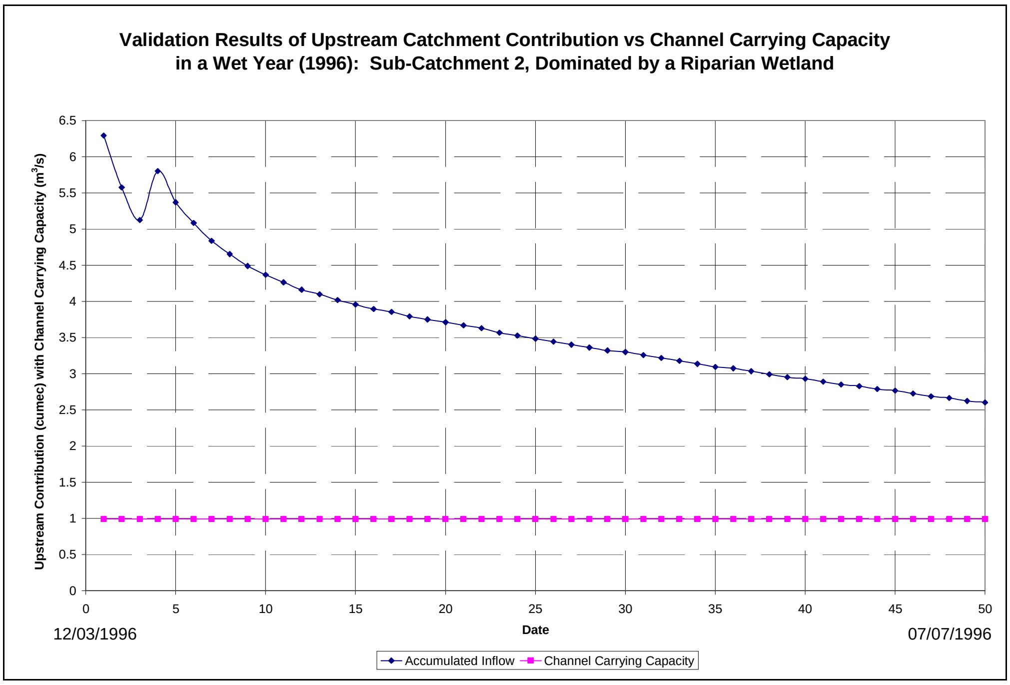


Figure 7.3 Representative time-series of simulated streamflow contributions to a riparian wetland in a wet year (blue diamonds), in m^3/s, and channel carrying capacity (pink squares), also in m^3/s (Catchment area 186.59 km^2, wetland area 9.54 km^2)

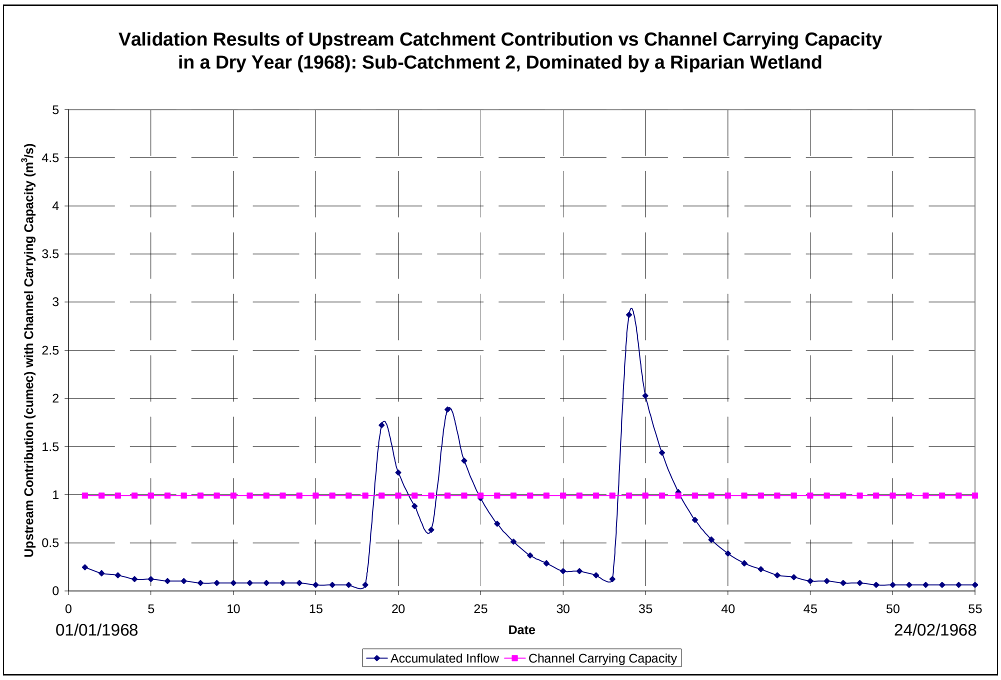


Figure 7.4 Representative time-series of simulated streamflow to a riparian wetland contributions in a dry year (blue diamonds), in m^3/s, and channel carrying capacity (pink squares), also in m^3/s (Catchment area 186.59 km^2, wetland area 9.54 km^2)

series, but does not always cause spilling from the channel onto the surrounding wetland. Spilling (pink squares in **Figure 7.2***)* from the channel only occurs when there are sufficient upstream streamflow contributions and rain is falling directly onto the wetland. This causes spilling from the channel to the surrounding wetland topsoil, thus increasing the soil water store. The soils never reach saturation and thus there is no quickflow response (red triangles in **Figure 7.2**). Hence, all the water spilling from the channel or landing on the wetland soils is infiltrating, keeping the soils wetter for longer periods than in a catchment without wetlands (**Hypothesis 2**).

7.3 Processes of Wetland Soil Water Fluxes, Simulated with the *ACRU* Model

An important component of wetland functioning is the way in which the surface water and water in the soil profile interact. The *ACRU* Wetland Routine contains five variables that show how water flows through the soil horizons and eventually results in attenuated discharges. These five variables are as follows:

- the Topsoil Store **–** the soil water content of the topsoil at the end of a given day;
- the Topsoil drainage – i.e. the volume of water (mm) drained from the topsoil to the subsoil for a given day, if the topsoil is above its field capacity;
- the Subsoil Store **–** the soil water content of the subsoil at the end of a given day;
- the Subsoil drainage **–** i.e. the volume of water (mm) drained from the subsoil to the baseflow store for a given day, if the subsoil is above its field capacity; and
- the Baseflow **–** baseflow contributions from a wetland's baseflow store on a given day as a contribution to the total streamflow leaving the wetland area.

When rain (light blue bars) falls onto the wetland soil it infiltrates into the topsoil, as illustrated for the same riparian wetland in **Figure 7.5** (pink triangles). The increase in soil water content in the topsoil facilitates water movement down the profile into the subsoil when the topsoil's water content exceeds its field capacity. The water movement between the topsoil and subsoil is shown by the topsoil discharge (as defined above) into the subsoil (dark blue diamonds), with the increase in subsoil water content depicted by the subsoil store (green circles). As the subsoil water content increases above its field capacity, the soil water flow from the subsoil to the baseflow store increases, as depicted by the subsoil discharge (purple squares). The baseflow store holds this water in a store assumed to be of unlimited capacity and releases it in the form of baseflow, based on a decay function of the stored volume (red lines).

As the process moves soil water from the topsoil down to the baseflow, the relative impact decreases as the topsoil's thickness is set at less than the subsoil's thickness. Not only is the proportional volume of stored water decreasing down the soil profile, but the timing of the movement changes from a short sharp increases in the topsoil's storage to a smaller and more attenuated changes in storage of water in the subsoil. This principle is carried through the process, with the most marked decrease in flow volume and the biggest attenuation seen in the baseflow. This is well depicted in **Figure 7.5**, with the topsoil store and the topsoil discharge having relatively large sharp increases after a rainfall event. On the other hand, the subsoil store and the subsoil discharges display relatively smaller changes in volume over a longer time period. The full attenuation effect can be best presented by comparing the topsoil store increases (43.4 mm to 80.2 mm in one day) after a 30.4 mm rainfall event on 19/01/1968 to the prolonged increase in baseflow release (18 mm/d to 26 mm/d over eight days) from the system for a total of 65.7 mm of rainfall from 19/01/1968 to 26/01/1968.

The increase in storage in the topsoil is proportionally (i.e. relatively) larger than in the subsoil, in spite of the subsoil having a greater storage volume. The decrease in relative impact down the profile is due to the availability of soil water. The topsoil will hold as much as its field capacity will allow, and only the excess water will be percolated down into the subsoil. Once the topsoil is saturated, any further rainfall will run off the wetland in the form of quickflow (**Figure 7.1**), thus preventing further infiltration of excess rainfall into the subsoil beyond the topsoil's discharge rate. Evapotranspiration from the soil will also impact on the relative increase in soil water storage. The subsoil water content is significantly larger than the topsoil water content. This is a function of soil depth, with the subsoil (0.55 m) being deeper than the topsoil (0.30 m) in the case of this example (cf. **Hypothesis 4**).

The wetland attenuates and retains large rainfall events and releases the infiltrated rainfall out of the wetland over a longer period of time through baseflow. This shows that the *ACRU* model is simulating the attenuation and retention characteristics of wetlands, as hypothesised (**Hypothesis 7**).

The principles behind the wetland processes in *ACRU* are relatively simple, and they have been proved to be conceptually correct through the various examples shown. This type of validation had never before been undertaken at such a level of detail with the *ACRU* Model. These principles are used as a base for the following section, in which simulations are performed on catchments assuming baseline land cover, both with and without wetlands in the landscape.

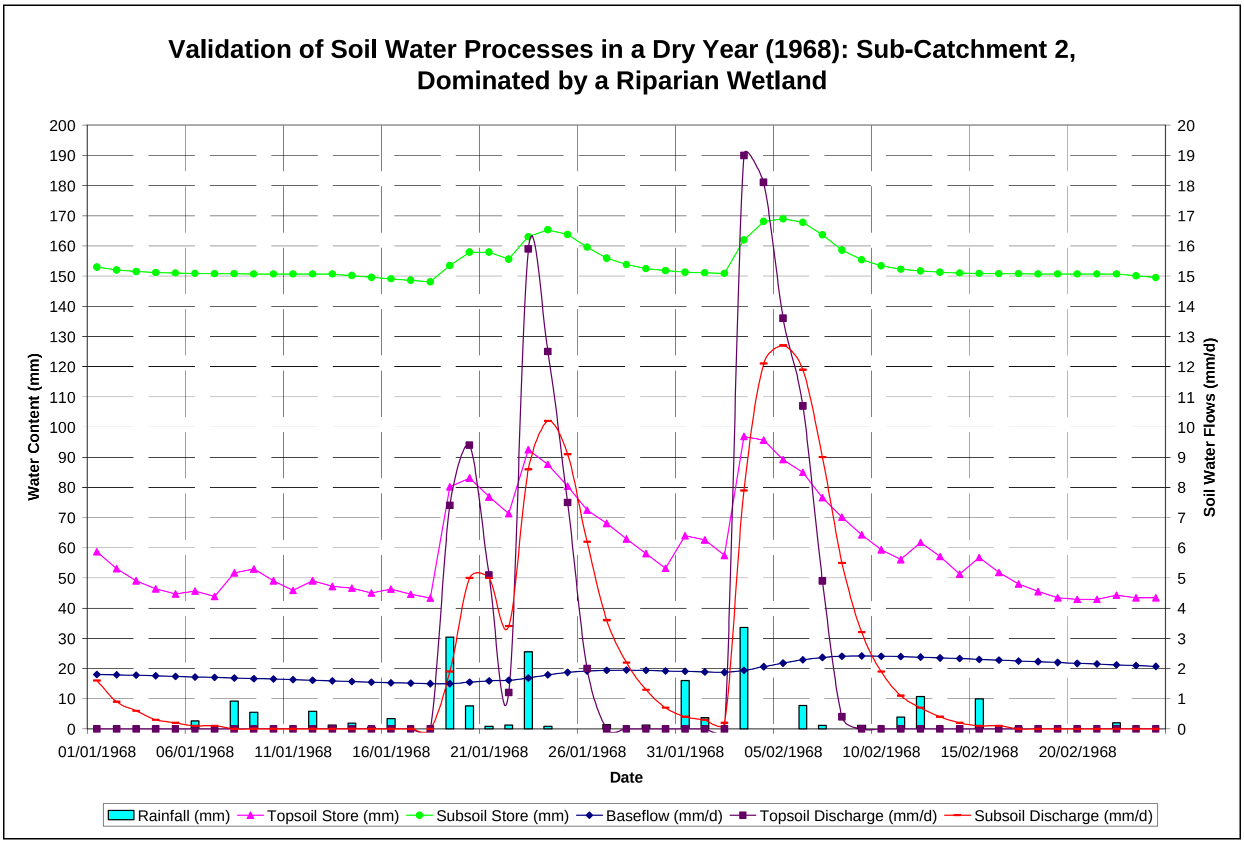


Figure 7.5 Simulated soil water movement within a riparian wetland catchment (Catchment area 186.59 km^2, wetland area 9.54 km^2)

7.4 Comparison of Hydrological Responses from Catchments With and Without Wetlands, Assuming the Catchment to be Under Baseline Land Cover

Based on the literature review presented in **Chapter 2** of this dissertation, certain hypotheses can be postulated by considering the effects which wetlands can have on catchment hydrological responses. These are assessed by using the simulated results produced by the *ACRU* Model run on a catchment with a baseline land cover represented by Acock's (1988) Veld Types. These hypotheses include the following:

Hypothesis 8: A wetland, specifically a riparian wetland, will have a smaller attenuation and storage influence on a catchment with a large contributing area, and thus large accumulated inflows, than it would on a catchment with a small contributing area and relativelv lower accumulated inflows.

Hypothesis 9: A wetland will have a smaller attenuation and storage influence during a wet year compared to a dry year due to the increased soil water content throughout the soil profile, which reduces the available soil water storage; thus allowing more water to run off as quickflow.

Hypothesis 10: A wetland will generally have a higher topsoil water content than the non-wetland part of the catchment due to the increased frequency of replenishment of water via wetland channel spills, in addition to the contributions from rainfall.

Hypothesis 11: In summary, the impact of a wetland on attenuation and storage is, to a large degree dependent on the relative volume of streamflow entering it.

These hypotheses were tested using daily time-series results from simulations of a typical catchment with the wetland routines switched on and off in the *ACRU* Model. The assessment was carried out for a dry year (1968) and a wet year (1996) on Sub-catchment 2 in the relatively wet Drakensberg region to the south-east of the catchment.

Table 7.1 shows a day-by-day account of the accumulated streamflow for a dry year (1968) exiting a sub-catchment with and without a riparian wetland simulated. Similarly, **Table 7.2** shows the same comparison for the same catchment during a wet year (1996). Both sets of results are presented for a comparatively *small* catchment, 186.59 km^2, with a riparian wetland area of 9.54 km^2.

The rows highlighted in blue are examples of the attenuation effect that the wetland is having on the accumulated streamflow leaving the outlet of the catchment (e.g. 19/01/1968 – 25/01/1968). The attenuation effect is characterised by a significantly larger rise in streamflow in the catchment simulated without a wetland in comparison to the same catchment simulated with a wetland (e.g. 19/01/1968). Similarly, the rows highlighted in orange are examples of the storage effect that the wetlands have on the accumulated streamflow leaving the outlet of the catchment (e.g. 26/01/1968 – 02/02/1968). The storage effect is characterised by the higher daily streamflows shortly after a rainfall event in the catchment simulated with wetlands as opposed to the lower flows presented in the catchment simulated without wetlands (e.g. 26/01/1968).

Table 7.1 Individual effects of a relatively large riparian wetland (9.54 km^2) on hydrological responses of a relatively small catchment (186.59 km^2) during a dry year (1968)

Date	Accumulated Streamflow With Wetlands (mm)	Accumulated Streamflows Without Wetland (mm)
12/01/1968	0.08	0.04
13/01/1968	0.08	0.04
14/01/1968	0.08	0.04
15/01/1968	0.08	0.04
16/01/1968	0.08	0.04
17/01/1968	0.08	0.03
18/01/1968	0.08	0.03
19/01/1968	0.38	0.83
20/01/1968	0.38	0.59
21/01/1968	0.38	0.43
22/01/1968	0.35	0.31
23/01/1968	0.39	0.91
24/01/1968	0.39	0.65
25/01/1968	0.39	0.47
26/01/1968	0.39	0.34
27/01/1968	0.30	0.25
28/01/1968	0.24	0.18
29/01/1968	0.19	0.14

Date	Accumulated Streamflow With Wetlands (mm)	Accumulated Streamflows Without Wetland (mm)
30/01/1968	0.16	0.11
31/01/1968	0.16	0.10
01/02/1968	0.14	0.08
02/02/1968	0.12	0.07
03/02/1968	0.40	1.38
04/02/1968	0.40	0.98
05/02/1968	0.40	0.69
06/02/1968	0.40	0.50
07/02/1968	0.40	0.36
08/02/1968	0.33	0.26
09/02/1968	0.26	0.19
10/02/1968	0.21	0.14
11/02/1968	0.18	0.11
12/02/1968	0.15	0.08
13/02/1968	0.14	0.07
14/02/1968	0.12	0.06
15/02/1968	0.12	0.05
16/02/1968	0.11	0.04
17/02/1968	0.10	0.04
18/02/1968	0.10	0.03
19/02/1968	0.10	0.03
20/02/1968	0.09	0.03
21/02/1968	0.09	0.03

* NOTE * Orange Shading = Storage Effect, while Blue Shading = Attenuation Effect

Table 7.2 Individual effects of a relatively large riparian wetland (9.54 km^2) on hydrological responses of a relatively small catchment (186.59 km^2) during a wet year (1996)

Date	Accumulated Streamflow With Wetlands (mm)	Accumulated Streamflow Without Wetlands (mm)
13/03/1996	2.92	2.73
14/03/1996	2.37	2.51
15/03/1996	2.81	2.84
16/03/1996	2.63	2.64
17/03/1996	2.23	2.49
18/03/1996	2.10	2.37
19/03/1996	1.96	2.28
20/03/1996	1.93	2.20
21/03/1996	1.85	2.14
22/03/1996	1.77	2.09
23/03/1996	1.72	2.04
24/03/1996	1.73	2.00
25/03/1996	1.66	1.97
26/03/1996	1.61	1.94
27/03/1996	1.58	1.91
28/03/1996	1.61	1.89
29/03/1996	1.57	1.86

Date	Accumulated Streamflow With Wetlands (mm)	Accumulated Streamflow Without Wetlands (mm)
30/03/1996	1.52	1.84
31/03/1996	1.54	1.81
01/04/1996	1.77	1.79
02/04/1996	1.61	1.77
03/04/1996	1.51	1.75
04/04/1996	1.46	1.73
05/04/1996	1.42	1.71
06/04/1996	1.41	1.69
07/04/1996	1.38	1.67
08/04/1996	1.36	1.65
09/04/1996	1.34	1.63
10/04/1996	1.43	1.61
11/04/1996	1.35	1.59
12/04/1996	1.33	1.57
13/04/1996	1.31	1.55
14/04/1996	1.29	1.54
15/04/1996	1.46	1.52
16/04/1996	1.29	1.50
17/04/1996	1.31	1.48
18/04/1996	1.28	1.47
19/04/1996	1.25	1.45
20/04/1996	1.21	1.43
21/04/1996	1.19	1.41
22/04/1996	1.16	1.40
23/04/1996	1.14	1.38
24/04/1996	1.14	1.37
25/04/1996	1.13	1.35
26/04/1996	1.11	1.33
27/04/1996	1.09	1.32
28/04/1996	1.17	1.30
29/04/1996	1.08	1.29
30/04/1996	1.06	1.27
01/05/1996	1.05	1.26
02/05/1996	1.05	1.24
03/05/1996	1.04	1.23
04/05/1996	0.95	1.04
05/05/1996	0.95	1.03
06/05/1996	0.96	1.01
07/05/1996	0.96	1.00
08/05/1996	0.96	0.99
09/05/1996	0.96	0.98
10/05/1996	0.96	0.97
11/05/1996	0.96	0.96
12/05/1996	0.95	0.95
13/05/1996	0.95	0.94
14/05/1996	0.95	0.93
15/05/1996	0.95	0.84

Date	Accumulated Streamflow With Wetlands (mm)	Accumulated Streamflow Without Wetlands (mm)
16/05/1996	0.95	0.83
17/05/1996	0.96	0.82
18/05/1996	0.96	0.81
19/05/1996	0.96	0.81
20/05/1996	0.95	0.80
21/05/1996	0.95	0.79
22/05/1996	0.95	0.78
23/05/1996	0.94	0.78
24/05/1996	0.94	0.77
25/05/1996	0.94	0.76
26/05/1996	0.93	0.76
27/05/1996	0.93	0.75
28/05/1996	0.93	0.74
29/05/1996	0.93	0.74
30/05/1996	0.92	0.73
31/05/1996	0.92	0.72
01/06/1996	0.92	0.72
02/06/1996	0.91	0.71
03/06/1996	0.91	0.70
04/06/1996	0.91	0.70
05/06/1996	0.90	0.69
06/06/1996	0.90	0.69
07/06/1996	0.90	0.68
08/06/1996	0.89	0.67
09/06/1996	0.89	0.67
10/06/1996	0.89	0.66

* NOTE * Orange Shading = Storage Effect, while Blue Shading = Attenuation Effect

It was also deduced that the attenuation and storage effects of a riparian wetland on a relatively small catchment are reduced when the catchment is saturated in a wet year. **Table 7.3** shows that there is a marked decrease in the effect of the riparian wetland in a wet year.

Table 7.3 Summary showing the averaged effects of a relatively large riparian wetland on hydrological responses of a small catchment in a wet and a dry year

Year	Averaged Percentage Impact on Attenuation between Wet and Dry Years	Averaged Percentage Impact on Storage between Wet and Dry Years
WET YEAR - 1996	12.68%	33.49%
DRY YEAR - 1968	35.90%	89.24%

The percentage impact was assessed by determining the absolute percentage increases or decreases between the two simulations of the catchment, with the wetlands routine switched on and off.

Table 7.3 shows that there is a 35.90% decrease in flows in the dry year as opposed to the 12.68% reduction in flows in the wet year. Similarly, there is an 89.24% increase in storage in the dry year in comparison to the 33.49% increase in storage in the wet year. This illustrates that there is greater attenuation effect and storage retention with a more gradual release over time in the drier year. This confirms the validity of **Hypothesis 9**.

Tables 7.4 and **7.5** present the results from a similar analysis to that of the previous example; however, in this case the analysis was undertaken on a *large* catchment with a *small* riparian wetland with the riparian wetlands routine switched on and off. The contributing area has increased to 4 371.98 km^2 (from 186.59 km^2) with the riparian wetland area decreased to 0.68 km^2 (from 9.54 km^2). This is an exaggerated example of a large contributing area's streamflow discharging into a significantly smaller riparian wetland area than in the previous example. This case was selected to test **Hypotheses 8** and **11** set out in the beginning of this subsection. **Table 7.6** shows the comparative percentage impact for the wet and dry years.

Table 7.4 Individual effects of a small riparian wetland (0.68 km^2) on hydrological responses of a large catchment (4 371.98 km^2) during a dry year (1968)

Date	Accumulated Streamflow With Wetlands (mm)	Accumulated Streamflow Without Wetlands (mm)
01/01/1968	0.07	0.06
02/01/1968	0.06	0.05
03/01/1968	0.05	0.04
04/01/1968	0.04	0.03
05/01/1968	0.04	0.03
06/01/1968	0.08	0.07
07/01/1968	0.08	0.07
08/01/1968	0.06	0.05
09/01/1968	0.11	0.10
10/01/1968	0.08	0.07
11/01/1968	0.06	0.06
12/01/1968	0.05	0.04
13/01/1968	0.04	0.04
14/01/1968	0.04	0.03

Date	Accumulated Streamflow With Wetlands (mm)	Accumulated Streamflow Without Wetlands (mm)
15/01/1968	0.18	0.17
16/01/1968	0.13	0.13
17/01/1968	0.10	0.09
18/01/1968	0.08	0.07
19/01/1968	0.06	0.05
20/01/1968	0.05	0.04
21/01/1968	0.04	0.03
22/01/1968	0.03	0.03
23/01/1968	0.57	0.74
24/01/1968	0.62	0.67
25/01/1968	0.42	0.48
26/01/1968	0.28	0.34
27/01/1968	0.2	0.24
28/01/1968	0.15	0.18
29/01/1968	0.21	0.26
30/01/1968	0.18	0.20
31/01/1968	0.11	0.14
01/02/1968	0.08	0.10
02/02/1968	0.06	0.08
03/02/1968	0.05	0.06
04/02/1968	0.04	0.05
05/02/1968	0.04	0.04
06/02/1968	0.04	0.03
07/02/1968	0.04	0.03
08/02/1968	0.04	0.02
09/02/1968	0.04	0.02
10/02/1968	0.03	0.02
11/02/1968	0.03	0.02
12/02/1968	0.04	0.02
13/02/1968	0.03	0.02
14/02/1968	0.03	0.02
15/02/1968	0.03	0.01
16/02/1968	0.03	0.01
17/02/1968	0.03	0.01
18/02/1968	0.03	0.01
19/02/1968	0.03	0.01

* NOTE * Orange Shading = Storage Effect, while Blue Shading = Attenuation Effect

Table 7.5 Individual effects of a small riparian wetland (0.68 km^2) on hydrological responses of a large catchment (4 371.98 km^2) during a wet year (1996)

Date	Accumulated Streamflow With Wetlands (mm)	Accumulated Streamflow Without Wetlands (mm)
03/10/1996	0.14	0.12
04/10/1996	0.14	0.12
05/10/1996	0.14	0.13

Date	Accumulated Streamflow With Wetlands (mm)	Accumulated Streamflow Without Wetlands (mm)
06/10/1996	0.14	0.12
07/10/1996	0.13	0.12
08/10/1996	0.13	0.12
09/10/1996	0.13	0.12
10/10/1996	0.13	0.12
11/10/1996	0.13	0.12
12/10/1996	0.13	0.11
13/10/1996	0.14	0.13
14/10/1996	0.14	0.13
15/10/1996	0.13	0.12
16/10/1996	0.13	0.12
17/10/1996	0.12	0.11
18/10/1996	0.12	0.11
19/10/1996	0.12	0.11
20/10/1996	0.54	0.53
21/10/1996	0.43	0.42
22/10/1996	1.71	1.87
23/10/1996	1.33	1.35
24/10/1996	0.93	0.98
25/10/1996	0.68	0.72
26/10/1996	0.52	0.54
27/10/1996	0.41	0.42
28/10/1996	0.34	0.33
29/10/1996	0.28	0.29
30/10/1996	0.30	0.28
31/10/1996	0.24	0.23
01/11/1996	0.19	0.20
02/11/1996	0.17	0.17
03/11/1996	0.16	0.15
04/11/1996	0.15	0.14
05/11/1996	0.14	0.13
06/11/1996	0.20	0.18
07/11/1996	0.17	0.16
08/11/1996	0.15	0.14
09/11/1996	0.14	0.13
10/11/1996	0.13	0.12
11/11/1996	0.13	0.11
12/11/1996	0.18	0.18
13/11/1996	0.16	0.15
14/11/1996	0.15	0.13
15/11/1996	0.13	0.12
16/11/1996	0.15	0.15
17/11/1996	0.22	0.21
18/11/1996	0.17	0.17
19/11/1996	0.15	0.15
20/11/1996	0.14	0.13
21/11/1996	0.12	0.12

Date	Accumulated Streamflow With Wetlands (mm)	Accumulated Streamflow Without Wetlands (mm)
22/11/1996	0.12	0.11
23/11/1996	0.11	0.10
24/11/1996	0.11	0.10
25/11/1996	0.11	0.09
26/11/1996	0.10	0.09
27/11/1996	0.10	0.09
28/11/1996	0.10	0.09
29/11/1996	0.10	0.09
30/11/1996	0.10	0.08
01/12/1996	0.10	0.08
02/12/1996	0.10	0.09
03/12/1996	0.10	0.09
04/12/1996	0.23	0.25
05/12/1996	0.21	0.20
06/12/1996	0.16	0.16
07/12/1996	2.39	2.59
08/12/1996	1.91	2.02
09/12/1996	1.39	1.48
10/12/1996	1.00	1.07
11/12/1996	0.74	0.80
12/12/1996	0.57	0.59
13/12/1996	0.41	0.44
14/12/1996	0.48	0.51
15/12/1996	0.40	0.41
16/12/1996	0.36	0.36
17/12/1996	0.26	0.27

* NOTE * Orange Shading = Storage Effect, while Blue Shading = Attenuation Effect

Table 7.6 Summary showing the averaged effects of a relatively small riparian wetland on hydrological responses of a large catchment in a wet and a dry year

Year	Averaged Percentage Impact on Attenuation between Wet and Dry Years	Averaged Percentage Impact on Storage between Wet and Dry Years
WET YEAR - 1996	5.24%	17.40%
DRY YEAR - 1968	9.12%	68.96%

As with the previous example for a small catchment, the dry year has a greater impact on the attenuation and storage of the system. However, the attenuation and storage characteristics of the relatively small wetland have been reduced by the large contributing catchment area. These results confirm **Hypothesis 8**.

The final set of analyses presented in this section was simulated for an upland wetland, which was assumed to have a contributing area equal to that of its wetland. Two variables were assessed, namely accumulated streamflow exiting the wetland, which was analysed to assess the attenuation and storage impacts of an upland wetland in comparison to a riparian wetland, and the topsoil storage, in order to assess whether wetlands have a higher topsoil water content in comparison to an identical sub-catchment without a wetland.

Table 7.7 and **7.8** show the accumulated streamflow leaving the sub-catchment, with the wetlands routine switched on and off, for a wet (1996) and dry (1968) year. As in the case of the previous example, a summary table showing percentage impacts is presented in **Table 7.9**.

Table 7.7 Individual effects of an upland wetland on hydrological responses of a catchment during a dry year (1968)

Date	Accumulated Streamflow With Wetlands (mm)	Accumulated Streamflow Without Wetlands (mm)
03/02/1968	0.37	0.87
04/02/1968	0.30	0.65
05/02/1968	0.24	0.49
06/02/1968	0.20	0.37
07/02/1968	0.16	0.28
08/02/1968	0.13	0.21
09/02/1968	0.11	0.17
10/02/1968	0.09	0.13
11/02/1968	0.07	0.10
12/02/1968	0.06	0.08
13/02/1968	0.05	0.07
14/02/1968	0.04	0.05
15/02/1968	0.04	0.04
16/02/1968	0.03	0.04
17/02/1968	0.03	0.03
18/02/1968	0.03	0.03
19/02/1968	0.02	0.02
20/02/1968	0.02	0.02
21/02/1968	0.02	0.02
22/02/1968	0.02	0.02
23/02/1968	0.02	0.02
24/02/1968	0.02	0.02
25/02/1968	0.02	0.01
26/02/1968	0.01	0.01
BREAK		
15/09/1968	0.01	0.01

Date	Accumulated Streamflow With Wetlands (mm)	Accumulated Streamflow Without Wetlands (mm)
16/09/1968	0.01	0.00
17/09/1968	0.01	0.00
18/09/1968	0.01	0.00
19/09/1968	0.01	0.00
20/09/1968	0.01	0.00
21/09/1968	0.01	0.00
22/09/1968	0.01	0.00
23/09/1968	0.01	0.00
24/09/1968	0.01	0.00
25/09/1968	0.01	0.00
26/09/1968	0.00	0.00

* NOTE * Orange Shading = Storage Effect, while Blue Shading = Attenuation Effect

Table 7.8 Individual effects of an upland wetland on hydrological responses of a catchment during a wet year (1996)

Date	Accumulated Streamflow With Wetlands (mm)	Accumulated Streamflow Without Wetlands (mm)
15/03/1996	1.77	2.05
16/03/1996	1.75	2.00
17/03/1996	1.72	1.95
18/03/1996	1.69	1.89
19/03/1996	1.66	1.84
20/03/1996	1.63	1.80
21/03/1996	1.60	1.76
22/03/1996	1.57	1.72
23/03/1996	1.54	1.69
24/03/1996	1.51	1.66
25/03/1996	1.49	1.63
26/03/1996	1.47	1.61
27/03/1996	1.45	1.58
28/03/1996	1.43	1.56
29/03/1996	1.41	1.54
30/03/1996	1.39	1.52
31/03/1996	1.37	1.50
01/04/1996	1.35	1.48
02/04/1996	1.34	1.47
03/04/1996	1.32	1.45
04/04/1996	1.30	1.43
05/04/1996	1.29	1.41
06/04/1996	1.27	1.40
07/04/1996	1.26	1.38
08/04/1996	1.24	1.36
09/04/1996	1.23	1.35
10/04/1996	1.21	1.33
11/04/1996	1.20	1.32

Date	Accumulated Streamflow With Wetlands (mm)	Accumulated Streamflow Without Wetlands (mm)
12/04/1996	1.18	1.30
13/04/1996	1.17	1.28
14/04/1996	1.16	1.27
15/04/1996	1.14	1.25
16/04/1996	1.13	1.24
17/04/1996	1.12	1.23
18/04/1996	1.10	1.21
19/04/1996	1.09	1.20
20/04/1996	1.08	1.18
21/04/1996	1.06	0.90
22/04/1996	1.05	0.89
23/04/1996	1.04	0.88
24/04/1996	1.03	0.87
25/04/1996	1.02	0.87
26/04/1996	1.00	0.86
27/04/1996	0.99	0.85
28/04/1996	0.98	0.84
29/04/1996	0.97	0.84
30/04/1996	0.96	0.83
01/05/1996	0.95	0.82
02/05/1996	0.94	0.81
03/05/1996	0.92	0.81
04/05/1996	0.91	0.80
05/05/1996	0.90	0.79
06/05/1996	0.89	0.79
07/05/1996	0.88	0.78
08/05/1996	0.87	0.77
09/05/1996	0.86	0.76
10/05/1996	0.85	0.76
11/05/1996	0.84	0.75
12/05/1996	0.83	0.74
13/05/1996	0.82	0.74
14/05/1996	0.81	0.73
15/05/1996	0.80	0.72
16/05/1996	0.79	0.72
17/05/1996	0.78	0.71
18/05/1996	0.77	0.70
19/05/1996	0.77	0.70
20/05/1996	0.76	0.69
21/05/1996	0.75	0.69
22/05/1996	0.74	0.68
23/05/1996	0.73	0.67
24/05/1996	0.72	0.67
25/05/1996	0.71	0.66
26/05/1996	0.71	0.66
27/05/1996	0.70	0.65
28/05/1996	0.69	0.64

Date	Accumulated Streamflow With Wetlands (mm)	Accumulated Streamflow Without Wetlands (mm)
29/05/1996	0.68	0.64
30/05/1996	0.67	0.63
31/05/1996	0.67	0.63
01/06/1996	0.66	0.62
02/06/1996	0.65	0.61
03/06/1996	0.64	0.61
04/06/1996	0.63	0.60
05/06/1996	0.63	0.60
06/06/1996	0.62	0.59
07/06/1996	0.61	0.59
08/06/1996	0.61	0.58
09/06/1996	0.60	0.58
10/06/1996	0.59	0.57

* NOTE * Orange Shading = Storage Effect, while Blue Shading = Attenuation Effect

Table 7.9 Summary showing the averaged effects of an upland wetland on hydrological responses in a wet and a dry year

Year	Averaged Percentage Impact on Attenuation between a Wet and Dry Year	Averaged Percentage Impact on Storage between a Wet and Dry Year
WET YEAR – 1996	9.21%	38.24%
DRY YEAR – 1968	10.70%	Undefined (division by zero)

The simulated results of the upland wetland display the highest impact on storage in a wet year, with only a small impact on attenuation for the same conditions. The impact in a dry year is low, with the attenuation impact being comparable to that of a relatively small riparian wetland at the outlet of a large catchment. The impact of storage is minor, with only 0.01 mm equivalent streamflow being released per day. The percentage impact could not be quantified due to the zero flow in the catchment simulated without a wetland over the same time period. It is postulated that these impacts are the result of reduced flow volumes due to the smaller accumulated catchment area assumed in this study for an upland wetland. The reduced area generates less streamflow entering the wetland, which reduces the occurrence of the wetland's channel spilling on to the adjacent topsoil, thereby retarding the attenuation and storage processes. In a wet year with higher flows the impact is more pronounced than in a dry year.

The comparative impacts between the three simulations show that the effect of a wetland on its catchment is dependent on the streamflow volume entering it. Large flow results in the wetland soils consistently being near saturation, which limits the overall impact on the system. Little streamflow, on the other hand, results in fewer channel spills onto the wetland topsoil, thereby reducing the wetland's effect on hydrological responses. This validates **Hypothesis 11**.

The following results, given in **Table 7.10** and **7.11**, confirm that the topsoil of a catchment simulated with a wetland generally has a higher soil water content than that of the same catchment simulated without a wetland. This analysis was undertaken for the upland wetland scenario as that would be less sensitive to changes in soil water content than a riparian wetland, the catchment of which is invariably larger than the wetland area. Thus, if there was an increase in soil water content in the upland wetland scenario, it would apply to all wetland scenarios. Note that in a dry year there is only a minor increase in topsoil water content of an upland wetland (**Table 7.10**), while in a wet year (**Table 7.11**) the differences are more marked.

Table 7.10 Individual effects of an upland wetland's topsoil water content during a dry year (1968)

Date	Topsoil Water Store for a Catchment With an Upland Wetland (mm)	Topsoil Water Store for a Catchment Without an Upland Wetland (mm)
01/01/1968	47.1	45.6
02/01/1968	45.7	44.5
03/01/1968	44.7	43.7
04/01/1968	44.0	43.2
05/01/1968	43.5	43.2
06/01/1968	44.1	44.0
07/01/1968	43.2	43.2
08/01/1968	49.8	49.8
09/01/1968	50.1	50.0
10/01/1968	47.3	47.2
11/01/1968	46.2	46.0
12/01/1968	48.9	48.7
13/01/1968	47.0	46.7
14/01/1968	46.1	45.8
15/01/1968	45.2	44.9
16/01/1968	45.8	45.6
17/01/1968	44.8	44.5
18/01/1968	44.1	43.8
19/01/1968	67.8	67.1
20/01/1968	70.8	70.2
21/01/1968	67.0	66.0
22/01/1968	61.7	60.5
23/01/1968	74.0	73.0

Date	Topsoil Water Store for a Catchment With an Upland Wetland (mm)	Topsoil Water Store for a Catchment Without an Upland Wetland (mm)
24/01/1968	71.1	70.3
25/01/1968	67.3	66.2
26/01/1968	60.3	59.0
27/01/1968	56.0	54.7
28/01/1968	52.2	50.9
29/01/1968	48.7	47.9
30/01/1968	46.7	46.2
31/01/1968	57.8	57.4
01/02/1968	57.1	56.6
02/02/1968	53.5	53.0
03/02/1968	73.6	72.8
04/02/1968	69.4	68.2
05/02/1968	63.9	62.1
06/02/1968	62.4	60.2

Table 7.11 Individual effects of an upland wetland's topsoil water content during a wet year (1996)

Date	Topsoil Water Store for a Catchment With an Upland Wetland (mm)	Topsoil Water Store for a Catchment Without an Upland Wetland (mm)
03/10/1996	63.8	54.9
04/10/1996	60.6	51.9
05/10/1996	69.7	62.2
06/10/1996	65.2	56.6
07/10/1996	67.6	58.9
08/10/1996	71.5	64.0
09/10/1996	68.1	59.8
10/10/1996	69.9	61.6
11/10/1996	72.0	65.3
12/10/1996	68.8	61.3
13/10/1996	64.6	56.5
14/10/1996	67.7	590
15/10/1996	65.4	56.0
16/10/1996	62.8	53.6
17/10/1996	59.6	50.5
18/10/1996	56.7	48.1
19/10/1996	53.4	45.9
20/10/1996	61.6	55.2
21/10/1996	67.4	60.2
22/10/1996	67.4	59.5
23/10/1996	64.8	56.2
24/10/1996	59.8	51.3
25/10/1996	58.2	51.0
26/10/1996	81.5	76.5
27/10/1996	94.1	88.4
28/10/1996	98.0	91.3

Date	Topsoil Water Store for a Catchment With an Upland Wetland (mm)	Topsoil Water Store for a Catchment Without an Upland Wetland (mm)
29/10/1996	90.3	83.4
30/10/1996	82.1	75.7
31/10/1996	75.7	69.9
01/11/1996	70.7	63.3
02/11/1996	73.7	67.7
03/11/1996	80.6	75.9
04/11/1996	82.7	78.7
05/11/1996	84.2	80.6
06/11/1996	77.4	74.1
07/11/1996	72.0	69.0
08/11/1996	68.1	63.2

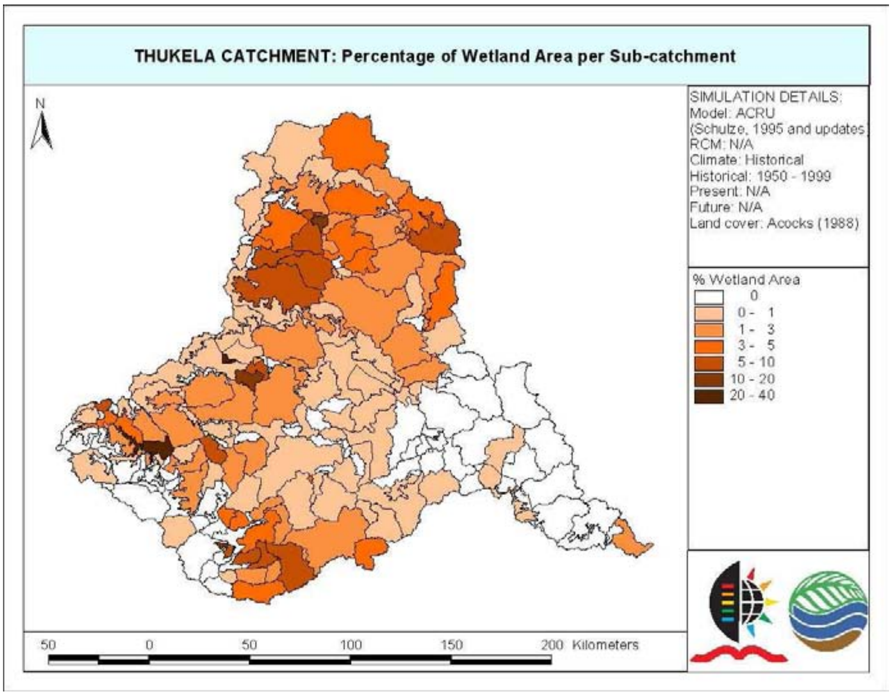
The results presented in this Chapter validate that the *ACRU* Model simulates wetlands hydrological processes in a manner that was expected from the literature presented. It needs to be stressed once again that no such detailed validation studies had been done before. The way in which *ACRU* simulates wetlands is, of course, a simplification of the real-world processes that occur. However, for the purposes of evaluating the techniques for assessing hydrological responses of wetlands under varying climate scenarios, the simulated results presented in this validation Chapter show that the model is capable of simulating the main wetlands hydrological responses realistically. It is therefore considered that the *ACRU* Model will provide sufficiently realistic results to show what impact, if any, wetlands might have on hydrological responses at a catchment scale, and what impacts climate change scenarios might have on wetlands responses within the hydrological system.

These results will be presented and discussed in the following Chapter.

8 RESULTS AND DISCUSSION FROM CATCHMENT-SCALE WETLAND HYDROLOGICAL REPONSES UNDER VARYING CLIMATIC CONDITIONS

In this Chapter results are presented of wetlands hydrological responses under varying climatic conditions in the Thukela catchment with its widely ranging climatic regimes. The first sub-section will describe results simulated from historical climate inputs, both with and without wetlands, including the effects of wetter vs. drier regions on wetland hydrological responses.

Figure 8.1 shows the percentage area of wetlands per sub-catchment in the Thukela. This information provides a reference for the magnitude of impacts that wetlands may have on hydrological responses, and later the impacts of climate change on wetlands hydrological responses. The second sub-section presents results from hydrological simulations based on climate change scenarios using outputs from the C-CAM Regional Climate Model (Engelbrecht, 2005) as inputs to the *ACRU* Model.

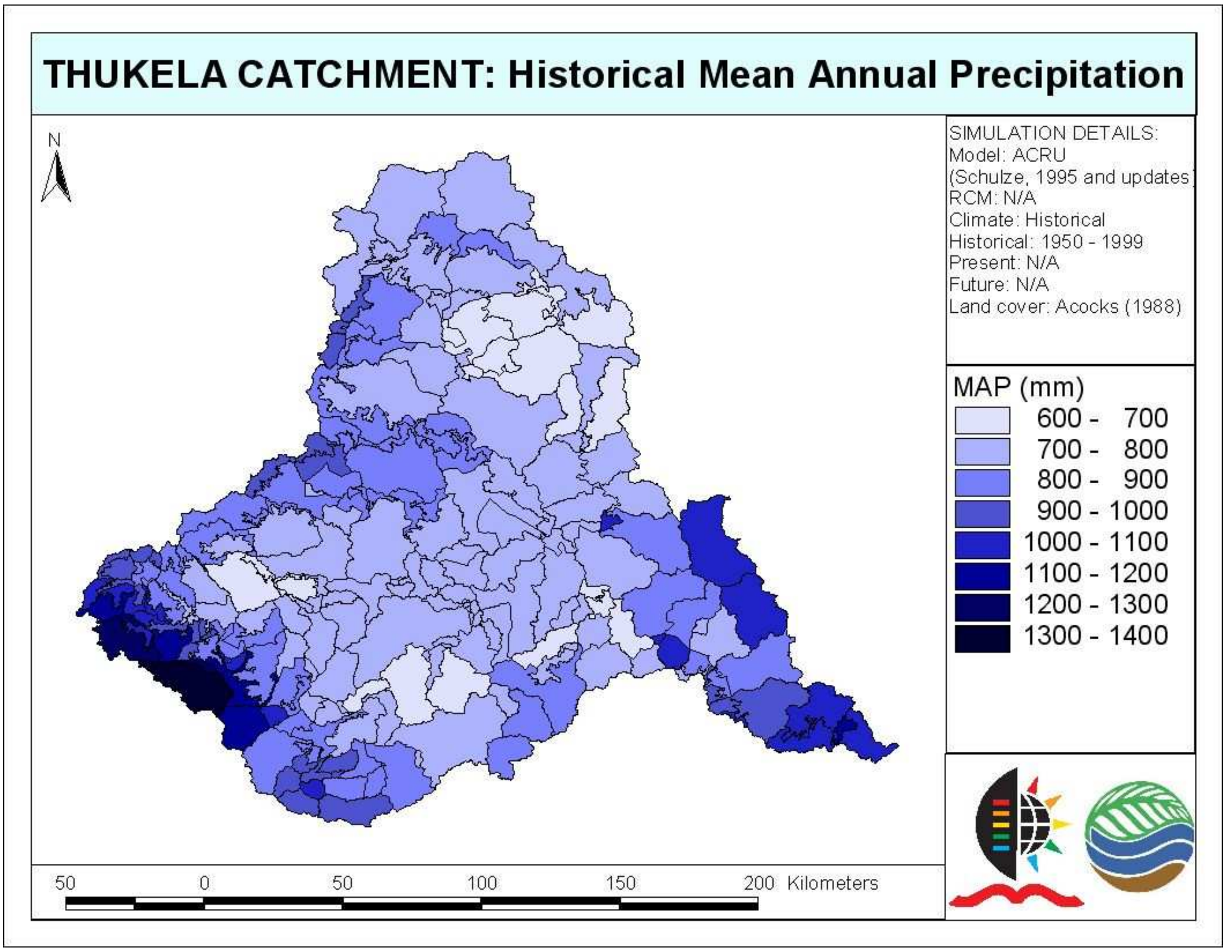


*** NOTE *** "Kilometers" is spelled as such in the figure as a result of the ArcView 3.2 software

Figure 8.1 Percentage of the area of wetlands for each of the 235 configured sub-catchments in the Thukela catchment

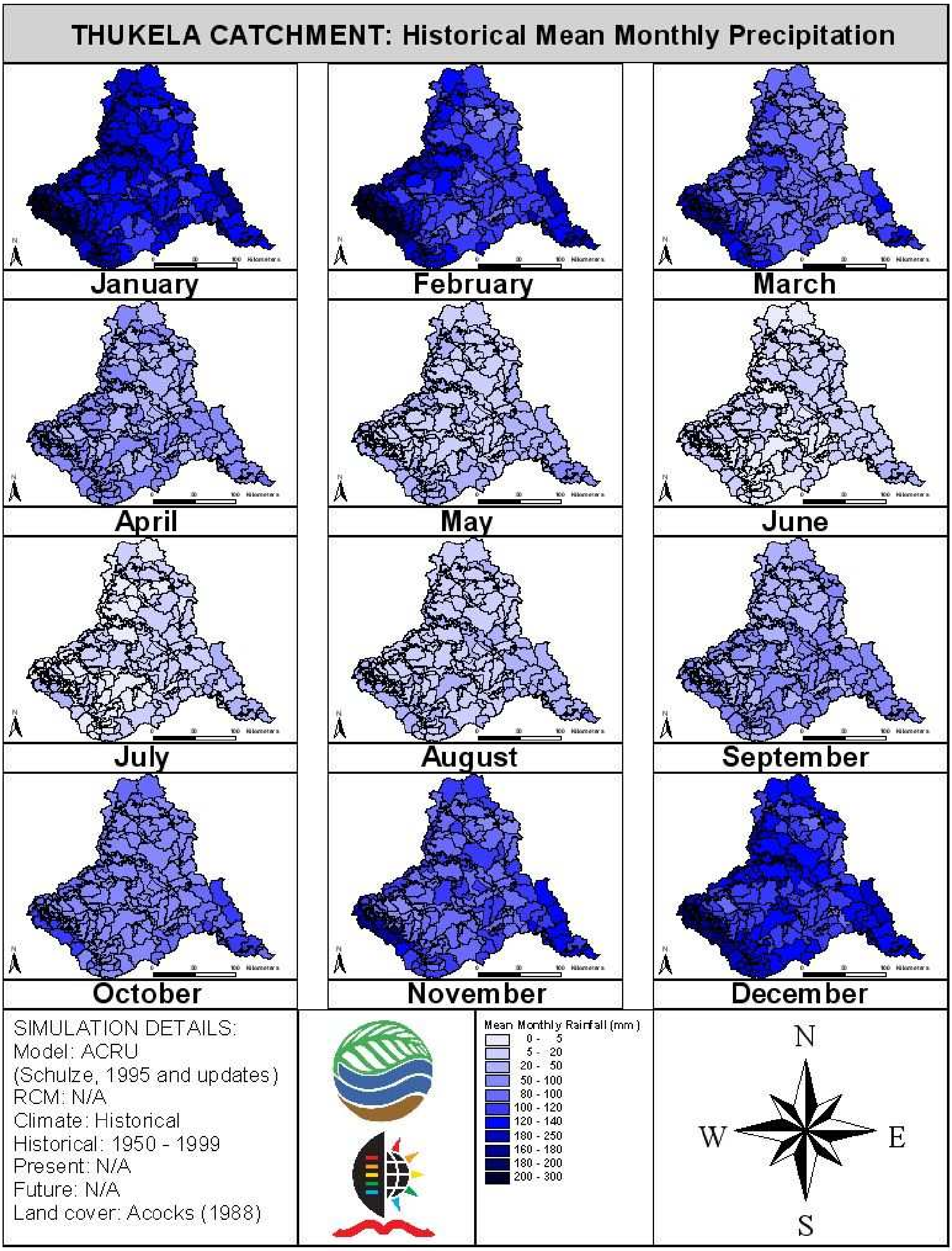
8.1 Results Based on Historical Climatic Input

In order to assist in the interpretation of results on impacts of wetlands on catchment hydrological responses, the baseline (historical) rainfall of the Thukela catchment is shown to illustrate the range in Mean Annual Precipitation (MAP) and Mean Monthly Precipitation (MMP) across the catchment. **Figure 8.2** shows the MAP (mm) for each of the 235 sub-catchments, with **Figure 8.3** depicting the mean monthly precipitation (mm) for the 235 sub-catchment configuration.



*** NOTE *** "Kilometers" is spelled as such in the figure as a result of the ArcView 3.2 software

Figure 8.2 Historical MAP used in hydrological simulations of the Thukela catchment, showing a range from 600 to 1 400 mm



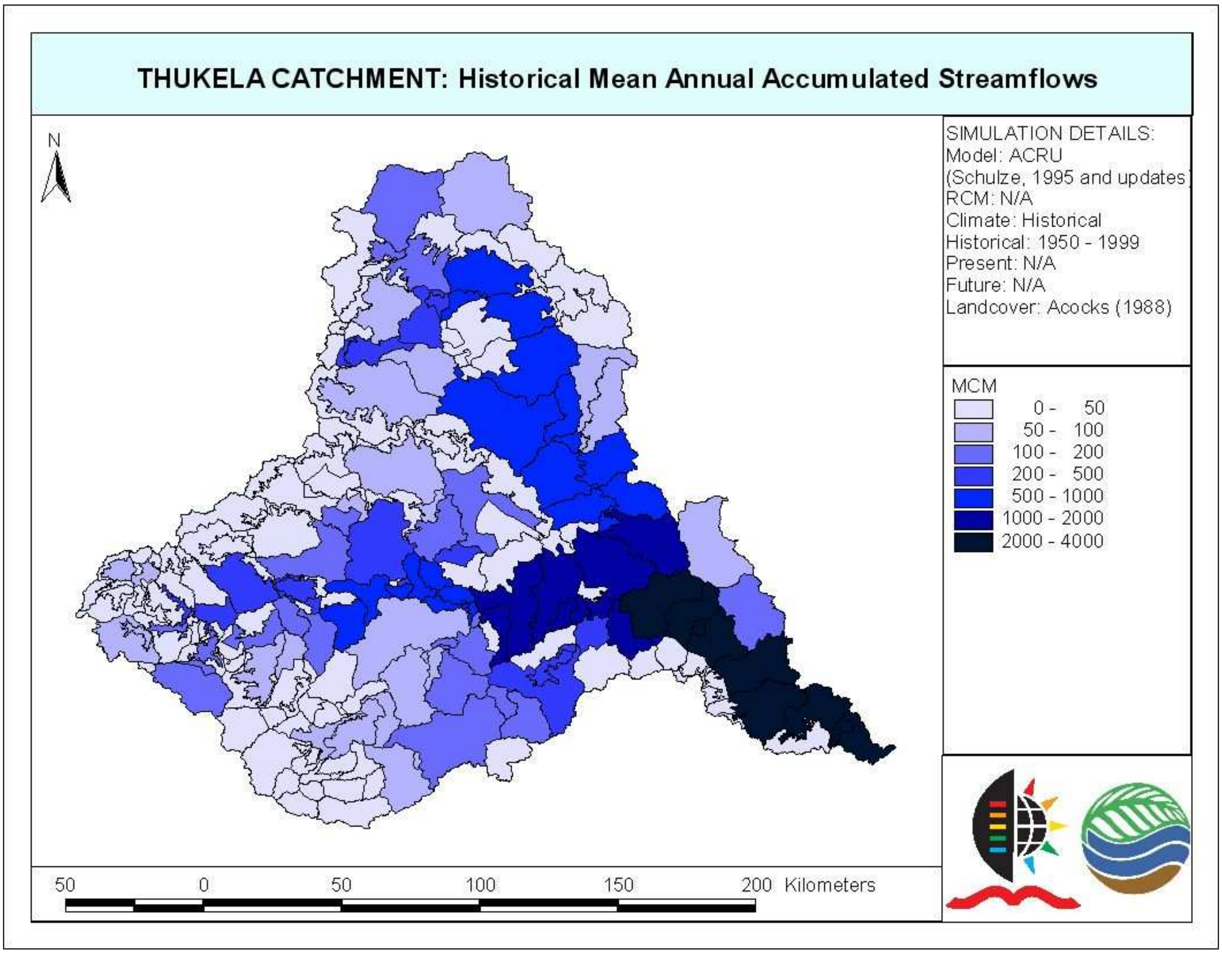
*** NOTE *** "Kilometers" is spelled as such in the figure as a result of the ArcView 3.2 software

Figure 8.3 Historical MMP used in hydrological simulations of the Thukela catchment, showing a range from less than 5 to over 300 mm

The historical MAP depicted in **Figure 8.2** ranges from 600 – 1 400 mm across the catchment (dark to royal blue shading). The Drakensberg mountain range in the west experiences the highest MAP of between 1 000 – 1 400 mm per year. The coastal region to the east of the catchment, where the Thukela River discharges into the Indian Ocean, also has a relatively high MAP (900 – 1 100 mm) in relation to the majority of the catchment. The central portion of the catchment running in a north-south direction has the lowest MAP (light blue shading), ranging from 600 – 900 mm. This middle portion of the Thukela catchment makes up the majority of the area, and as such the majority of the Thukela catchment falls within the relatively low MAP range. Based on these results, one would expect to see a difference in impacts of wetlands on hydrological responses between the wetter and drier regions.

The historical mean monthly rainfall varies greatly across the months, as shown in **Figure 8.3**. The wet season can be classed as October to March (moderate to dark blue shading), with monthly rainfall depths generally above 100 mm per month for all sub-catchments. The dry season can be defined as April to September, with monthly rainfall generally below 100 mm in all sub-catchments (light blue shading). Owing to the pronounced rainfall differences in wet and dry seasons, one would expect to observe marked differences in wetlands hydrological responses between seasons.

Figure 8.4 presents the Mean Annual Accumulated Streamflows, abbreviated as MAR, using historical climate for the simulation without the presence of wetlands. Similarly, **Figure 8.5** illustrates the monthly trends of the Mean Monthly Accumulated Streamflows, abbreviated as MMR, for the hydrological simulations with historical climate data, again without the presence of wetlands. The mean annual and mean monthly accumulated streamflow maps show the catchments characterised by the Thukela River and its major tributaries, which are characterised by the darker blue shading, becoming more dominant in a west-southwest direction. This illustrates the accumulation of streamflows down the catchment towards the Indian Ocean. The monthly accumulated streamflows presented in **Figure 8.5** also show the seasonal variability within the Thukela catchment, as discussed previously for the MAP and MMP results.

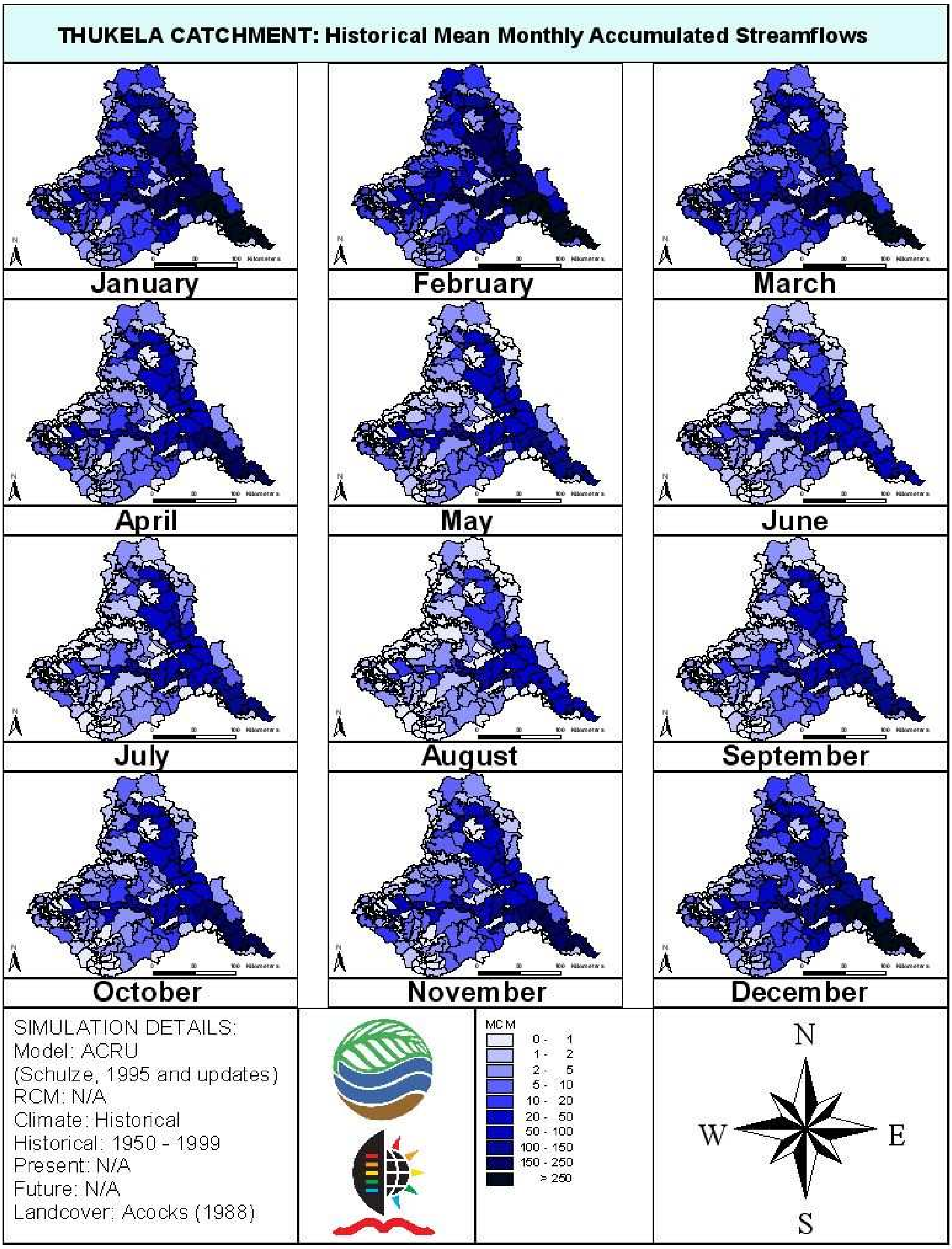


*** NOTE *** "Kilometers" is spelled as such in the figure as a result of the ArcView 3.2 software

Figure 8.4 Historical MAR, in millions of m^3, obtained from hydrological simulations with historical climate data in the Thukela catchment, without wetlands

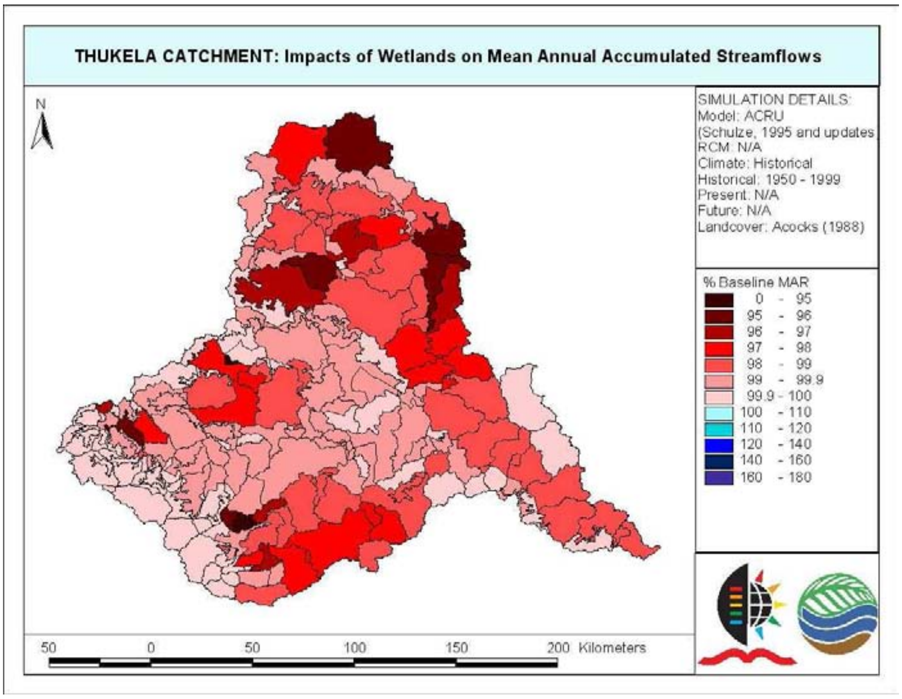
Figure 8.6 presents impact of wetlands on accumulated streamflows for historical baseline conditions, expressed as a percentage of change in MAR. Similarly, **Figure 8.7** shows the impact of wetlands on accumulated monthly streamflows for historical baseline conditions, again expressed as a percentage change.

The percentage change in the Coefficient of Variation (CV%) of inter-annual accumulated streamflows is presented in **Figure 8.8**. **Figure 8.9** illustrates the monthly impacts of wetlands on the CV% of flows.



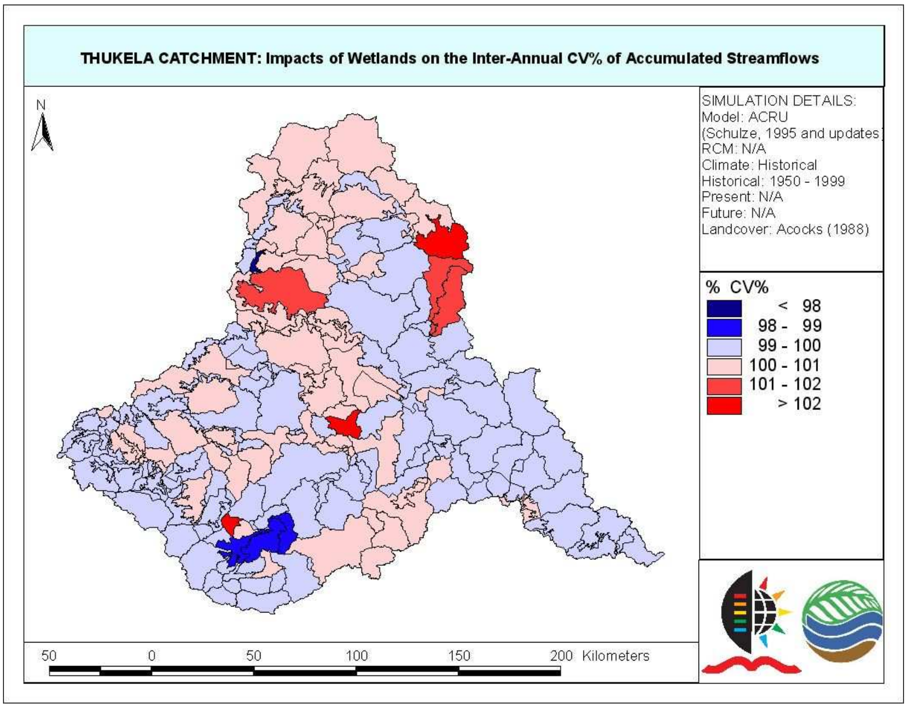
*** NOTE *** "Kilometers" is spelled as such in the figure as a result of the ArcView 3.2 software

Figure 8.5 Historical MMR, in millions of m^3, obtained from hydrological simulations with historical climate data in the Thukela catchment, without wetlands



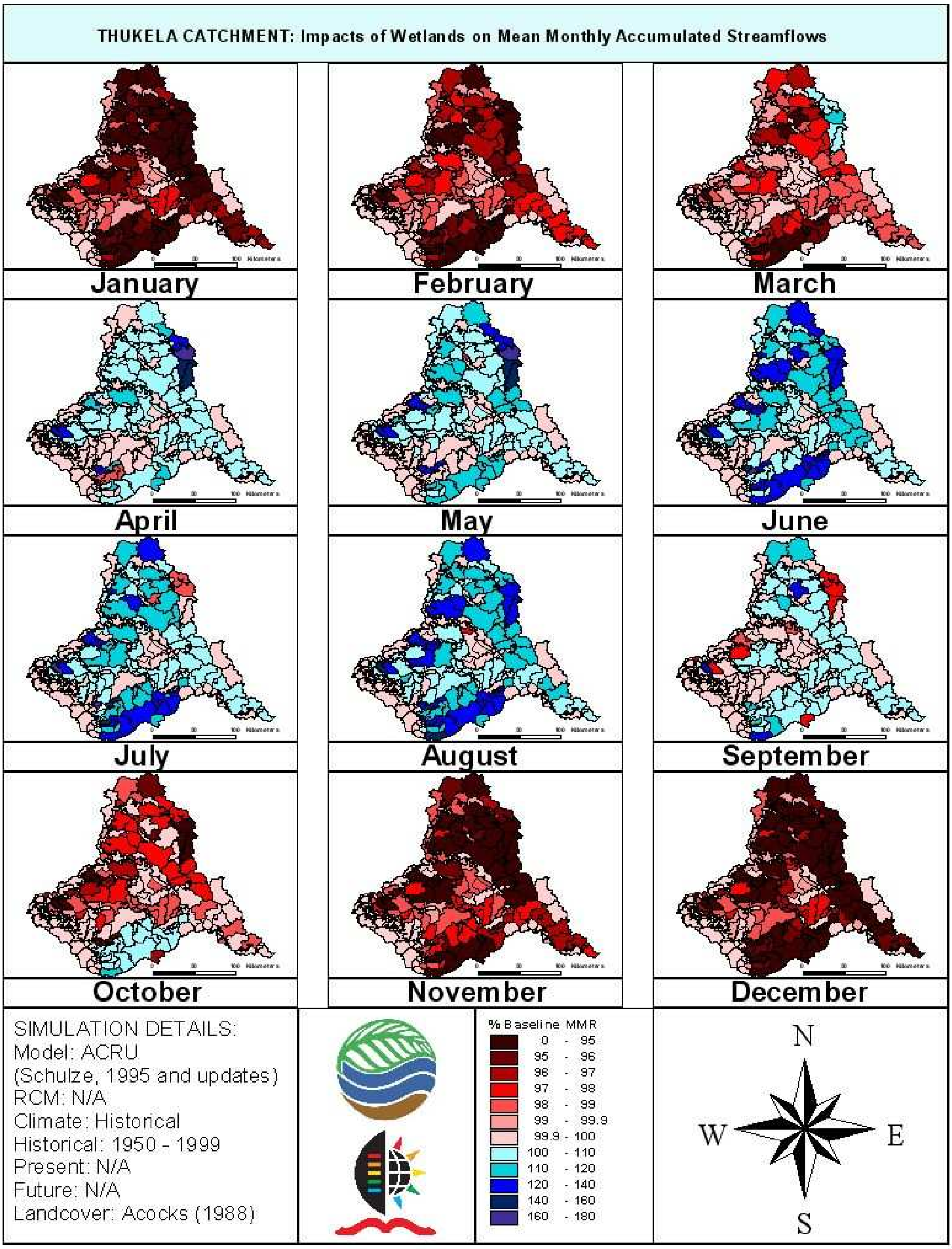
* NOTE * "Kilometers" is spelled as such in the figure as a result of the ArcView 3.2 software

Figure 8.6 Impacts of wetlands on mean annual accumulated streamflows under historical climatic conditions, expressed as a percentage change



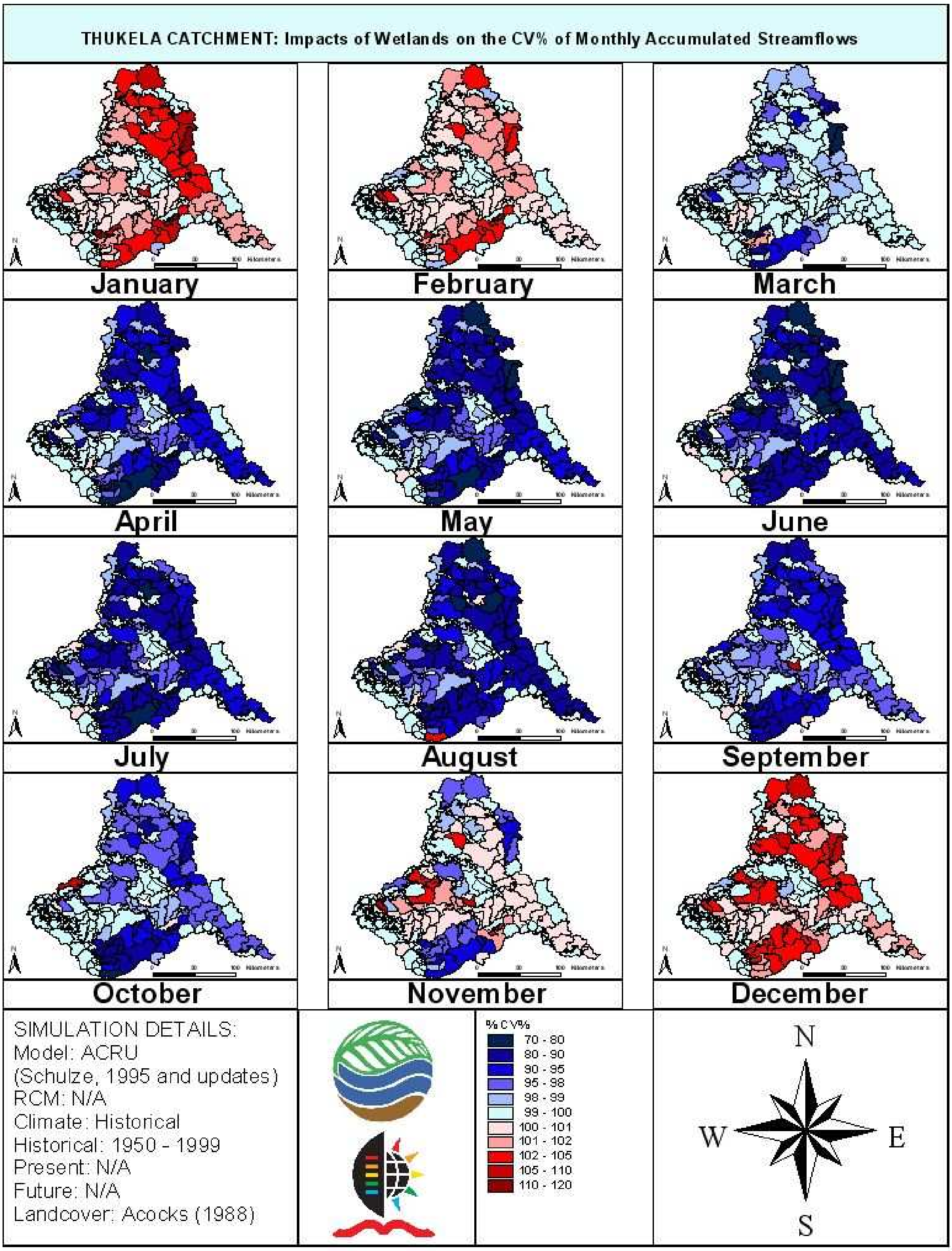
* NOTE * "Kilometers" is spelled as such in the figure as a result of the ArcView 3.2 software

Figure 8.8 Impacts of wetlands on the inter-annual CV% of accumulated streamflows under historical climatic conditions, expressed as a percentage change



*** NOTE *** "Kilometers" is spelled as such in the figure as a result of the ArcView 3.2 software

Figure 8.7 Impacts of wetlands on mean monthly accumulated streamflows under historical climatic conditions, expressed as a percentage change



*** NOTE *** "Kilometers" is spelled as such in the figure as a result of the ArcView 3.2 software

Figure 8.9 Impacts of wetlands on the CV% of monthly accumulated streamflows under historical climatic conditions, expressed as a percentage change

Figure 8.6 shows only a small reduction in MAR across the whole catchment when comparing accumulated streamflows across the Thukela catchment without and with wetlands. The reduction in MAR ranges from 0.01 – 5.00 %, with the sub-catchments exhibiting the largest reductions corresponding to those with the highest percentage wetland area (cf. **Figure 8.1**). These reductions are shown in the dark red shading in the north-northeast of the catchment, the bright red shading in the south-southwest of the catchment and the bright to dark red shading inland on the northwest corner of the catchment. The map also illustrates that the drier areas in the north-northeast of the catchment show a higher percentage decrease in MAR than the wetter regions, illustrating that wetlands have a higher impact on streamflows in drier regions. This was also shown clearly in the validation Chapter (**Chapter 7**).

The small reduction in MAR between the simulations without and with wetlands could be as a result of increased total evaporation from the wetlands (**Figures 8.10** and **8.11**) due to increased soil water availability in wetlands (cf. **Chapter 7**), as postulated by Begg (2001).

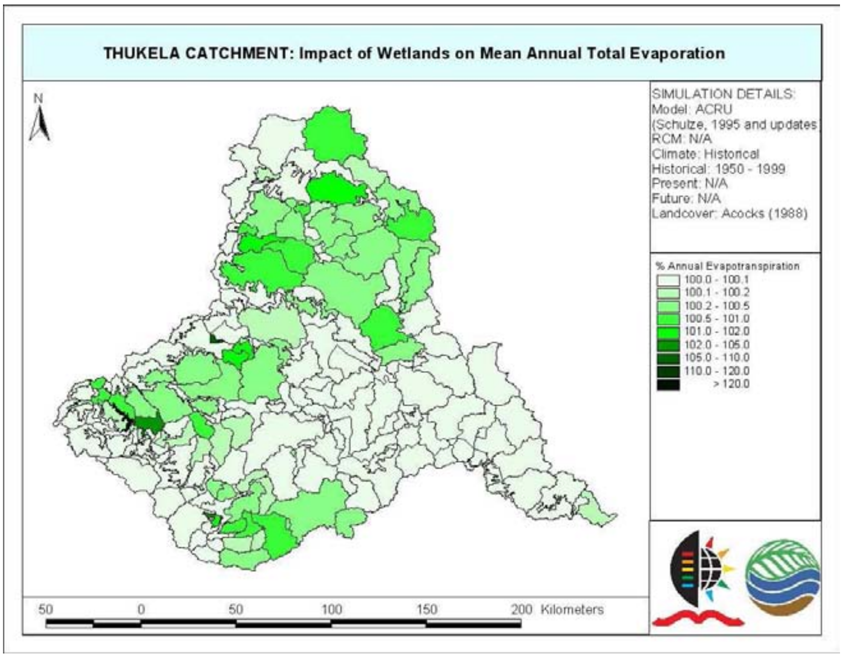
Similarly, **Figure 8.8** shows how the inter-annual CV% displays only small changes, both positive and negative, when the hydrological system of the Thukela catchment is simulated with wetlands, as opposed to simulations under baseline land cover without wetlands. There are, however, a few sub-catchments which respond in a more marked manner, with a higher increase or decrease in inter-annual CV% of up to 2 %. The increased effects on the CV% observed in these sub-catchments is due to the presence of relatively large wetland areas in comparison to contributing catchment areas (most common in external sub-catchments, which only have their respective catchment area contributing to the wetland). This enables the wetland functioning to have a more pronounced effect, as shown in **Chapter 7**.

Figure 8.7 presents the results from the mean monthly accumulated streamflow comparison between simulations with and without wetlands. Results show a distinct seasonal impact in MMR. The overriding result of **Figure 8.7** is one of flood attenuation in the high flow months and storage releases from the wetlands in the low flow months.

The wet season, October to March, shows a general decrease in MMR (shades of red, with the darkest red being a 5% decrease in MMR), while the dry season, April to September, shows increases in MMR of up to 30% (shades of blue with the darkest being an increase in MMR of up to 80%). **Figure 8.7** illustrates clearly the flow regulation characteristics of wetlands on hydrological responses (Duever, 1988; Kotze *et. al.*, 2005) and, to a lesser extent, wetland's flood attenuation characteristics (Schulze, 1979; Mitsch and Gosselink, 1986; Lymberopoulos and James, 1993). The flood attenuation effects of wetlands in the Thukela catchment are only considered to be partially depicted in **Figure 8.7**, as the figure shows some reduction in MMR in the wetter months, which is assumed to be, in part, made up of excess spills and absorption of peak flows by the wetland soils (cf. **Chapter 7**). However, without simulating individual peak discharge events, there is a certain amount of uncertainty as to the amount of flood attenuation a wetland is responsible for. This uncertainty is amplified by the timing of the flood and the physical characteristics of the wetland, as the soil water content, size and topographical position of the wetland in relation to the size of the flood will also impact on the level of flood attenuation that a wetland can achieve (cf. **Chapter 7**).

Similar trends to those presented above can be seen in **Figure 8.9**. The monthly changes in CV% with and without wetlands show two distinct seasonal patterns. However, in this case, the patterns of changes are similar for a November to February wet period and a March to October dry period. The four months over the wet season show a general increase in CV% of monthly accumulated streamflows (red shading showing an increase of up to 20%), with the remaining eight months showing a general decrease in CV% monthly accumulated streamflows (blue shading showing a decrease of up to 30%). This seasonal change in CV% of monthly accumulated streamflows highlights the decreases in CV% in the dry months, and further confirms the streamflow regulation and flood attenuation characteristics of wetlands. In this case the flood attenuation effects of wetlands are more evident in the wet months, with the continued streamflow regulation of wetlands generally decreasing the CV% over most months because of the averaged effects of stored baseflow releases. However, in the wettest months with the highest rainfalls, the CV% increases. This shows that wetlands attenuate the smaller floods in October and March when soils are slightly drier, hence the reduction in CV%, whereas in the wettest four months when the wetlands soils are more than likely wet or saturated, the flood peaks are too large to be attenuated to an extent significant enough, thereby increasing the CV% of accumulated streamflows of those four months through the increased frequency of stormflow flashes (cf. **Chapter 7**).

The final set of historical simulation results assessing the impact of wetlands on catchment hydrological responses is on changes in total evaporation (i.e. actual evapotranspiration), both for changes in the mean annual total evaporation (**Figure 8.10**) and in mean monthly total evaporation (**Figure 8.11**).

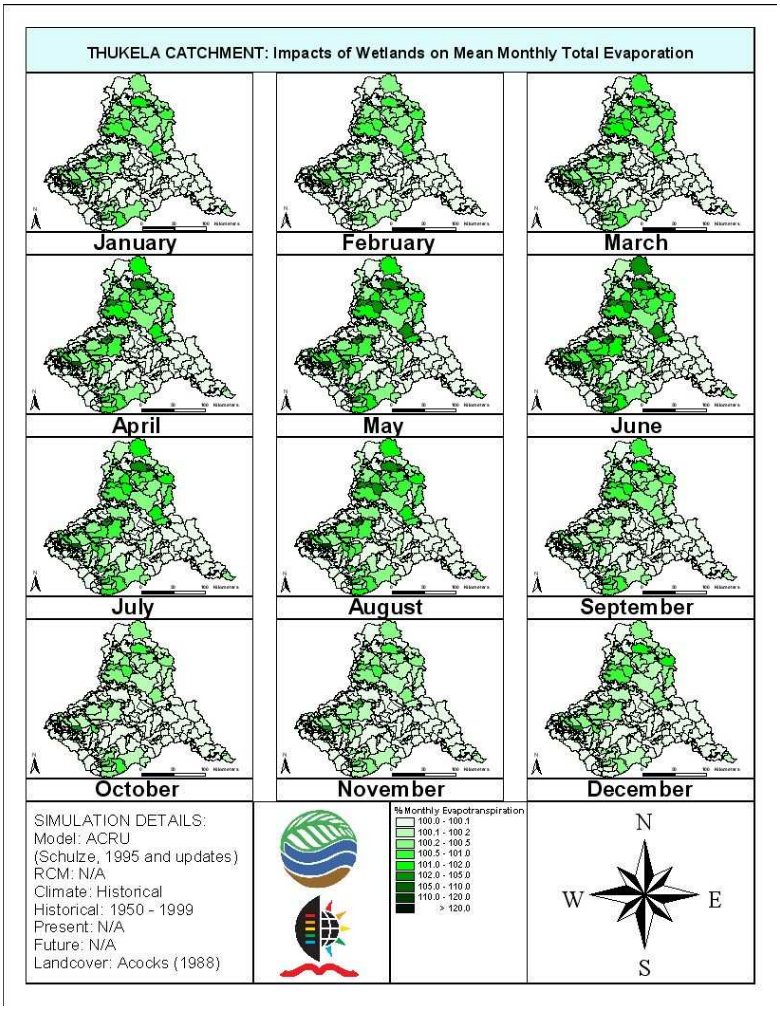


*** NOTE *** "Kilometers" is spelled as such in the figure as a result of the ArcView 3.2 software

Figure 8.10 Impacts of wetlands on mean annual total evaporation in the Thukela catchment under historical climatic conditions, expressed as a percentage change

Figure 8.10 shows a very strong relationship between the increase in mean annual total evaporation in a sub-catchment and the percentage area of wetlands within the same sub-catchment (cf. **Figure 8.1**). This is due to the increased availability of soil water of wetland soils, as validated in **Chapter 7**. The increase in total evaporation depicted in **Figure 8.10** (by up to 20% in the cases of dark green shading) could account for the minor decreases in MAR which were illustrated in **Figure 8.4**. This concurs with Begg's (2001) postulations. The figure shows that all sub-catchments display positive changes, i.e. show an increase in mean annual total evaporation for the simulation when wetlands are included. This is due to the increased accumulation of streamflows in the drier months which keep the sub-catchment soils wetter, thereby increasing the potential for evapotranspiration. The soils are wetter in summer too, as "flood" waters can re-infiltrate and increase the soil moisture content.

Figure 8.11 shows the relationship between the percentage of wetland area in a sub-catchment and the relative increase in mean monthly total evaporation. The figure also shows that there is a greater percentage increase in mean monthly total evaporation in the drier months than there is in the wetter months. This trend is due to the increase in soil water availability from the



*** NOTE *** "Kilometers" is spelled as such in the figure as a result of the ArcView 3.2 software

Figure 8.11 Impacts of wetlands on mean monthly total evaporation in the Thukela catchment under historical climatic conditions, expressed as a percentage change wetland soils during the drier months (bright to dark green shading showing increases of up to 20%). This allows for a greater percentage increase in total evaporation in the drier months, when compared to the wetter months. In the wetter months, the wetland total evaporation is approximately 0 – 5% higher than that simulated without wetlands (light green shading).

* * * * *

The results presented above, and the accompanying discussion, show that with wetlands there is streamflow attenuation in the summer months and streamflow releases (regulation) in the winter months. The monthly results provide a better insight of the effects which wetlands have on catchment hydrological responses, because the mean annual values tend to mask intra-seasonal differences. The above results, specifically the monthly results, and the relationship between the percentage impacts on hydrological responses and the percentage wetland area per sub-catchment provide a further validation of the *ACRU* Wetland Routine, albeit a visual one, to be viewed in conjunction with the findings presented in Chapter 7.

The following sub-section presents the results of the climate change scenarios undertaken using the C-CAM RCM's climate outputs as inputs for simulations with the *ACRU* Model.

8.2 Impact of Climate Change on Wetland Hydrological Responses

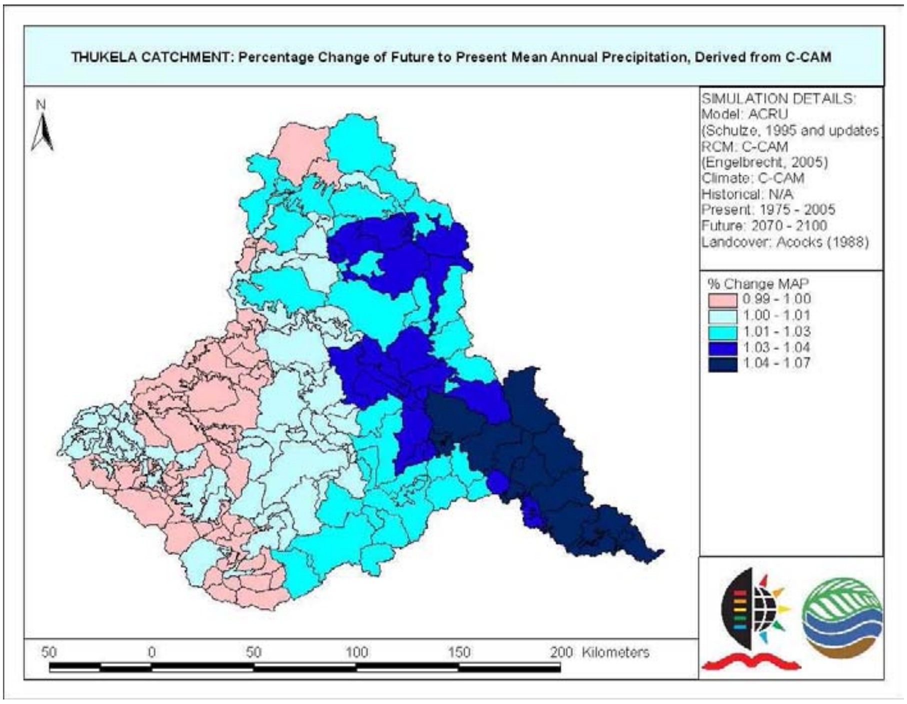
When assessing the impacts of climate change on streamflows and wetland hydrological responses in this section, it is necessary to re-iterate first, that downscaled GCM outputs were used for the climate change scenarios, both without and with wetlands considered, and for both annual and monthly responses, and secondly, that the main focus in this dissertation is not on climate change *per se*, but that it should be seen as a case study of the sensitivity of wetland responses to climate. This case study uses outputs from a single GCM, *viz.* C-CAM, as inputs for the *ACRU* Model, and the author acknowledges the uncertainties that are associated with using output from only one GCM (cf. **Chapter 4**) when assuming climate change impacts.

In addition to the uncertainties of using only a single GCM, the C-CAM RCM has been shown previously to over-estimate precipitation (Schulze *et al.*, 2005b; Schulze *et al.*, 2005c) and, as a result, transfers this tendency for over-estimation to hydrologically simulated streamflows, most likely in an amplified manner (Schulze *et al.*, 2005c).

In order to mitigate any inherent errors in the C-CAM Model, *ratios* of future (2070 – 2100) to present (1975 - 2005) output are therefore used to assess the relative impact of climate change on wetland hydrological responses (cf. **Chapter 6**). In the results to follow the ratio of future to present impacts will be represented as a percentage, i.e. < 100% represents a relative reduction in the future hydrological responses and > 100% illustrates a relative increase in the hydrological responses of a future climate scenario.

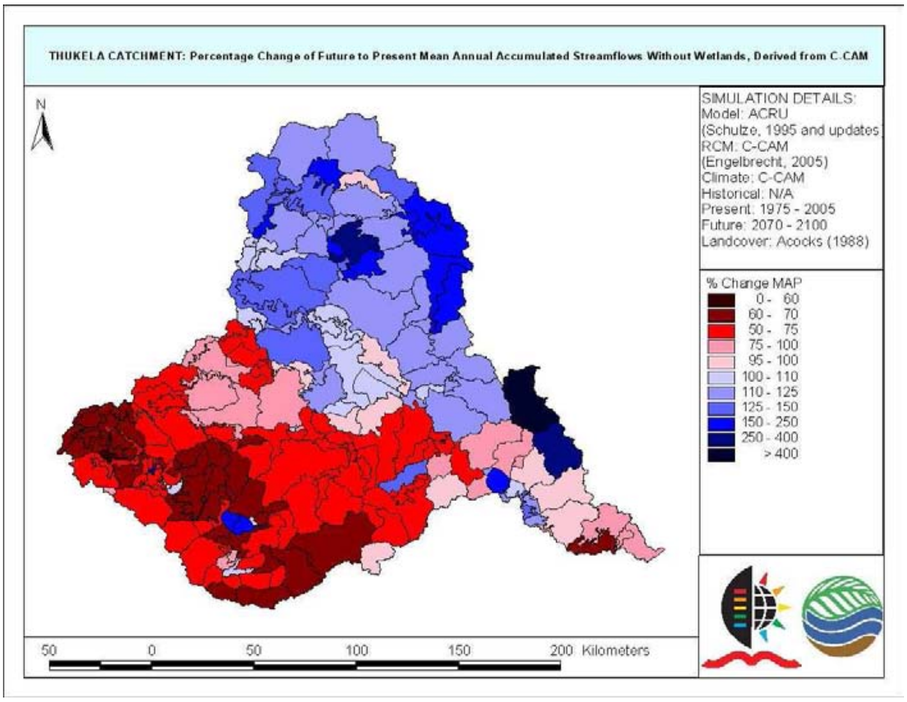
Figure 8.12 shows the percentage change of future to present mean annual precipitation, derived from C-CAM, while in **Figure 8.13** the percentage change of future to present mean annual accumulated streamflows, without wetlands, is shown. The percentage change of future to present mean annual accumulated streamflows with wetlands is illustrated in **Figure 8.14**. A comparison between the results of **Figure 8.13** and **8.14** is provided in **Figure 8.15** to depict the impact of wetlands on hydrological responses when compared to the same impact by a climate change scenario.

Similarly, **Figures 8.16** to **8.18** show the percentage changes from future to present scenarios, but for mean monthly outputs, and thereby providing an indication of any changes in seasonal distribution trends. **Figure 8.19** illustrates the impact of wetlands on monthly hydrological responses when compared to the impact of a climate change scenario (i.e. comparing the results from **Figures 8.17** and **8.18**).



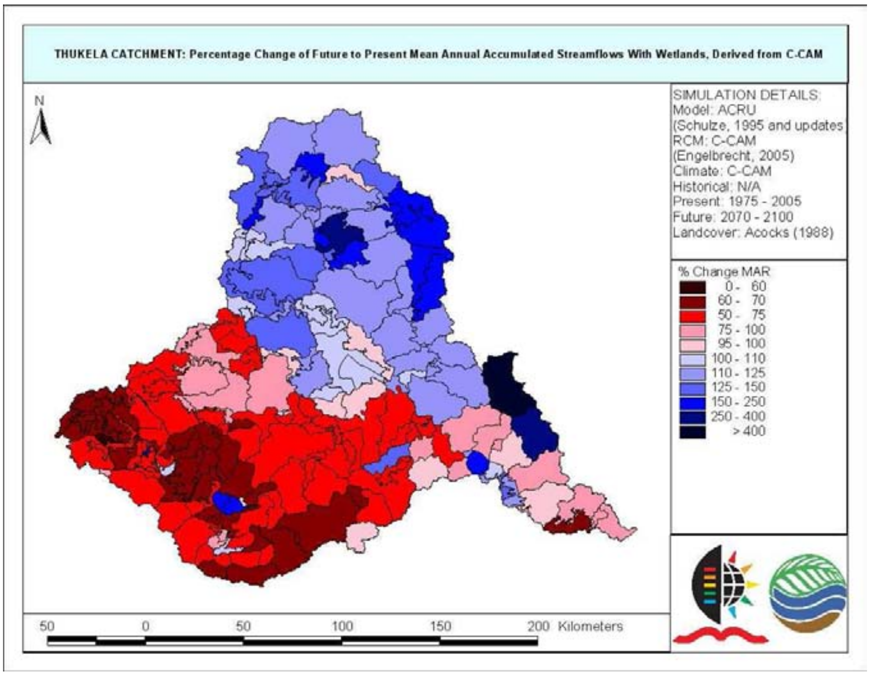
*** NOTE *** "Kilometers" is spelled as such in the figure as a result of the ArcView 3.2 software

Figure 8.12 Percentage change of future to present mean annual precipitation for the Thukela catchment, derived from C-CAM



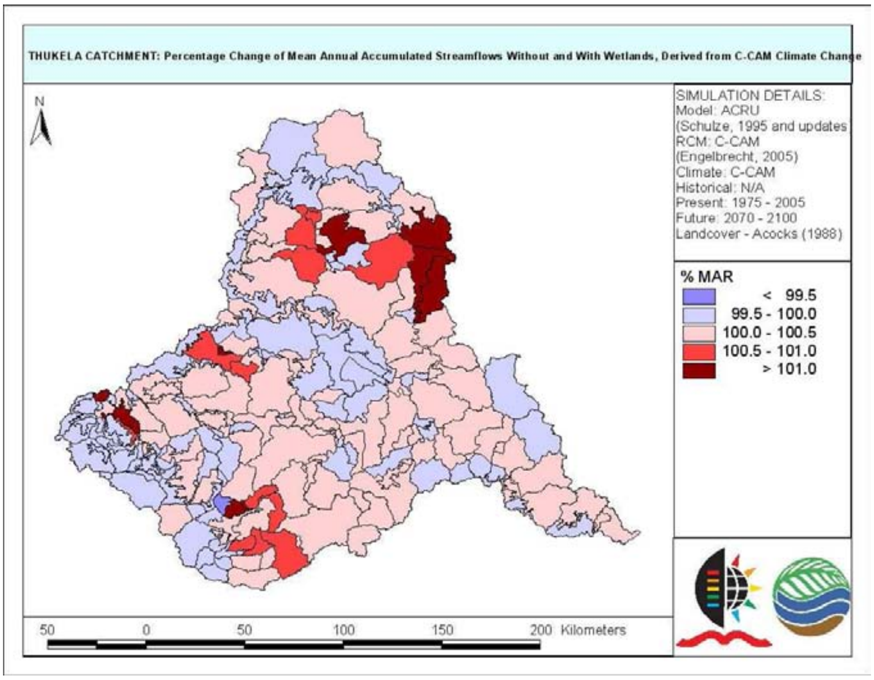
*** NOTE *** "Kilometers" is spelled as such in the figure as a result of the ArcView 3.2 software

Figure 8.13 Percentage change of future to present mean annual accumulated streamflows for the Thukela catchment, without wetlands, derived from C-CAM



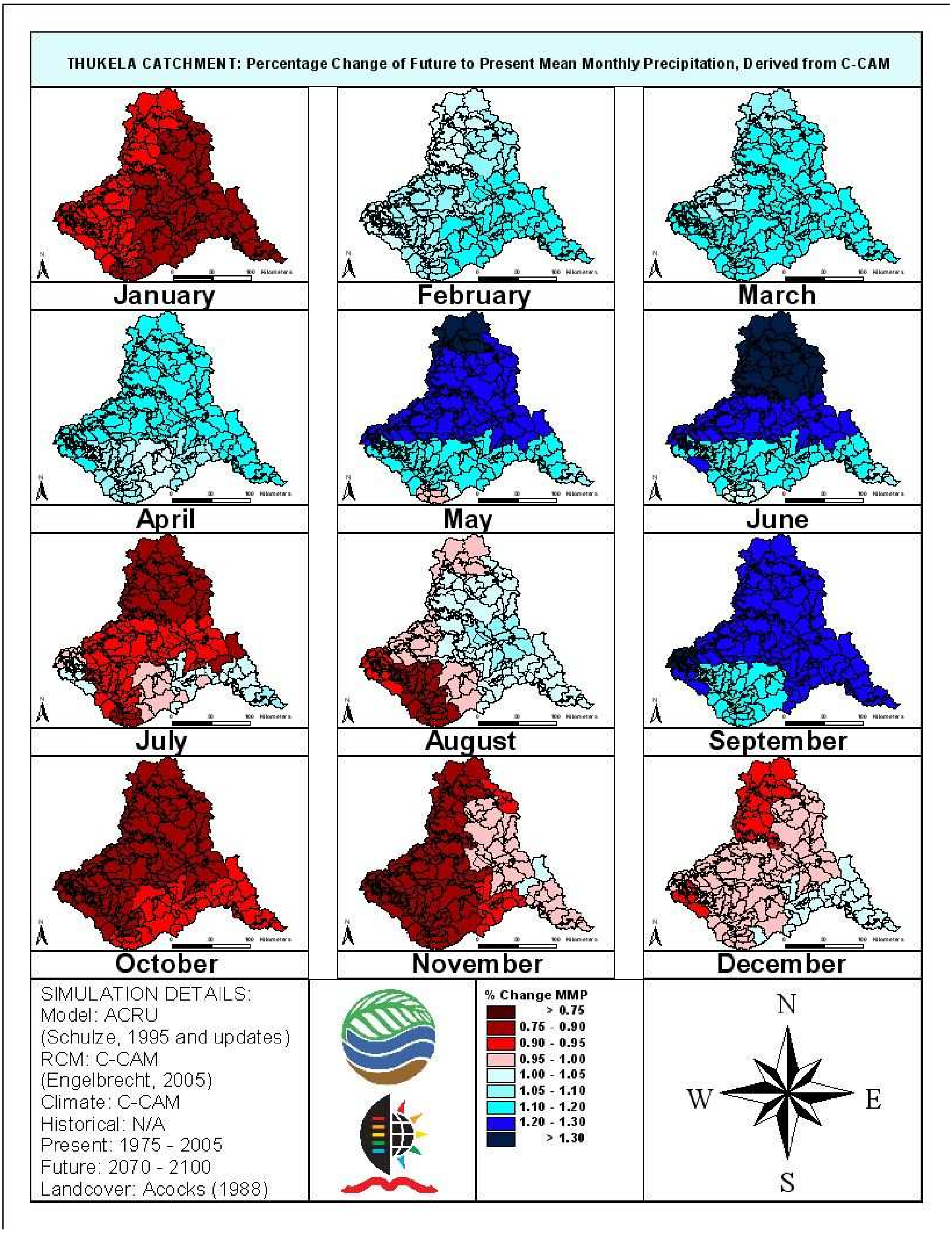
*** NOTE *** "Kilometers" is spelled as such in the figure as a result of the ArcView 3.2 software

Figure 8.14 Percentage change of future to present mean annual accumulated streamflows for the Thukela catchment, with wetlands, derived from C-CAM



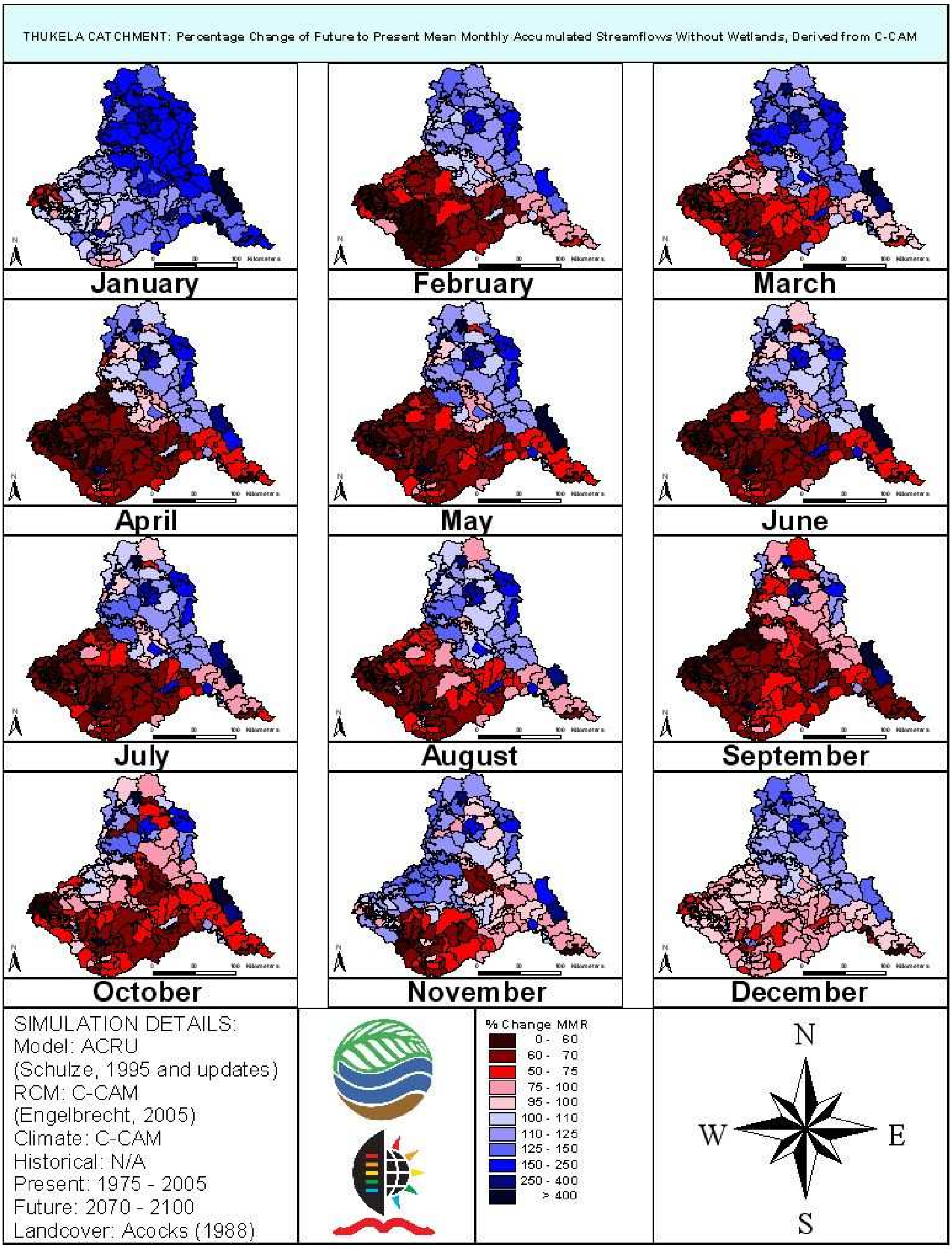
NOTE * "Kilometers" is spelled as such in the figure as a result of the ArcView 3.2 software

Figure 8.15 Percentage change from future to present mean annual accumulated streamflows for the Thukela catchment as a result of the inclusion of wetlands, derived from C-CAM



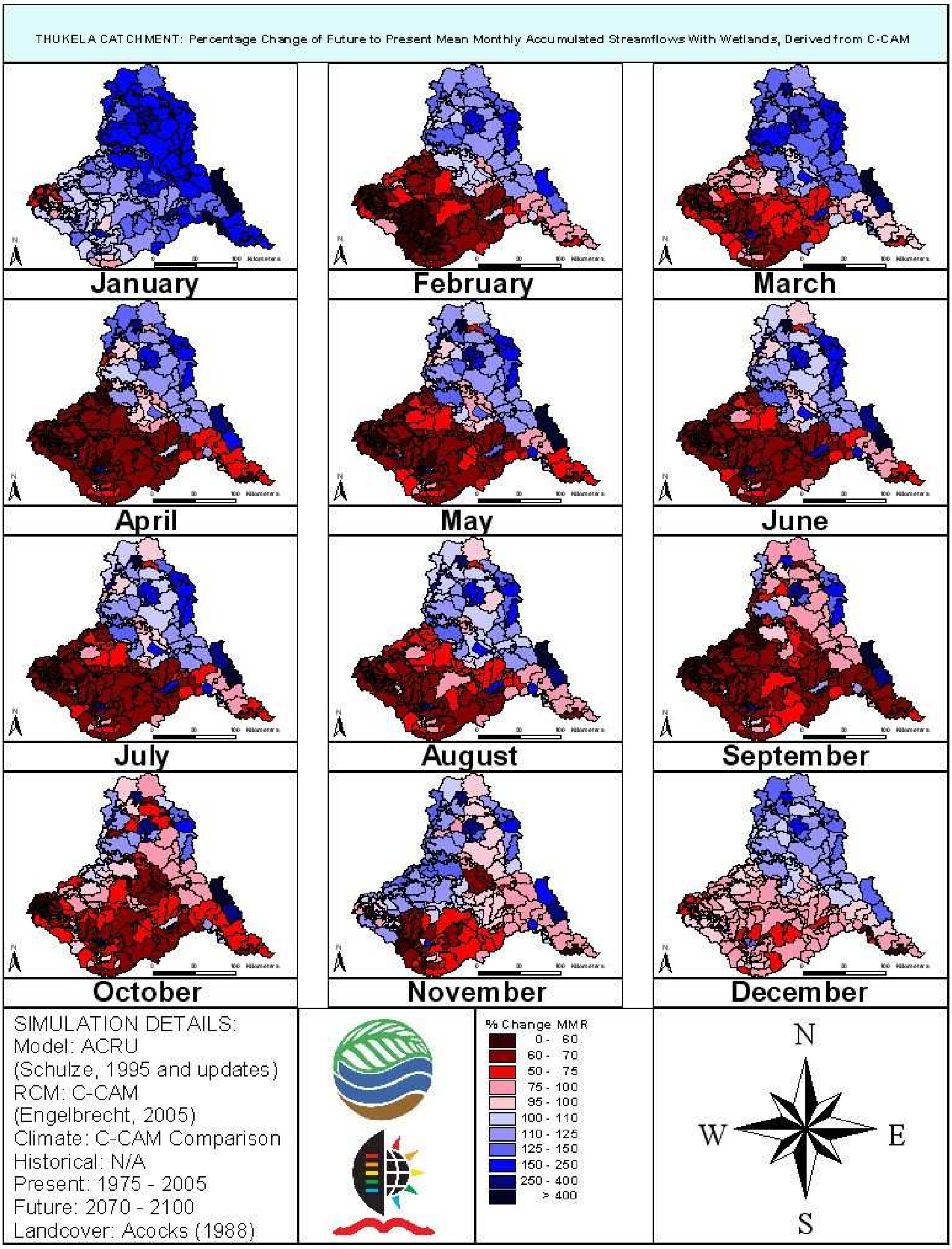
*** NOTE *** "Kilometers" is spelled as such in the figure as a result of the ArcView 3.2 software

Figure 8.16 Percentage change of future to present mean monthly precipitation for the Thukela catchment, derived from C-CAM



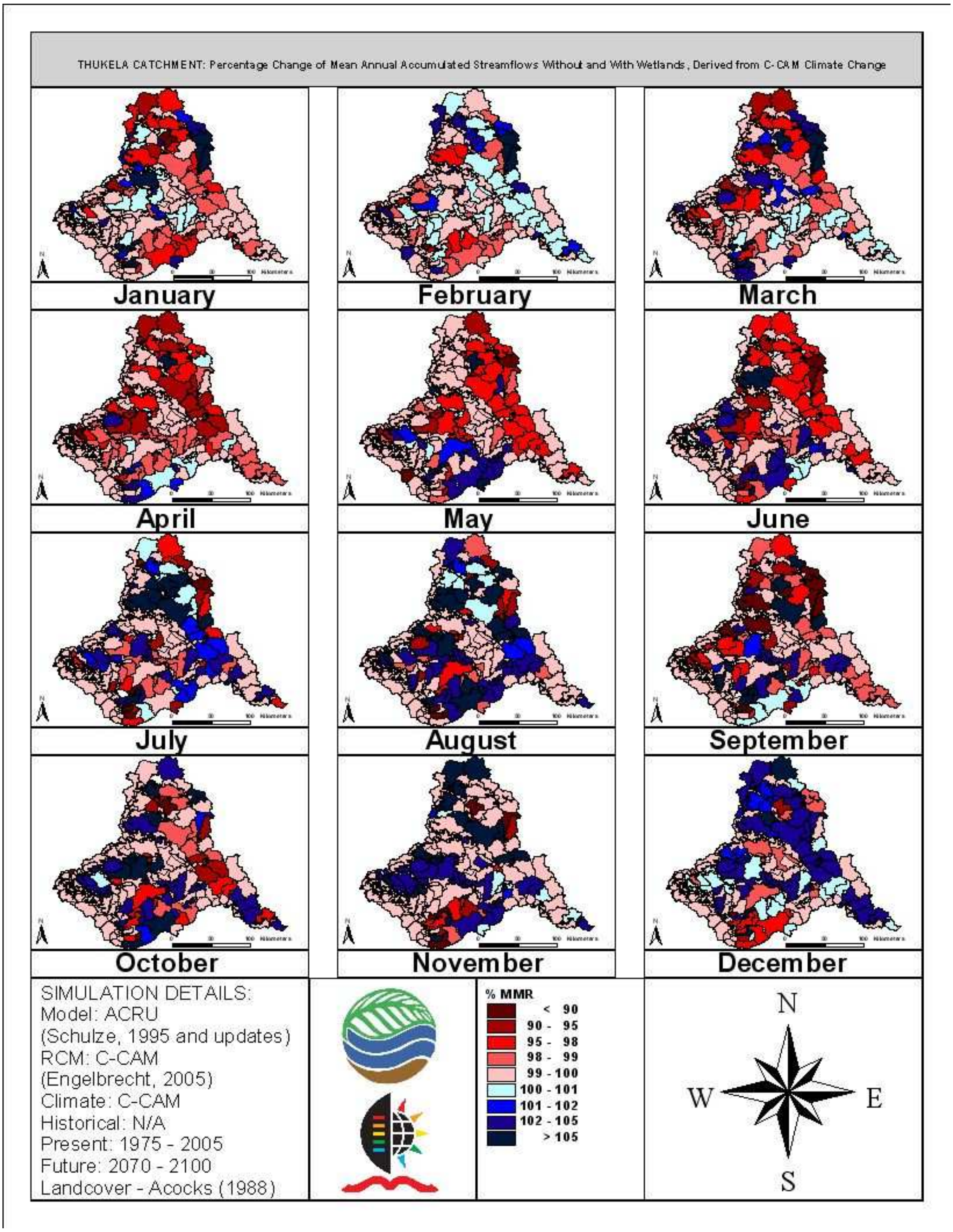
*** NOTE *** "Kilometers" is spelled as such in the figure as a result of the ArcView 3.2 software

Figure 8.17 Percentage change of future to present mean monthly accumulated streamflows for the Thukela catchment, without wetlands, derived from C-CAM



* **NOTE** * "Kilometers" is spelled as such in the figure as a result of the ArcView 3.2 software

Figure 8.18 Percentage change between future and present mean monthly accumulated streamflows for the Thukela catchment, with wetlands, derived from C-CAM



*** NOTE *** "Kilometers" is spelled as such in the figure as a result of the ArcView 3.2 software

Figure 8.19 Percentage change between future and present mean monthly accumulated streamflows for the Thukela catchment as a result of the inclusion of wetlands, derived from C-CAM

In interpreting **Figure 8.12**, i.e. the percentage change (derived from C-CAM) of future to present mean annual precipitation for the Thukela catchment, it may be seen that the Drakensberg mountain area in the west of the catchment is projected to experience either small increases (light blue shading) or decreases (light red shading) in MAP. The percentage change of MAP from future to present is projected to become progressively larger (increases in MAP) as one proceeds eastward across the Thukela catchment.

Figures 8.13 and **8.14**, which illustrate the percentage change of future to present mean annual accumulated streamflows, without and with wetlands, both show the same trend, which has a distinct latitudinal boundary splitting the northern and southern portions of the Thukela catchment. The northern portion of the Thukela catchment is projected by C-CAM to generally experience increased mean annual accumulated streamflows into the future (100 % +), according to C-CAM scenarios. Conversely, the southern section of the Thukela catchment is projected to generally experience a decrease in mean annual accumulated streamflows (< 50 - 100 %). This split between the northern and southern regions could have impacts on potable water supply, agriculture (changes in the growing season and available irrigation water) and the ecological environment (through changes in flow regimes, freshette timing and other flow related triggers).

A further observation when viewing **Figures 8.13** and **8.14** is the similarity between the two maps. Only minor differences between the two figures are visible to the eye. This small difference between the two sets of results on annual streamflows, i.e. without and with wetlands respectively, indicates that the effects of this climate change scenario markedly outweighs the impacts of wetlands on flows. Hence, on the basis of results using the C-CAM climate scenarios, climate change impacts on overall annual streamflow changes appear to be far more significant than the impacts of wetlands *per se*. In **Figure 8.15**, it is observed that the overall impact of wetlands on hydrological responses under conditions of climate change (from the single C-CAM scenario) was very small on an annual basis (< 1%). This further corroborates the conclusion that the impacts of the climate change scenarios markedly outweigh the impacts of wetlands on the same hydrological responses (i.e. streamflow) in the same catchment (Thukela).

Figure 8.16 illustrates varying percentage changes of future to present mean monthly precipitation (MMP) throughout a year. The trends seem to generally follow the following:

- October – January, and also the dry month of July, generally exhibit a decrease in MMP between future and present C-CAM scenarios, while
- February – September, excluding July, generally experience an increase in MMP between future and present C-CAM scenarios.

In addition to the above two points, the five months illustrating a general decrease in MMP appear to have an east to west gradation, with the direction of change variable. The remaining seven months, generally showing an increase in MMP, depict a north to south gradation, which is especially dominant in May, June and September. This is likely to have impacts on the distribution and timing of changes in streamflows.

Figures 8.17 and **8.18** illustrate a similar trend to that discussed for **Figures 8.13** and **8.14**, *viz.*, that there are only minor differences in monthly streamflow changes between the two simulations, i.e. without and with wetlands, respectively. Again, this shows that the impact of climate change using C-CAM outputs as inputs to the *ACRU* Model has a more pronounced effect on the hydrological responses than the wetlands *per se*. Further to this, both maps show a similar future wetting in the north of the Thukela catchment, whereas the south of the catchment appears to be generally drier in the future (January being the only exception to this statement). **Figure 8.19** further illustrates the trends described above, with wetlands having only a small impact (5 – 10%) on hydrological responses when compared to impacts of a climate change scenario. **Figures 8.15** and **8.19** further confirm the increased impact observed at a monthly time scale as opposed to an annual timescale.

If one compares the monthly trends illustrated in **Figure 8.16** (MMP), with those shown in **Figures 8.17** (MMR without wetlands) and **8.18** (MMR with wetlands), 10 of the months (February – October and December) show a greater percentage impact in the southern portion of the Thukela catchment in the mean monthly accumulated streamflow than in the mean monthly precipitation. This presents an example of the hydrological cycle amplifying changes in precipitation. In this case the trend shows a decrease in mean monthly accumulated streamflows.

Alternatively, seven months (January, February, July, August and October – December) show a positive trend in the northern portion of the catchment, with the mean monthly accumulated streamflows generally increasing in relation to the percentage change in mean monthly precipitation.

* * * * *

In the first section of this chapter the influence of wetlands on hydrological responses was assessed, at both annual and monthly time scales, for historical climate. While the impact of wetlands on annual streamflow was shown to be relatively small, major impacts occur at the monthly level in regard to attenuation in the wetter months and regulation, evident mainly in the drier months. The second half of the Chapter focussed on the impact of a future climate scenario on hydrological responses from the Thukela catchment, again at annual and monthly time scales, and again without and with wetlands considered. The overriding conclusion from this section was the dominance of climate impacts over those of wetlands by themselves.

The following Chapter provides a conclusion to this study, ending with recommendations for possible future research determined from experiences gained in this study.

9 CONCLUSIONS AND RECOMMENDATIONS

This Chapter is divided into two sub-sections, namely conclusions from the research presented in this dissertation followed by recommendations for possible future research in related fields.

9.1 Conclusions from the Study

The conclusions presented in this sub-section are based on the results and discussion provided in **Chapter 8**.

The re-configured *ACRU* Wetland Routine, based on the author's work in this study, simulates realistic results when assessing impacts of wetlands on catchment hydrological responses, *viz.* flood attenuation in months with high flows and streamflow regulation in months with low flows (cf. **Chapter 8**).

The impact of wetlands on flood attenuation and streamflow regulation is relatively small when assessing historical mean *annual* streamflows (< 5% decrease; cf. **Figure 8.6**). However, the simulated impact on historical mean *monthly* accumulated streamflows clearly shows the flood attenuation and streamflow regulation characteristics of wetlands on catchments hydrological responses (cf. **Figure 8.7**). These results show a decrease in wet season MMR, with an increase in CV% of wet season MMR, and an increase in dry season MMR, with a decrease in CV% of dry season MMR (cf. **Figure 8.9**). The increase in dry season MMR is as a result of previously stored baseflow releases, which manifest themselves later in the season. The increase in wet season CV% of MMR is as a result of the increase in stormflow flashes due to the wetter wetlands soils being unable to infiltrate additional spills onto the wetlands topsoil.

The magnitude of impacts of wetlands on hydrological responses is dependent on the relative volume of streamflow entering the wetland from the catchment upstream in comparison to the area of the wetland relative to that of the upstream catchment (cf. **Chapter 7**). This influence is due to resultant soil water content being higher in cases of small wetlands with large relative inflows. The greater the soil water content is, the lower the amount of wetland spills that can infiltrate into the wetland's soil profile, thus allowing more streamflow to leave the wetland as stormflow. Conversely, if the soils have a higher capacity to infiltrate any wetland channel spills, more water is infiltrated and ultimately stored in the baseflow store, and this water is then released gradually over a longer period (cf. **Chapter 7**).

The impact of wetlands on mean annual accumulated streamflows was a small decrease (< 2%). This minor reduction is hypothesised to be the result of the increased total evaporation in wetlands sub-catchments. The increase in mean annual total evaporation is reinforced by the increases in mean monthly total evaporation, especially for the winter period, as the wetland soils are wetter for longer, and there is increased resultant evapotranspiration (cf. **Figure 8.11**).

The impact of wetlands on mean annual accumulated streamflows for a climate change scenario was negligible (cf. **Figure 8.15**). The minor changes between the mean annual, and then mean monthly, accumulated streamflow results without and with wetlands, derived from C-CAM, indicate that the impacts of a climate change scenario on the hydrological responses of the Thukela catchment is dominant when compared to the impacts of wetlands *per se*.

From the above discussion, it may be seen that the three main objectives of this study, *viz*:

- A validation of the *ACRU* Model's Wetland Routine to ensure sufficiently realistic results from simulations of wetlands hydrological responses;
- Assessing the impacts of wetlands on catchment hydrological responses on a daily time-step for varying climatic regions and historical climatic conditions, i.e. impacts in a wetter region vs. a drier region, and impacts in a wetter year vs. a drier year, using daily time-step hydrological simulation modelling; and
- Assessing the impacts of wetlands on catchment hydrological responses for climate change scenarios when using output from a single Regional Climate Model (RCM) as a case study,

have been met successfully.

In conclusion, the *ACRU* Wetland Routine simulated the impacts of wetlands on hydrological responses in the Thukela catchment under varying climatic conditions and provided realistic results, showing both flood attenuation and streamflow regulation of accumulated streamflows (cf. **Chapters 7** and **8**). This analysis of the potential impacts that wetlands have on a hydrological system can be extended. In light of that, some recommendations for possible future research follow in the final section of this Chapter.

9.2 Recommendations for Possible Future Research Based on the Findings of this Study

The broad recommendations provided below are based on the experiences gained by the author whilst undertaking this study.

- The *ACRU* Model Wetland Routine should be further refined to enable it to simulate the open water component of wetlands and to simulate groundwater-surface water interactions more explicitly.
- In light of assumptions made to the *ACRU* Model Wetland Routine during this study, further verifications against a gauged wetland catchment should be undertaken to assess the validity of the magnitude of flood attenuation and streamflow regulation simulated by the *ACRU* Model Wetland Routine in its current revised configuration.
- Further studies on wetlands effects on flood attenuation should be undertaken by invoking the Peak Discharge routine within the *ACRU* Model. This would enable the assessment of changes to flood peak flows, including individual event flood hydrographs, by calculating peak discharge, including routing of flood hydrographs to downstream sub-catchments, and assessing the impact of wetlands on a range of return period flood peaks. This could be used to determine a relationship between the wetland area and the capacity of a wetland to attenuate peak flows.
- Simulation of sediment transport through a catchment network, including wetlands, should be undertaken to assess impacts of wetlands on sediment trapping. This could be undertaken within the *ACRU* Model using the Sediment Yield routine linked with flow routing and with hydrographs generated during the peak discharge calculations. This could be used, *inter alia*, to assess how the upstream wetlands could reduce sediment depositions in downstream reservoirs, or how the removal of upstream wetlands from a catchment system would affect the sedimentation rate in reservoirs. This is no trivial task, however.

- Outputs from wetlands hydrological simulations should be used to assess how wetlands affect water quality on a catchment scale. Examples of water quality parameters that could be assessed include agricultural nutrients (such as nitrates, phosphates and potassium), heavy metals, organic pollutants and water temperature. Again, this would be no trivial task.
- The concept of depression storage in flood attenuation should be addressed in future.
- The impacts of wetlands on a catchment, with respect to the small decreases in mean annual streamflows and the changes in monthly accumulated streamflow variability (as illustrated in the results of this study), could affect the water resources yield of a catchment system and thus impact on assurance of supply from existing and future water resource supply systems. By using outputs from hydrological simulations without and with wetlands, as inputs into the Water Resources Yield Model, for example, yield analyses could be undertaken to determine the impact of wetlands on water resources yields.
- Finally, in regard to climate change studies, the use of outputs from multiple GCMs could confirm the findings in this study made from a single climate change scenario, and thereby reduce some of the uncertainties regarding effects of climate change on hydrological responses from wetlands.

10 REFERENCES

Acocks, J.P.H. 1988. Veld Types of Southern Africa. Botanical Research Institute, Pretoria, RSA. *Botanical Survey of South Africa Memoirs,* Vol 57, pp 146.

Applegate, A.D. 1991. ArcView 3.2a. Environmental Research Institute, Inc.

Appleton, C.C. 2003. Alien and Invasive Freshwater Gastropoda in South Africa. *African Journal of Aquatic Science*, 28, 69 - 81.

Arnell, N. 1996. *Global Warming, River Flows and Water Resources*. Water Science Series. Wiley, Chichester, UK.

Arnell, N. 2002. *Hydrology and Global Environmental Change.* Pearson, Essex, UK.

Barichievy, K.R. 2005. Wetland Functioning: A Hydrological Perspective. Unpublished Honours Project, School of Bioresource Engineering and Environmental Hydrology, University of KwaZulu-Natal, Pietermartizburg, South Africa.

Barichievy, K.R. and Schulze, R.E. 2010. Results 4: Time Series Analyses of Water Temperatures with Climate Change in the Thukela Catchment Using the ECHAM5/MPI-OM General Circulation Model. *In:* Schulze, R.E., Hewitson, B.C., Barichievy, K.R., Tadross, M.A., Kunz, R.P., Horan, M.J.C. and Lumsden, T.G. *Methodological Approaches to Assessing Eco-Hydrological Responses to Climate Change in South Africa*. Water Research Commission, Pretoria, RSA, WRC Report 1562/1/10. Chapter 14, 169 - 191.

Begg, G. 2001. The Values and Benefits of Wetlands. [Internet]. http://www.nctwr.org.au/ publications/valueandbenefits.html#storage. Available from: Bergant, K., Bogataj, L. K. and Trdan, S. 2006. Uncertainties in modelling of climate change impact in future: An example of onion thrips (*Thrips tabaci* Lindeman) in Slovenia. *Ecological Modelling*, 194, 244 - 255.

Bester, C. 2003. School of Applied Environmental Sciences, University of KwaZulu-Natal. Soil Scientist. Personal Communication, Soil Science 314 Lecture Notes, Pietermaritzburg, RSA.

Beven, K.J. 2001. *Rainfall - Runoff Modelling*. Wiley, Chichester, UK. pp 306.

Bezuidenhout, C.N. 2005. Development and Evaluation of Model Based Operational Yield Forecasts in the South African Sugar Industry. PhD Thesis, University of KwaZulu-Natal, School of Bioresources and Environmental Hydrology, Pietermaritzburg, RSA. pp 137.

Breen, C.M., Kotze, D.C., Klug, J.R., Darroch, M.A.G. and Oellermann, R.G. 1994. Wetland Preservation Valuation and Management Practices Applied to Wetlands. Water Reseach Commission, Pretoria, RSA. WRC Report No 501/5/94.

Brugnach, M., van der Keur, P., Henriksen, H.J. and Mysiak, J. (Editors) 2009. *Uncertainty in Adaptive Water Management: Concepts and Guidelines*. Prepared under contract from the European Commission, Integrated Project in PRIORITY 6.3 Global Change and Ecosystems in the 6th EU Framework Programme. University of Osnabrück, Institute of Environmental Systems Research, Osnabrück, Germany.

Carter, V., Bedinger, M.S., Novitzki, R.P. and Wilen, W.O. 1978. Water Resources and Wetlands. *In*: Greeson, P.E., Clark, J.R. and Clark, J.E. (Editors) *Wetland Functions and Values: The State of Understanding*. American Water Resources Association, Minneapolis, Minnesota USA.

Cavè, L., Beekman, H. and Weaver, J. 2003. The Impact of Climate Change on Groundwater Resources. *In:* Schulze R. E. (Editor) *The Thukela Dialogue: Managing Water Related Issues on Climate Variability and Climate Change in South Africa*. DWC-Report no. DWCSSO-01. pp 99.

Chapman, R.A. 1990. Determination and Modelling of Evapotranspiration from Wetlands. Unpublished MSc dissertation, Department of Agricultural Engineering, University of Natal, Pietermaritzburg, RSA.

Chow, V.T. 1986. *Handbook of Applied Hydrology*. McGraw-Hill, New York, USA.

Colvin, C., Ellery, W., Conrad, J.E., Chevallier, L., Le Maitre, D. and Nel, J. 2005. Case Studies of Aquifer Dependent Ecosystems in South Africa. *Australian Journal of Botany*, 54, 181 - 192.

Cowan, G.I. 1995. *Wetlands of South Africa*. Department of Environmental Affairs and Tourism, Pretoria. RSA.

Cowardin, L.M., Carter, V., Golet, F.C. and LaRoe, E.T. 1979. *Classification of Wetlands and Deepwater Habitats of the United States*. U.S. Department of the Interior, Fish and Wildlife Service, Washington, D.C. Jamestown, ND.

Dent, M.C., Lynch, S.D. and Schulze, R.E. 1989. Mapping Mean Annual and other Rainfall Statistics over Southern Africa. Water Research Commission, Pretoria, RSA. Report 109/1/89. pp 198 + appendices.

Donkin, A.D. 1994. An Investigation into the Hydrology of the Ntabamhlope Wetland with Particular Reference to the Estimation of Total Evaporation, .Unpublished Masters dissertation, Department of Agricultural Engineering, University of Natal, Pietermaritzburg, RSA.

Duever, M.J. 1988. Hydrologic Processes for Models of Freshwater Wetlands. *In:* Mitsch, W.J., Straskraba, M. and Jorgensen, S.E. (Editors). *Wetland Modelling*. Elsevier Publishing, New York. 9 - 41.

Eagleson, P.S. 1983. Some Problems of Parameterization of Land Surface Heat and Moisture Fluxes. *Report to the Fourth Session of the Joint Scientific Committee*, Venice, Italy. World Meteorological Organisation, Geneva, Switzerland. 77 - 97.

Ellery, W., Grenfell, M., Grenfell, S., Kotze, D., McCarthy, T. S., Tooth, S., Grundling, P. L., Bechedahl, H., Le Maitre, D., Ramsay, L. 2009. WET-Origins: Controls on the Distribution and Dynamics of Wetlands in South Africa. WRC Report TT 334/09.

Engelbrecht, F. 2005. Simulations of Climate and Climate Change over Southern and Tropical Africa with the Conformal-Cubic Atmospheric Model. *In:* Schulze, R.E. (Editor) *Climate Change and Water Resources in Southern Africa: Studies on Scenarios, Impacts, Vulnerabilities and Adaptation.* Water Research Commission, Pretoria, RSA, WRC Report 1430/1/05. Chapter 4, 57 - 74.

Falkenmark, M. and Lannerstad, M. 2004. Consumptive Water Use to Feed Humanity - Curing a Blind Spot. *Hydrology and Earth System Sciences Discussions*, 1, 7 - 40.

Faulkner, S.P. and Richardson, C.J. 1989. Physical and Chemical Characteristics of Freshwater Wetland Soils. *In*: Hammer, D.A. (Editor) *Constructed Wetlands for Wastewater Treatment: Municipal, Industrial and Agricultural*. Lewis Publishers, USA. 41 - 72.

Finlayson, M. and Moser, M. 1991. *Wetlands*. International Waterfowl and Wetlands Research Bureau. Toucan Books Limited, London, UK.

Giorgi, F., Diffenbaugh, N.S., Gao, X.J., Coppola, E., Dash, S.K., Frumento, O., Rauscher, S.A., Remedio, A., Seidou Sanda, I., Steiner, A., Sylla, B. and Zakey, A.S. 2008. The Regional Climate Change Hyper-Matrix Framework. *EOS*, 89, 445 - 446.

Hammer, D.A. and Bastian, R.K. 1989. Wetland Ecosystems: Natural Water Purifiers? *In*: Hammer, D.A. (Editor) *Constructed Wetlands for Wastewater Treatment: Municipal, Industrial and Agricultural*. Lewis Publishers, USA. 5 - 19.

Hargreaves, G.H. and Samani, Z.A. 1985. Reference Crop Evapotranspiration from Temperature. *Transactions of the American Society of Agricultural Engineers*, 1, 96 - 99.

Hewitson, B., Tadross, M. and Jack, C. 2005. Climate Change Scenarios: Conceptual Foundations, Large Scale Forcing, Uncertainty and the Climate Context. *In:* Schulze, R.E. (Editor) *Climate Change and Water Resources in Southern Africa: Studies on Scenarios, Impacts, Vulnerabilities and Adaptation.* Water Research Commission, Pretoria, RSA, WRC Report 1430/1/05. Chapter 2, 21 - 38.

Hjulstrom, F. 1935. Studies of the Morphological Activities of Rivers as Illustrated by the River Fyris. *Bulletin of the Geological Institute, University of Uppsala*, Sweden, 25, 221 - 527.

Horan, M.J.C. 2006. University of KwaZulu-Natal, School of Bioresourses Engineering and Environmental Hydrology. Personal Communication.

Horan, M.J.C. 2010. University of KwaZulu-Natal, School of Bioresourses Engineering and Environmental Hydrology. Personal Communication.

Hulme, M.E. 1996. Climate Change and Southern Africa: An Exploration of Some Potential Impacts and Implications in the SADC Region. WWF International, Norwich, UK. 39 - 49.

IPCC, 2001. Summary for Policy Makers: Climate Change 2001: The Scientific Basis. Contribution of the Working For Water Group 1 to the Third Assessment Report of the Intergovernmental Panel on Climate Change. *In*: Houghton, J.T., Ding, Y., Griggs, D.J., Noguer, M., van den Linden, P.J., Dai, X., Mashell, K. and Johnson, C.A. (Editors), 75 - 105, 235 - 343, 381 - 417, 533 - 591, and 877 - 971. Cambridge University Press, Cambridge, UK and New York, NY, USA.

IPCC, 2007. Climate Change 2007: The Physical Science Basis. Contribution of Working Group I to the Fourth Assessment Report of the Intergovernmental Panel on Climate Change. Solomon, S., Quin, D., Manning, M., Chen, Z., Marquis, M., Averyt, K.B., Tignor, M. and Miller, H.L. (Editors). Cambridge University Press, Cambridge, UK. pp 996.

Jones, J. A. A., Changming, L., Ming-Ko, W. and Hsiang-Te, K. (Editors) 1996. Regional Hydrological Resonse to Climate Change. The GeoJournal Library, 38. Kluwer Academic Publishers, Dordrecht, The Netherlands. pp. 429.

Jones, P. 2009. Global Temperature Record. [Internet]. Available from: http://www.cru.uea.ac.uk/cru/info/warming/ [Accessed 17 August, 2009].

Kabat, P., Schulze, R.E., Hellmuth, M.E. and Veraart, J.A. 2003. Coping with Impacts of Climate Variability and Climate Change in Water Management: A Scoping Paper. DWC-Report no. DWCSSO-01 International Secretariat of the Dialogue on Water and Climate, Wageningen, Netherlands. 6 - 10.

Kadlec, R.H. and Kadlec, J.A. 1978. Wetlands and Water Quality. *In*: Greeson, P.E., Clark, J.R., and Clarck, J.E. (Editors) *Wetland Functions and Values: The State of Our Understanding*. American Water Resources Association, Minneapolis. 436 - 456.

Knoesen, D., Schulze, R., Pringle, C., Summerton, M., Dickens, C. and Kunz, R. 2009. *Water for the Future: Impacts of Cliamte Change on Water Resources in the Orange-Senqu River Basin.* Report to NeWater, a project funded under the Sixth Research Framework of the European Union. Institute of Natural Resources, Pietermaritzburg, South Africa.

Kotze, D.C., Marneweck, G.C., Batchelor, A.L., Lindley, D.S. and Collins, N.B. 2005. WET-EcoServices: A Technique for Rapidly Assessing Ecosystems Services Supplied by Wetlands. Department of Tourism, Environmental and Economic Affairs, Free State, RSA.

Kurukulasuria, P. and Rosenthal, S. 2003. Climate Change and Agriculture: A Review of Impacts and Adaptions. Yale University, USA. 1 - 9.

Land Type Survey Staff, 1986. *Memoirs, Agricultural Natural Resources.* Department of Agriculture and Water Supply, Pretoria, RSA.

Lumsden, T.G., Jewitt, G. and Schulze, R.E. 2003. Modelling the Impacts of Land Cover and Land Management Practices on Runoff Responses. Water Research Commission, Pretoria, RSA. Report No. 1015/1/03. pp 80.

Lymberopoulos, G. and James, C.S. 1993. Modelling Flood Attenuation in Wetlands. *In*: *Proceedings of the Sixth South African National Hydrological Symposium*, Pietermaritzburg, RSA.

Lynch, S.D. 2004. Development of a Raster Database of Annual, Monthly and Daily Rainfall for Southern Africa. Water Research Commission, Pretoria, RSA. WRC Report 1156/1/04. pp 78.

Marble, A.D. 1992. *A Guide to Wetland Functional Design*. Lewis Publishers, London, UK.

McColl, S., Hicks, J., Craig, L. and Shortreed, J. 2000. *Environmental Health Risk Management: A Primer for Canadians*. Institute for Risk Research, University of Waterloo, Ontario, Canada.

McGregor, J.L. 1997. Regional Climate Modelling. *Meteorology and Atmospheric Physics*, 63, 105 - 117.

McGregor, J.L. and Dix, M.R. 2001. The CSIRO Conformal-Ccubic Atmospheric GCM. *In:* Hodnett, P.F. (Editor). *IUTAM Symposium on Advances in Mathematical Modelling of Atmosphere and Ocean Dynamics.* Kluwer, Dordrecht, Netherlands, 197 - 202.

Michaud, J.P. 2005. At Home with Wetlands: A Landowner's Guide. Washington State Department of Ecology. [Internet]. Ecology Publication #90-31, http://www.ecy.wa.gov/programs/sea/pubs/90031/#RTFToC7.

Mitsch, W.J. and Gosselink, J.G. 1986. *Wetlands*. Von Nostrand Reinhold, New York, USA.

Mitsch, W.J. and Gosselink, J.G. 1993. *Wetlands (2nd Ed.)*. Von Nostrand Reinhold, New York, USA.

Mucina, L. and Rutherford, M.C. (Editors) 2006. *The Vegetation of South Africa, Lesotho and Swaziland.* South African National Biodiversity Institute, Pretoria, RSA.

Mukheibir, P. and Sparks, D. 2003. Water Resource Management and Climate Change in South Africa: Visions, Driving Factors and Sustainable Development Indicators. Energy and Development Research Centre, University of Cape Town, Cape Town, RSA. 1 - 16.

Newson, M. 2009. *Land, Water and Development: Sustainable and Adaptive Management of Rivers*. Routledge, London, UK. pp 441.

NWA, 1998. National Water Act, Act 36 of 1998. Department of Water Affairs, Republic of South Africa. pp 200.

O'Brien, N.A.L. and Motts, W.S. 1980. Hydrogeological Evaluation of Wetland Basins for Land-Use Planning. *Water Resources Bulletin*, 16, 785 - 789.

Ogawa, H. and Male, J.W. 1986. Simulating the Flood Mitigation Role of Wetlands. *Journal of Water Resource Planning Management - ASCE*, 112, 114 - 128.

Otieno, F.A.O. and Ochieng, G.M.M. 2004. Water Management Tools as a Means of Averting a Possible Water Scarcity in South Africa by the Year 2025. *Water SA*, 30, 120 - 124.

Perks, L.A. 2001. Refinement of Modelling Tools to Assess Potential Agrohydrological Impacts of Climate Change in South Africa. Unpublished PhD Thesis., University of Natal, School of Bioresources Engineering and Environmental Hydrology, Pietermaritzburg, RSA. pp 463.

Pike, A. 1988. The Use of Temperature-Based Evaporation Equations in Southern Africa. Unpublished BSc (Honours) Seminar. University of Natal, Pietermaritzburg, RSA, Department of Agricultural Engineering. pp 31.

Pike, A. and Schulze, R.E. 1995. AUTOSOIL Version 3: A Soils Decision Support System for South African Soils. University of Natal, Pietermaritzburg, RSA, Department of Agricultural Engineering.

RAMSAR. 2002. Climate Change and Wetlands: Impacts, Adaptation and Mitigation. Ramsar COP8 - DOC. 11.

Renwick, J.A., Katzfey, K.C., McGregor, J.L. and Nguyen, K.C. 1999. On regional model simulations of climate change over New Zealand. *Weather and Climate*, 19, 3 - 14.

Rosenzweig, C. and Hillel, D. 1995. Potential Impacts of Climate Change on Agriculture and Food Supply. *Consequences*, 1, 1 - 16.

Rowlands, I.H. (Editor), 1998. *Climate Change Cooperation in Southern Africa*. Earthscan Publications Limited, London, UK. 1 - 8.

Rowlston, W. 2003. Water Policy Makers' Needs on Climate Variability and Climate Change in South Africa. *In:* Schulze, R.E. (Editor). *The Thukela Dialogue: Managing Water Related Issues on Climate Variability and Climate Change in South Africa., Proceedings of the DWC Thukela Dialogue Workshop.* University of Natal, Pietermaritzburg, RSA, School of Bioresources Engineering and Environmental Hydrology, ACRUcons Report, 44.

Rutherford, M.C., O'Callaghan, M., Powrie, L.W., Hurford, J.L. and Schulze, R.E. 1996. Predicting Survival in New Environments Through Analytical GIS Application. *Environmental Software*, 11, 113 - 121.

Sather, J. and Smith, R. 1984. *An Overview of Major Wetland Functions and Values*. U.S. Fish and Wildlife Service Publication. Washington DC, USA.

Schulze, R.E. 1979. *Hydrology and Water Resources of the Drakensberg*. Natal Town and Regional Planning Commission, Pietermaritzburg, RSA. pp 179.

Schulze, R.E. 1987. Developing and Testing of Models for Assessment of Impact of Land Use and Management on the Quality and Quantity of river runoff. *In*: Thornton, J.A. (Editor) *Proceedings, Symposium on Modelling of Aquatic Systems*. Ecosystems Programme, FRD-CSIR, Pretoria, RSA. Occasional Report, 24, 27 - 46.

Schulze, R.E. 1995. *Hydrology and Agrohydrology: A Text to Accompany the ACRU 3.00 Agrohydrological Modelling System*. Water Research Commission, Pretoria. RSA. Report TT70/95. pp 552.

Schulze, R.E. 1997. *South African Atlas of Agrohydrology and Climatology*. Water Research Commission, Pretoria, RSA. WRC Report TT82/96. pp 276.

Schulze, R.E. 2001a. Hydrological Responses at River Basin Scales. University of Natal, Pietermaritzburg, School of Bioresources Engineering and Environmental Hydrology. *ACRU*cons Report, 35. pp 102.

Schulze, R.E. 2001b. Thoughts on Models and Modelling for Integrated Water Resources Management: Some background Concepts, Basic Premises and Model Requirements. *Proceedings, 10th South African National Hydrology Symposium*. University of Natal, Pietermaritzburg, RSA, School of Bioresources Engineering and Environmental Hydrology. pp 25 (on CD-Rom).

Schulze, R.E. 2003a. On Models and Modelling for Integrated Water Resources Management : *In:* Schulze, R. E. (Editor) *Modelling as a Tool in Integrated Water Resources management: Conceptual Issues and Case Study Applications*. Water Research Commission, Pretoria, RSA, WRC Report 749/1/02, Chapter 2, 20 - 46.

Schulze, R.E. 2003b. The Thukela Dialogue: Managing Water Related Issues on Climate Variability and Climate Change in South Africa. *Proceedings of the DWC Thukela Dialogue Workshop*. University of Natal, Pietermaritzburg, RSA, School of Bioresources Engineering and Environmental Hydrology, *ACRU*cons Report, 44.

Schulze, R.E. 2004a. River Basin Responses to Global Change and Anthropogenic Impacts. *In:* Kabat, P., Claussen, M., Dirmeyer, P.A., Gash, J.H.C., Bravo de Guenni, L., Meybeck, M., Pielke, R.A. Snr., Vörösmarty, C.J., Hutjes, R.W.A. and Lütkemeier, S. (Editors)

Vegetation, Water, Humans and the Climate. A New Perspective on an Interactive System. Springer-Verlag, Heidelberg, Germany. Chapter D.3, 339 - 374.

Schulze, R.E. 2004b. Determination of baseline land cover variables for application in assessing land use impacts on hydrological responses in South Africa. *In:* Schulze, R. E. and Pike, A. (Editors) *Development and Evaluation of an Installed Modelling System.* Water Research Commission, Pretoria, RSA, WRC Report No. 1155/1/04. Chapter 3, 37 - 50.

Schulze, R.E. 2005a. Looking Into the Future: Why Research Impacts of Possible Climate Change on Hydrological Responses in Southern Africa? *In:* Schulze, R.E. (Editor) *Climate Change and Water Resources in Southern Africa: Studies on Scenarios, Impacts and Adaptaion.* Water Research Commision, Pretoria, RSA. WRC 1430/1/05. Chapter 1, 1-1 to 1-15.

Schulze, R.E. 2005b. School of Bioresources Engineering and Environmental Hydrology, University of KwaZulu-Natal, Pietermaritzburg, RSA. Personal Communication, May 2005.

Schulze, R.E. 2005c. Selection of a Suitable Agrohydrological Model for Climate Change Impact Studies over Southern Africa. *In:* Schulze, R.E. (Editor) *Climate Change and Water Resources in Southern Africa: Studies on Scenarios, Impacts, Vulnerabilities and Adaptation.* Water Research Commission, Pretoria, RSA, WRC Report 1430/1/05. Chapter 7, 95 - 110.

Schulze, R.E. 2005d. Setting the Scene: The Current Hydroclimatic "Landscape" in Southern Africa. *In:* Schulze, R.E. (Editor) *Climate Change and Water Resources in Southern Africa: Studies on Scenarios, Impacts, Vulnerabilities and Adaptation.* Water Research Commission, Pretoria, RSA, WRC Report 1430/1/05. Chapter 6, 83 - 94.

Schulze, R.E. 2010. Methods 3: Modelling Impacts of Climate Change on the Hydrological System: Model Requirements, Selection of the *ACRU* Model, its Attributes and Computations of Major State Variables and Outputs. *In:* Schulze, R.E., Hewitson, B.C., Barichievy, K.R., Tadross, M.A.., Kunz, R.P., Horan, M.J.C. and Lumsden, T.G. *Methodological Approaches to Assessing Eco-Hydrological Responses to Climate Change in South Africa*. Water Research Commission, Pretoria, RSA, WRC Report 1562/1/10. Chapter 8, 75 - 88.

Schulze, R.E., Dlamini, D.J.M. and Horan, M.J.C. 2005a. The Thukela Catchment: Physical and Socio-Economic Background. *In:* Schulze, R.E. (Editor) *Climate Change and Water Resources in Southern Africa: Studies on Scenarios, Impacts, Vulnerabilities and Adaptation*. Water Research Commission, Pretoria, RSA, WRC Report 1430/1/05. Chapter 10, 191 - 209.

Schulze, R.E., Hallowes, L.A., Horan, M.J.C., Lumsden, T.G., Pike, A., Thornton-Dibb, S. and Warburton, M. 2007. *South African Quaternary Catchments Database*. *In:* Schulze, R.E. (Editor). 2007. *South African Atlas of Climatology and Agrohydrology*. Water Research Commission, Pretoria, RSA, WRC Report 1489/1/06, Section 2.3.

Schulze, R.E., Horan, M.J.C. and Gray, R.P. 2005b. Sensitivity Studies of Hydrological Responses in the Thukela Catchment to Spatial and Temporal Representations When Using a Baseline and a Projected Future Climate Scenario. *In:* Schulze, R.E. *(Editor) Climate Change and Water Resources in Southern Africa: Studies on Scenarios, Impacts, Vulnerabilities and Adaptation*. Water Research Commission, Pretoria, RSA, WRC Report 1430/1/05. Chapter 11, 211 - 232.

Schulze, R.E., Lumsden, T.G., Horan, M.J.C., Warburton, M. and Maharaj, M. 2005c. An Assessment of Impacts of Climate Change on Agrohydrological Responses Over Southern Africa. *In:* Schulze, R.E. (Editor) *Climate Change and Water Resources in Southern Africa: Studies on Scenarios, Impacts, Vulnerabilities and Adaptation*. Water Research Commission, Pretoria, RSA, WRC Report 1430/1/05. Chapter 9, 141 - 189.

Schulze, R.E., Lumsden, T.G., Horan, M.J.C., Warburton, M. and Maharaj, M. 2005d. An Assessment of Impacts of Climate Change and Water Resources in Southern Africa. *In:* Schulze, R.E. (*Editor*) *Climate Change and Water Resources in Southern Africa: Studies on Scenarios, Impacts, Vulnerabilities and Adaptation*. Water Research Commission, Pretoria, RSA. WRC Report 1430/1/05. Chapter 9, 9 - 13.

Schulze, R.E. and Maharaj, M. 2004. *Development of a Database of Gridded Daily Temperatures for Southern Africa*. Water Research Commission, Pretoria, RSA. WRC Report 1156/2/04. pp 83.

Schulze, R.E. and Perks, L.A. 2000. Assessment of the Impact of Climate Change on Hydrology and Water resources in South Africa. *ACRU*cons Report 33. Report to the South African Country Studies for Climate Change Programme. School of Bioresources Engineering and Environmental Hydrology, University of Natal, Pietermaritzburg, South Africa. pp 70.

Schulze, R.E. and Smithers, J.C. 2003. The *ACRU* Modelling System as of 2002 : Background, Concepts, Structure, Output, Typical Applications and Operations. *In:* Schulze, R. E. *(Editor) Modelling as a Tool in Integrated Water Resources management: Conceptual Issues and Case Study Applications*. Water Research Commision, Pretoria, RSA, WRC Report 749/1/02. Chapter 2, 47 - 83.

Segius, L., Cappelaere, B., Milesi, G., Peugeot, C., Massuel, S. and Favreau, G. 2004. Simulated Impacts of Climate Change and Land-Clearing on Runoff from a Small Sahelian Catchment. *Hydrological Processes*, 18, 3401 - 3413.

Smith, J.B., Klein, J.T. and Huq, S. (Editors) 2004. *Climate Change, Adaptive Capacity and Development*. Imperial College Press, London, UK.

Smithers, J.C. 1991. Modelling the Ntabamhlope Wetland: Initial Results. *Agricultural Engineering in South Africa*, 23, 440 - 449.

Smithers, J.C. and Schulze, R.E. 1995. *ACRU Agrohydrological Modelling System: User Manual Version 3.00*. Water Research Commission Pretoria, RSA. WRC Report TT70/95.

Smithers, J.C. and Schulze, R.E. 2003. Extreme Hydrological Events in South Africa: Approaches to, and Questions we Should be Asking In, Design Engineering. *In:* Schulze, R.E. (Editor). *The Thukela Dialogue: Managing Water Related Issues on Climate Variability and Climate Change in South Africa., Proceedings of the DWC Thukela Dialogue Workshop.* University of Natal, Pietermaritzburg, RSA, School of Bioresources Engineering and Environmental Hydrology, *ACRU*cons Report, 44.

Suter, G.W. 1993. *Ecological Risk Assessment*. Lewis Publishers, Michigan WI, USA. pp 538.

Van Dam, J.C. (Editor), 1999. *Impacts of Climate Change and Climate Variability on Hydrological Regimes*. Cambridge University Press, Cambridge, UK.

Von der Heyden, C.J. 2004. The Hydrology and Hydrogeology of Dambos: A Review. *Progress in Physical Geography*, 28, 4, 1 - 21.

Warburton, M.L. 2005. *Detection of Changes in Temperature and Streamflow Parameters over Southern Africa*. MSc Dissertation, University of KwaZulu-Natal, Pietermaritzburg, RSA, School of Bioresources Engineering and Environmental Hydrology. pp 156.

Warburton, M.L. and Schulze, R.E. 2005. Detection of Climate Change: A Review of Literature on Changes in Temperature, Precipitation and Streamflow, on Detection Methods and Data Problems. *In:* Schulze, R.E. *(Editor) Climate Change and Water Resources in Southern Africa: Studies on Scenarios, Impacts, Vulnerabilities and Adaptation.* Water Research Commission, Pretoria, RSA, WRC Report 1430/1/05. Chapter 15, 257 - 274.

Warburton, M.L., Schulze, R.E., Jewitt, G.P.W., Graham, L.P. and Yang, W. 2011. Dynamics Between Land Use Change and Climate Change in Three South African Catchments: Hydrological Responses. University of KwaZulu-Natal, Pietermaritzburg, RSA, School of Bioresources Engineering and Environmental Hydrology. Paper in preparation.

Yen, B.C. 2002. System and Component Uncertainties in Water Resources. *In*: Bogardi, J.J. and Kundzewicz, Z.W. (Editors) *Risk, Reliability, Uncertainty, and Robustness of Water Resources Systems.*, Cambridge University Press, Cambridge, UK. Chapter 15, 133 - 142.