PROJECTED IMPACTS OF CLIMATE CHANGE ON WATER QUALITY CONSTITUENTS AND IMPLICATIONS FOR ADAPTIVE MANAGEMENT

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DISSERTATION

Submitted in fulfilment of the academic requirements
for the degree of Master in Science in Hydrology in the School of Agricultural, Earth and
Environmental Sciences, University of KwaZulu-Natal.

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ABSTRACT

The past few decades have seen, amongst other topical environmental issues, increased concerns regarding the imminent threat of global warming and the consequential impacts of climate change on environmental, social and economic systems. Numerous groundbreaking studies conducted independently and cooperatively have provided abundant and conclusive evidence that global climates are changing and that these changes will almost certainly impact natural and socio-economic systems. Increased global change pressures, which include, *inter alia*, climate change, have increased concerns over the supply of adequate quality freshwater. There is an inadequate body of knowledge pertaining to linking basic hydrological processes which drive water quality (WQ) variability with projected climate change. Incorporating such research into policy development and governance with the intention of developing adaptive WQ management strategies is also overlooked. Thus, the aim of this study was the assessment of projected climate change impacts on selected WQ constituents in the context of agricultural non-point source pollution and the development of the necessary adaptation strategies that can be incorporated into WQ management, policy development and governance. This assessment was carried out in the form of a case study in the Mkabela Catchment near Wartburg in KwaZulu-Natal, South Africa. The research involved applying climate change projections derived from seven downscaled Global Circulation Models (GCMs) used in the Fourth Intergovernmental Panel on Climate Change (IPCC) Assessment Report, in the *ACRU*-NPS water quality model to assess the potential impacts on selected water quality constituents (*viz*. sediment, nitrogen and phosphorus). Results indicated positive correlations between WQ related impacts and contaminant migration as generated from agricultural fertilizer applications. *ACRU*-NPS simulations indicated increases in runoff and associated changes in WQ variable generation and migration from upstream sources in response to downscaled GCM projections. However, there was limited agreement found between the simulations derived from the various downscaled GCM projections in regard to the magnitude and direction (*i.e.* percent changes between present and the future) of these changes in WQ variables. The rainfall distribution analyses conducted on a daily time-step resolution for each selected GCM also showed limited consistency between the GCM projections regarding rainfall changes between the present and the future. The implication was that since hydrological and climate change modelling can inform adaptive catchment WQ management, these forms of modelling can be used to explore future

adaptation under climate change. However, adaptation to climate change in water quality management and policy development is going to require approaches that fully recognise the uncertainties presented by climate change and the associated modelling thereof. It was also considered crucial that equal attention be given to both climate change and natural variability, in order to ensure that adaptation strategies remain robust and effective under conditions of climate change and its respective uncertainties.

As the candidate's supervisor I have/~~have not~~ approved this dissertation for submission.

Signed: _____ Name: Professor G.P.W Jewitt Date: 4/1/203

ACKNOWLEDGEMENTS

PREFACE

The experimental work described in this dissertation was carried out in the Centre for Water Resources Research, University of KwaZulu-Natal, from January 2011 to November 2012, under the supervision of Professor G.P.W. Jewitt, Mr. T.G. Lumsden, Mrs. S. Stuart-Hill and Professor S.A.L Lorentz.
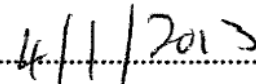
These studies represent original work by the author and have not otherwise been submitted in any form for any degree or diploma to any other tertiary institution. Where use has been made of the work of others it is duly acknowledged in the text.

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Professor G.P.W Jewitt (Supervisor)

COLLEGE OF AGRICULTURE, ENGINEERING AND SCIENCE

DECLARATION 1 –PLAGIARISM

I, Simphiwe Innocent Ngcobo, declare that:

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2. This dissertation has not been submitted for any degree or examination at any other University.

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DECLARATION 2 –PUBLICATIONS

DETAILS OF CONTRIBUTION TO PUBLICATIONS that form part and/or include research presented in this dissertation (including publications in preparation, submitted, *in press* and published and gives details of the contribution of each author to the experimental work and writing of each publication).

Publication 1 – Chapter 3

Ngcobo, S.I., Jewitt, G.P.W. and Lorentz, S.A. In preparation. Potential Impacts of Climate Change on Nutrient and Sediment Transfer Processes.

Research for this publication was conducted by S.I. Ngcobo with technical advice from G.P.W Jewitt and S.A. Lorentz. This publication was authored in its entirety by S.I. Ngcobo and all data tables, graphs and figures were produced by the same, unless otherwise referenced in the text of the paper. Editing and advice regarding conceptual and theoretical congruency of the paper was provided by G.P.W Jewitt and S.A. Lorentz.

Publication 2 – Chapter 4

Ngcobo, S.I., Lumsden, T.G., G.P.W. Jewitt, Lorentz, S.A. and J.K. Kollongei. In preparation. Projected Impacts of Climate Change and Mitigating Effects of a Perennial Wetland on Selected Water Quality Constituents in the Mkabela Catchment, South Africa.

Research for this publication was conducted by S.I. Ngcobo with technical advice from T.G. Lumsden and S.A. Lorentz. This publication was authored in its entirety by S.I. Ngcobo and all data tables, graphs and figures were produced by the same, unless otherwise referenced in the text of the paper. The maps and observed water quality datasets were provided by S.A. Lorentz and J.K. Kollongei, who also assisted in the configuration of the *ACRU*-NPS model. The observed climate datasets were sourced from the Centre for Water Resources Research databases and from the South African Sugarcane Research Institute (SASRI). Similarly, the climate change datasets, sourced from downscaled Global Circulation Models, used in this paper were supplied the CSIR and by CSAG (UCT). All climate and water quality datasets

used in this paper were prepared and analysed by S.I. Ngcobo. Editing and results interpretation advice was provided by T.G. Lumsden and G.P.W. Jewitt.

Publication 3 – Chapter 5

Ngcobo, S.I., Jewitt, G.P.W. and Lumsden, T.G. In preparation. Assessing Potential Changes in Daily Rainfall Distribution under Climate Change for the Mkabela Catchment, South Africa.

Research for this publication was conducted by S.I. Ngcobo with technical advice from G.P.W. Jewitt and T.G. Lumsden. This publication was authored in its entirety by S.I. Ngcobo and all data tables, graphs and figures were produced by the same, unless otherwise referenced in the text of the paper. The observed climate datasets were sourced from the Centre for Water Resources Research databases and from the South African Sugarcane Research Institute. The climate change datasets, sourced from downscaled Global Circulation Models, used in this paper were provided by the CSIR and by CSAG. All climate datasets used in this paper were prepared and analysed by S.I. Ngcobo. Editing and results interpretation advice was provided by G.P.W. Jewitt and T.G. Lumsden.

Publication 4 – Chapter 6

Ngcobo, S.I., Jewitt, G.P.W., Stuart-Hill, S and Lumsden, T.G. In preparation. Towards a Framework for the Adaptive Management of Water Quality Under Climate Change

Research for this publication was conducted by S.I. Ngcobo with technical advice from G.P.W Jewitt, S. Stuart-Hill and T.G. Lumsden. This publication was authored in its entirety by S.I. Ngcobo and all data tables, graphs and figures were produced by the same, unless otherwise referenced in the text of the paper. The observed climate datasets were sourced from the Centre for Water Resources Research databases and from the South African Sugar Research Institute. Similarly, the climate change datasets, sourced from downscaled Global Circulation Models, used in this paper were provided by the CSIR and by CSAG. All climate datasets used in this paper were prepared and analysed by S.I. Ngcobo. Editing and data interpretation advice was provided by G.P.W Jewitt, T.G. Lumsden and S. Stuart-Hill.

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CHAPTER ONE

Introduction and Background

1. INTRODUCTION AND BACKGROUND

The past few decades have seen, amongst other topical environmental issues, increased concerns regarding the imminent threat of global warming and the consequential impacts of climate change on environmental, social and economic systems. Numerous groundbreaking studies conducted independently (*e.g.* Houghton, 1994; Pittock, 2009) or co-operatively (*e.g.* IPCC, 2001; IPCC, 2007; Bates *et al.,* 2008; UNESCO, 2009) have provided abundant and conclusive evidence that global climates are changing and that these changes will almost certainly impact natural and socio-economic systems. Based on observational records and climate projections, these and other studies have shown that natural systems are highly vulnerable to climate change and have the potential to experience severe climate change related impacts (Low, 2005; Schulze, 2005; Nelson *et al.,* 2007). Of these systems, freshwater resources are considered to be the most exposed and highly vulnerable to climate change, considering the direct relationships that exist between prevailing climatic regimes and the hydrological cycle (Figure 1.1). Climate change is anticipated to significantly alter the behaviour of the hydrological cycle (Kundzewicz *et al.,* 2007) and, in many instances, climate change related increases in the frequency of extreme meteorological events (floods, droughts and heavy short-duration rainfall events) are already being observed (*e.g.* Rosenzweig *et al.,* 2001; Walther *et al.,* 2002; Parmesan and Yohe, 2003; Beniston *et al.,* 2007). This presents clear, pragmatic and direct implications for water resources management, particularly where water quantity and quality management is concerned (Mimikou *et al.,* 2000; Delpla *et al.,* 2011). Considering the importance of water for environmental, social and economic systems, it becomes evident that detailing the impacts of climate change on water resources, in both water quantity and quality contexts, is an important research endeavour.

As alluded to in the preceding discussion, living organisms and natural ecosystems have an inherent and profound dependence on freshwater for their basic survival (Falkenmark *et al.,* 1998; UNESCO, 2009). The requirement of a constant supply of water of adequate quality has been shown to be an important prerequisite for the continued functioning of both natural and socio-economic systems (Gleick, 2006; Nangia *et al.*, 2008). Water quality, in its broadest sense, may be defined as the physicochemical state of a water body at any given spatial or temporal scale (Novotny, 2003; Brainwood *et al.,* 2004).

High water temperatures, low oxygen concentration levels, high salinity, sedimentation and high nutrient status (from non-point sources of pollution), bacteria and pathogens and the proliferation of micro-pollutants, represent some of the most critical challenges associated with water quality deterioration (Van Vliet and Zwolsman, 2008; Delpla *et al.,* 2009).
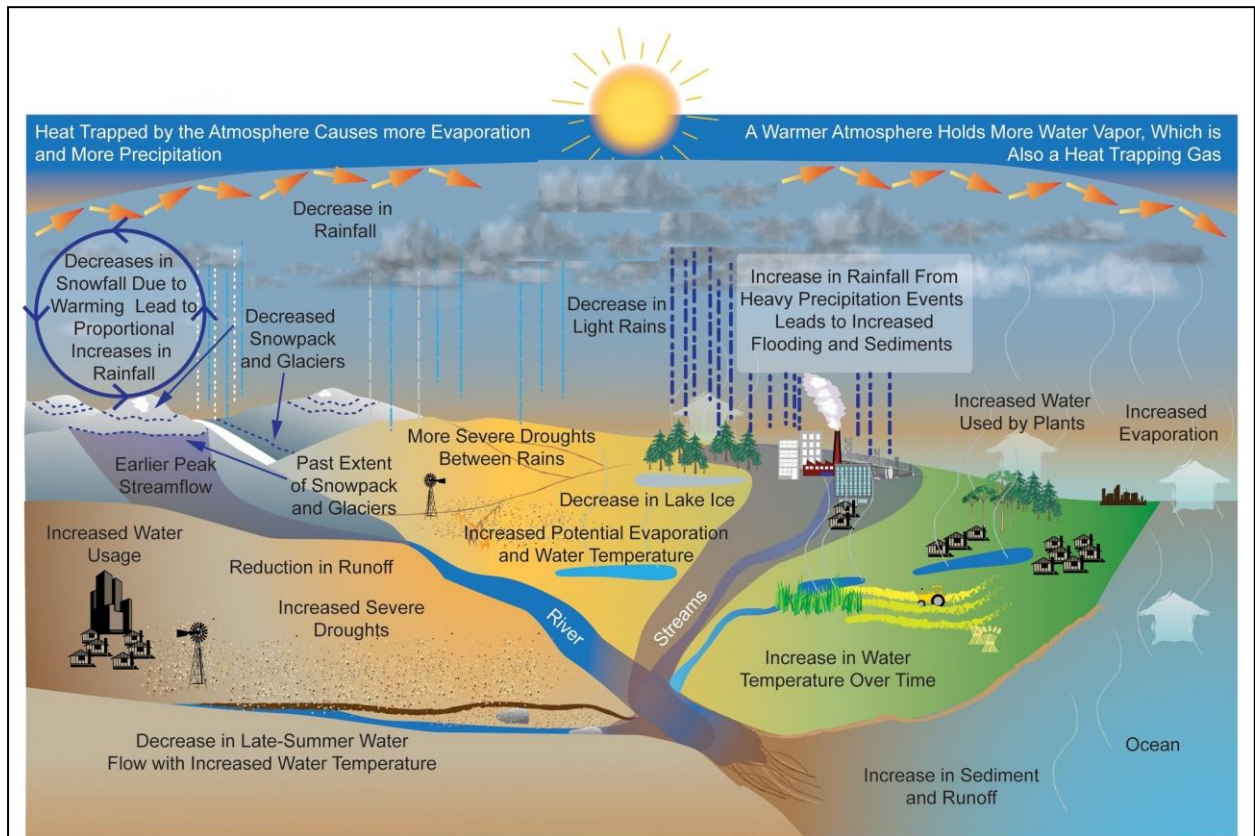
Figure 1.1   Relationships and feedbacks between the hydrological cycle and local climatic regimes. The impacts of climate change on water quality and quantity-related processes are also indicated in this Figure (Source: National Oceanic and Atmospheric Administration, 2009)

Although often considered separately, water quality and quantity are closely-related concepts concerned with water availability (Gleick, 2006; UNESCO, 2009). During extreme hydrological events, too much water (*e.g.* floods) or too little water (*e.g.* droughts) may cause water quality deterioration by serving as a conduit for the transport of pathogens or pollutants and affecting the dilution capabilities of rivers and other water bodies (Mimikou *et al.,* 2000; Tsujimura, 2004).

It therefore becomes apparent that water quantity problems can initiate quality problems and, alternatively, water quality problems can affect supply via increases in wastewater toxicity and the consequent reductions in readily utilisable water (Turton, 2008).

Being part of the current mosaic of global change, climate change could aggravate the water quality problems highlighted in the preceding discussion, by instigating rapid changes in the natural hydrological environment (Kundzewicz *et al.,* 2007). Thus, the quantity and quality of water required to meet human and environmental demands can also be expected to be affected by climate change (IPCC, 2001; IPCC, 2007; Bates *et al.,* 2008; Vairavamoorthy *et al.,* 2008; Pittock, 2009; UNESCO, 2009). South Africa is a country characterized by a high risk hydroclimatic environment (Schulze, 2005; Schulze *et al.*, 2005) and is expected to experience the impacts of severe climate change, which will be manifested through an amplification of the variability of an already highly variable local hydrological cycle (Schulze, 2005). This will have far-reaching direct and indirect impacts on water supply reliability, food production, health, energy and environmental sustainability for this country (Descheemaeker *et al.,* 2010). Therefore, for transitional countries such as South Africa, climate change is anticipated to compound the complexity of socio-economic development and environmental sustainability in an already complex water resources management background (UNESCO, 2009; Descheemaeker *et al.,* 2010; Mahjouri and Ardestani, 2011).

In many respects, South Africa has highly incisive water resources management policies (*e.g.* the internationally acclaimed National Water Act (36) of 1998 and the National Water Resource Quality Monitoring Programme), which are intended to explicitly uphold the integrity and highlight the paramount importance of water in this semi-arid country (DWAF, 1998; DWAF, 2004; Turton, 2008). However, South Africa is characterized by marked social and economic inequalities and, using water as a specific point of departure and a key strategic resource vital to social and economic development, these inequalities render many societal groups vulnerable to the anticipated impacts of climate change (Stuart-Hill and Schulze, 2010). This vulnerability is not limited to societal groups only, but also applies to natural and artificial water resource systems such as wetlands, dams, riparian buffers, wastewater treatment plants and water distribution infrastructure. Füssel (2006) considers vulnerability as "the degree to which a system is likely to experience harm due to exposure to a hazard" (Figure 1.2).

Therefore, depending on the extent of development inherent to a particular system, different societal groups or artificial systems may be expected to exhibit different levels of exposure, and thus, vulnerability, to the impacts of climate change (Füssel, 2006; Haines *et al.,* 2006; Ionescu *et al.,* 2009). This consequently implies that the ability and/or preparedness to adapt (*i.e.* adaptive capacity) to climate change will also differ according to the level of exposure characteristic of a particular societal group or system (Figure 1.2). Adaptive capacity will, therefore, limit engagement in adaptation action; *i.e.* adaptation is a function of adaptive capacity. Pittock (2009) defines adaptation as "a response to change that seeks to minimize adverse effects and maximize any benefits". Bates *et al.* (2008) consider adaptive capacity as the capability of an individual, group, community or country to effectively implement adaptation measures. Increased engagement in adaptation *action* is, therefore, *more likely* to occur with increased adaptive *capacity*. The concepts of adaptation, adaptive capacity and vulnerability will be expanded on in Chapter 2.
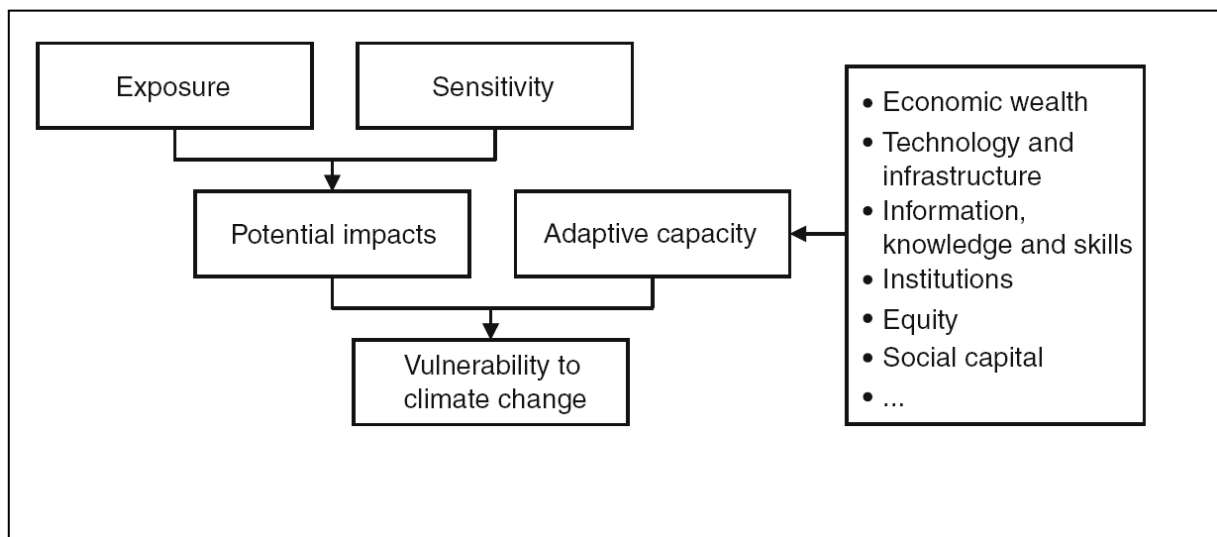
Figure 1.2   Schematic conceptualization of vulnerability to climate change as a function of adaptive capacity, sensitivity and exposure (Ionescu *et al.,* 2009).

The above discussion illustrates the necessity of building adaptive capacity in order to enhance engagement in adaptation action. Although substantial work has been done in both the fields of climate change-related adaptation (*e.g.* IPCC, 2001; Paavola and Adger, 2005; Adger and Vincent, 2005; IPCC, 2007; Vincent, 2007; Paavola, 2008; Firman *et al.,* 2011) and water quality management, based on catchment processes (Viney *et al.,* 2000; Novotny, 2003; Van Der Perk, 2006), there is an apparent disconnect between the two.

In other words, there is an inadequate body of knowledge pertaining to linking basic hydrological processes, which drive water quality (WQ) variability, with climate change projections; but also, there is a well-recognized, fundamental and applied need to detail the effects of a changing climate on catchment-wide nutrient and sediment transfer dynamics (Edwards and Withers, 2008; Han *et al.,* 2010; Shrestha *et al.,* 2012). Incorporating that understanding into policy development and governance, with the intention of developing adaptive WQ management strategies, is largely absent. Establishing these links is a critical step in building adaptive capacity and adequate adaptation activities and strategies.

Thus, it is important that the primary processes and parameters, which influence fluvial water quality, are understood. In the scope of this study, these are:

a) processes influencing sediment generation, transport (or transfer) and deposition, such as erosion, runoff, detachment, entrainment and settling, and

b) processes influencing nitrogen and phosphorus generation, transport and deposition, such as dissolution, leaching, runoff, adsorption and desorption.

Building on this understanding, the potential impacts of climate change on water quality through, for example, possible increases in the severity or frequency of extreme events can then be assessed with the help of water quality modelling and climate change projections. This is particularly important in the context of extreme events, whose potential on sediment, nitrogen (N) and phosphorus (P) dynamics have not been adequately assessed in South Africa and it is especially relevant in the predominantly agricultural and rural catchments of this country, where non-point source pollution (NPS) is widespread. The mechanisms that govern sediment yield, N and P distribution are anticipated to change under conditions of increased temperatures and altered rainfall patterns. However, the magnitude and direction of such changes in nutrients and sediment distribution are still not fully understood.

In summary, biophysical or catchment processes and linkages that are essential in understanding how NPS pollution and land use change influence water quality, have not been reconciled with adaptive water resources management, both in management and in policy and governance structures. Therefore, the assessment of the links between biophysical processes, climate change and adaptation is of significant importance in the pursuit of reducing vulnerabilities and building adaptive capacity.

In this study, an assessment of projected climate change impacts on selected WQ constituents is performed using the Mkabela Catchment (near Wartburg) in KwaZulu-Natal, South Africa as a case study. Through the research presented in this study, it is motivated that ascertaining the links between biophysical WQ related processes and adaptive water resources management should be a key focus in efforts to adapt to the projected impacts of climate change.

1.1 Aims and Objectives

The aims and objectives of this study relating to water quality, climate change and adaptation are as follows:

a) Review processes of sediment yield, nitrogen and phosphorus transport in local (agricultural) catchments and highlight the factors that influence the generation and transport of these water quality variables within local catchments.

b) Develop the ability to model the projected impacts of climate change on sediment yield, nitrogen and phosphorus in the Mkabela Catchment using the *ACRU*-NPS water quality model by incorporating projected changes in driver variables and, where necessary, modifying the variables based on expert opinion.

c) Assess the vulnerability and potential for adaptation with regard to water quality under conditions of climate change for the entire Mkabela Catchment and develop an adaptive water quality management framework based in this analysis.

d) Use the results from the above exercises to develop (or suggest) appropriate adaptation strategies relevant to the Mkabela Catchment and make recommendations for policy development and governance at local and regional levels.

1.2 Overview of Dissertation Structure

This dissertation consists of 7 (seven) chapters including 4 (four) chapters written as "publishable" papers and submitted according to the guidelines provided by the College of Agriculture, Engineering and Science of the University of KwaZulu-Natal. Chapters 1 and 2 form the introductory and literature review components of this study.

These chapters present the rationale behind this study (Chapter 1) and highlight the global and local state of research related to, *inter alia*, climate change, water quality management, vulnerability, adaptation and adaptive water resources management (Chapter 2).

Chapter 3 is the first "publishable" paper that specifically details the potential impacts of climate change on nutrient and sediment transfer processes. This paper follows a sequence, which initially describes the typical behaviour of each pollutant (*i.e.* nitrogen, phosphorus and sediment) across the landscape and follows with the association of those behaviours with generally accepted climate change projections. Although this paper is a literature review, it was written as a publishable paper and is in no way related or linked to the literature review presented in Chapter 2.

The second paper (Chapter 4), details the simulations performed in this study, using the *ACRU*-NPS water quality (WQ) module of the physical-conceptual agrohydrological *ACRU* model. This paper essentially presents the simulations performed, using historical data and data derived from seven downscaled Global Circulation Models (GCMs). These historical and GCM derived datasets were used as input in the *ACRU*-NPS model. The climate change projections described by the downscaled GCMs were used to assess impacts on selected WQ constituents (*viz.* sediment, nitrogen and phosphorus). The historical datasets were used to assess the influence of hydraulic controls (dams, wetlands and riparian buffers) on the downstream translocation of WQ constituents. The relative impacts of climate change on the selected WQ constituents were assessed by observing changes between two time periods *viz.* the present (1971-1990) and the future (2046-2065). The verification of the *ACRU*-NPS model is also presented in this paper.

The third paper (Chapter 5) is a detailed study of the potential changes in daily rainfall distribution under climate change for all the seven downscaled GCMs considered. It was deemed necessary to fully detail the probable changes in daily rainfall distribution between the present and the future as described by the selected downscaled GCM projections, in order to provide further insight into the simulation results presented in Chapter 4. This paper, therefore, presents a description of the projected changes in rainfall frequency by assessing changes in pre-defined rainfall event intervals and rainfall conservation statistics. Also

assessed in this paper are the relative changes in raindays and rainless days between the future and the present as described by the individual downscaled GCM projections.

In the fourth paper (Chapter 6), the application of the *ACRU*-NPS model simulations is presented to suggest or recommend appropriate adaptation strategies specifically geared towards WQ management, policy development and governance. This paper links the biophysical aspects of water quality management and the projected impacts of climate change on nutrients and sediment transfer processes detailed in the first and second papers (Chapters 3 and 4) with the more applied aspects of adaptive water quality management, policy development and governance, which are both presented in Chapter 2. Also presented in this paper is a framework designed to be applied in adaptive water quality management.

Chapter 7 presents the overall synthesis, as well as recommendations for further study. It is important to note that since this dissertation was written in paper format, some overlap may exist between the seven chapters, particularly amongst the four papers, as they are intended to be submitted to different local and international journal publications.

CHAPTER TWO

Literature Review

2. LITERATURE REVIEW

2.1 Vulnerability and Adaptation in the Context of Climate Change and Water Quality Management

2.1.1 Introduction

The climate change discussion has seen the formalised concepts of vulnerability and adaptation become profoundly embedded in the global change agenda. This is not surprising, as climate change is anticipated to induce pressures on aspects such as environmental health, food security and economic stability through its projected impacts on water resource systems (IPCC, 2001; Droogers and Aerts, 2005; IPCC, 2007; Heltberg *et al.,* 2009). It is widely acknowledged that the impacts of climate change will affect all water users (IPCC, 2001; Schulze, 2005; Haines *et al.,* 2006; Sadoff and Muller, 2007; IPCC, 2007; Bates *et al.,* 2008) with the spectrum of affected users being determined by their individual ability to effectively respond to such changes (Paavola, 2008). In the context of adaptation and vulnerability, the developing world is considered to have more limited adaptation capacity and to be highly vulnerable to the impacts of climate change (Desanker and Magadza, 2001; IPCC, 2001; Paavola and Adger, 2005). This is, as Heltberg *et al.* (2009) and Paavola and Adger (2005) indicate, due to the high dependence on climate-sensitive economic sectors, geographic exposure and low-income status characteristic of the developing world. Consequently, the most adverse climate change related impacts are anticipated to occur in the developing regions of the world, of which South Africa is a part of (Bates *et al.,* 2008). This serves to highlight the importance of understanding vulnerability and adaptation concepts for application in the most sensitive (*i.e.* highly exposed and least adaptive) regions of the world, including South Africa. Based on the above discussion, the aim of this section is, therefore, to define "vulnerability" and "adaptation" in the contexts of both climate change and water quality management.

2.1.2   Vulnerability and Adaptive Capacity as Determinants of Adaptation

The Oxford English Dictionary defines vulnerability as "exposure to the risk of being attacked or harmed, either physically or emotionally". Ionescu *et al.* (2009) consider vulnerability a relative property, denoting the vulnerability *of* something *to* something. In a more socio-ecological sense, vulnerability refers to the "degree to which a system is likely to experience harm due to exposure to a hazard" (Füssel, 2006; Ionescu *et al.,* 2009). Application of this term in climate change studies has been subject to much debate and scrutiny owing to its apparent ambiguity (Ionescu *et al.,* 2009). This ambiguity stems from the interdisciplinary nature of the term which has seen its application in ecology, agriculture, medicine, socio-economic development, food security and global change (Füssel, 2006; Füssel and Klein, 2006; Haines *et al.,* 2006). The Third Assessment Report (TAR) of the Intergovernmental Panel on Climate Change (IPCC) provided the now widely-accepted definition of vulnerability in the context of climate change by stating that, "vulnerability is the degree to which a system is susceptible to, or unable to cope with, adverse effects of climate change, including climate variability and extremes. Vulnerability is a function of the character, magnitude and rate of climate variation to which a system is exposed, its sensitivity and its adaptive capacity" (IPCC, 2001). However, as indicated in Figure 2.1, this definition is not only limited to climate change as an 'external disturbance', but can also include disturbances such as disease prevalence, access to human and financial capital and innate system sensitivity.

The collective insinuation of the definitions presented above, is that systems which are significantly exposed to adverse external factors that may bring harm to their normal functioning, are at high risk of collapsing and are therefore highly vulnerable. In South Africa and Africa as a whole, the general consensus regarding vulnerability is that the resilience of socio-economic, infrastructural and environmental systems to external disturbances such as climate change is very limited, making them highly vulnerable (Reid and Vogel, 2006; Sadoff and Muller, 2007; Paavola and Adger, 2005). Access to resources, aging infrastructure, stagnant economic growth and development, widespread environmental degradation, weakening social patterns and lack of access to information are some of the factors which have been identified as components that determine vulnerability in many African nations, including South Africa (Reid and Vogel, 2006; Gbetibouo *et al.,* 2010)

(Figure 2.1). Owing to the relative nature of vulnerability (Ionescu *et al.,* 2009), it is important that the vulnerabilities of various economic sectors, governmental groups and individuals be differentiated accordingly (Stuart-Hill and Schulze, 2010). This is an important consideration in the development of tailored and locally relevant adaptation strategies.

Another critical dimension to this argument also exists, which serves to accentuate two factors *viz*. sensitivity and adaptive capacity, as important aspects that determine the vulnerability of a system. Adaptive capacity or capacity of response refers to "the potential or ability of a system, region or community to adapt to the effects or impacts of climate change" (IPCC, 2001; Gallopìn, 2006; Smit and Wandel, 2006). Systems which have limited response options to cope with the impacts of climate change, are considered to have low adaptive capacity and are therefore considered highly vulnerable to these impacts (Reid and Vogel, 2006). Figure 2.1 presents the concept of vulnerability as a concept that is limited by the adaptive capacity of a system; using, in this case, an agricultural system.
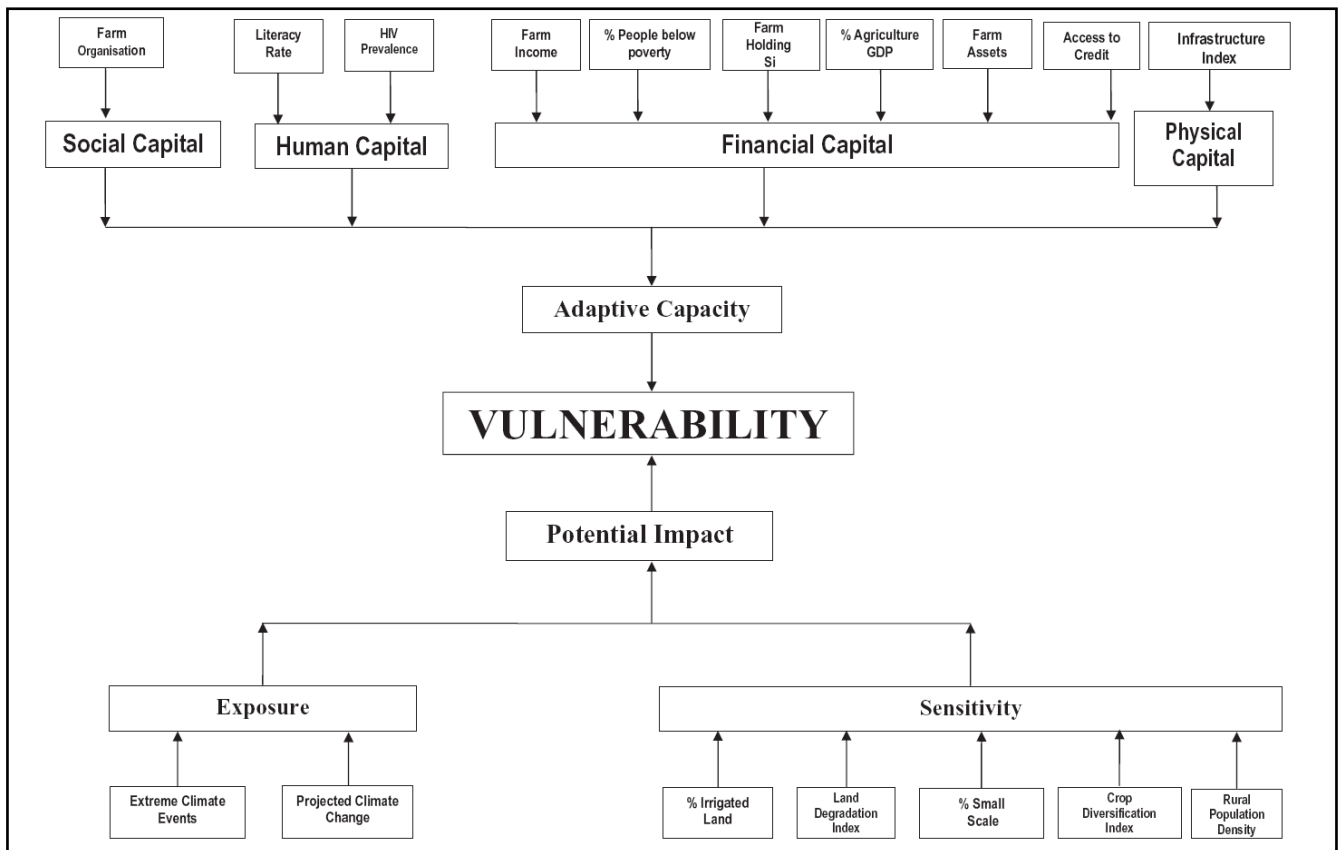
Figure 2.1   Conceptualization of vulnerability to climate change as a function of adaptive capacity and exposure to impacts in an agricultural production system (Gbetibouo *et al.,* 2010).

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As with vulnerability, adaptive capacity differs between individuals, groups, environmental systems, communities and even artificial systems. It is determined by various factors such as initial well-being (economic, physical or otherwise), livelihood resilience, social capital and societal protection (Cannon, 2000; Brooks *et al.,* 2005). Adaptive capacity cannot be easily measured due to the direct connections between socio-economic development, social cohesion, political stability and the level of environmental protection (Reid and Vogel, 2006). This is because of the dynamism of socio-economic and political systems. Therefore, in order to develop appropriate adaptation strategies, it is crucial to initially assess the "state of nature" of a system with regard to the extent of its adaptive capacity and hence vulnerability, in order to locate weaknesses and address these accordingly (Gallopìn, 2006; Smit and Wandel, 2006; Sadoff and Muller, 2007).

To effectively implement adaptation strategies, the ability of society, governance structures and institutions to act collectively is paramount, since adaptation is a dynamic, interdependent initiative (Adger, 2003; Brooks *et al.,* 2005). Not only will this increase the adaptive capacity of the most vulnerable environmental and socio-economic sectors but it might also create much more resilient governance structures that may be flexible enough to adapt to future environmental changes (Brooks *et al.,* 2005; Adger and Vincent, 2005). This will have to be grounded on sound scientific principles that will provide the necessary background critical to decision-making regarding biophysical changes that ultimately affect the economy, society and infrastructure. Consequently, monitoring existing adaptation policy or developing new policies will require constant updates from scientific research to ensure that the appropriate adaptation strategies are developed and updated.

This section has extensively described the meaning of vulnerability, adaptation and adaptive capacity in the context of climate change. However, as mentioned in this discussion, these terms can be ambiguous and can lead to some confusion in their application. Since the focus of this study is on adaptive policy development, adaptive governance *and* adaptive water quality management, the following sections describe the differences in the application of these terms in the aforementioned focus areas.

2.1.3   Vulnerability and Adaptation in Policy Development and Governance

The previous section defined vulnerability as "the degree to which a system is likely to experience harm due to exposure to a hazard" (Füssel, 2006; Ionescu *et al.,* 2009). Adaptive capacity was defined as "the potential or ability of a system, region or community to adapt to the effects or impacts of climate change" (IPCC, 2001; Gallopìn, 2006; Smit and Wandel, 2006). Therefore, by deduction, adaptation may be considered as a response to change which seeks to minimize vulnerability by enhancing adaptive capacity and maximising benefits (Pittock, 2009).

It is also important, at this juncture, to define governance and management in the overall context of this discussion. According to the Oxford English Dictionary, "governance" is essentially the exercise of imposing authority and asserting control and/or influence over the policies and affairs of a state. Management is the direct handling, supervision or control of a state, organization, people or resource. At first glance, the two terms appear to mean the same thing *i.e.* authority and control. However, closer inspection will reveal that they are actually two different activities. Governance can be thought of as the "top line" focus, which addresses the question of *what* task is being attempted to be accomplished while management can be thought of as the "bottom line" focus, addressing the question of *how* to accomplish a particular task. In other words, governance is doing the right things and management is doing things right. In the context of policy development and governance these definitions will be expanded on using, as a backdrop of the discussion, developing countries.

It is a well accepted fact that the long-term, sustainable economic development of developing countries is highly dependent on primary production systems (*e.g.* agriculture, forestry, fishing and mining). The maintenance and advancement of these systems requires efficient and sustainable management of their natural resource base (Barbier *et al.,* 1992). The role of the environment, therefore, as a source of important resources and ecological functions which support economic activity and human welfare needs to be duly recognised and protected. One of the most fundamental tools of environmental protection is the development and promulgation of environmental policies.

Developing countries, such as South Africa, usually have in place highly incisive environmental protection policies intended for the protection of natural resources. For instance, the South African National Water Act (Act 36 of 1998), considered globally as a "progressive, forward-thinking and ambitious Act" (MacKay *et al.*, 2003; Muller, 2002), has as one of its main objectives the protection, development, management and control of the nation's water resources (DWAF, 1998; DWAF, 2004; RSA, 1998; Pienaar and van der Schyff, 2007). Evidently, failure to effectively implement this Act can potentially expose South African water resources to a host of serious problems. Such failure would, in the sense of vulnerability defined above, increase the vulnerability of South African water resources to external disturbances (*e.g.* climate change), thus increasing the vulnerability of local production systems and ultimately, the vulnerability of the local economy.

In certain instances, where environmental policies are ineffectively implemented or are implemented without due monitoring of the implementation process, the potential deterioration or complete destruction of natural resources and ecosystems is facilitated. This essentially amounts to policy failure. Babier *et al.,* (1992) state that policy failure occurs when a policy "under or over corrects for a problem", provided the exact nature of the problem is expressly known and measures are taken to remedy the problem. Under such conditions, the State in their capacity as the legal custodians of the nation's natural resources, may engage in corrective measures that may either be ill-advised or detrimental to the long-term sustainability of natural resources (Huang and Xia, 2001).

Therefore, in the context of policy development and governance, the ability of environmental resources, inclusive of water, to cope with adverse external disturbances will be functions of how well environmental protection policies are formulated by governance structures and how effective management structures are in implementing these policies. Essentially, the more robust, realistic and effective a policy is, the higher the adaptive capacity of the system and the greater the potential for the system to adapt and, resultantly, the less vulnerable the system is to external disturbances. The following section highlights the differences between adaptation in the context of policy development and governance and adaptation in the context of water quality management.

2.1.4   Vulnerability and Adaptation in Water Quality Management

Water quality management and water-centric policy development are, in fact, closely linked focus areas that fall under the banner of water resources management. Effective water quality management requires a sound policy framework informed by well executed environmental studies and research (Brainwood *et al.,* 2004; Nangia *et al.*, 2008), as well as monitoring and evaluation. However, in many instances, there is a significant disconnect between the two. This disconnect can be attributed to a number of reasons including: significant time constraints for detailed catchment scale investigations which inform policy, information is usually disconnected in time, space and function and knowledge cannot be effectively generated from environmental studies, due to the disjointed nature of the information collected (Bennet *et al.*, 2005; Harrison, 2007; Nangia *et al.*, 2008). The result of this is usually the development of inadequate policies, redundant management instruments, inappropriate catchment biophysical process knowledge, missing or inadequate monitoring programs, unclear institutional responsibilities and lack of financing sources (Huang and Xia, 2001; Gourbesville, 2008). This consequently creates an environment where adaptive capacity is undermined and vulnerability is increased, thus limiting the effectiveness of adaptation action.

The current mosaic of global change issues, including climate change and population growth add further complexity to the already complex relationship between policy development and water quality management. With increasing precipitation variability and increased pollutant discharge and transport, particularly under climate change, the requirement for adaptive policy and thus adaptive water quality management has been made even more imperative. It is at this juncture that the importance of catchment scale investigations of pollutant discharge is highlighted, particularly as they ultimately contribute towards informing adaptive management. One of the primary tools used to improve the understanding of the processes controlling the release, fate and transport of pollutants across catchments is water quality modelling (Kadam and Kaluarachchi, 2006).

According to Bormann (2009), water quality models are increasingly used in decision-making despite calculations being fraught with input data errors, model errors and inadequate process knowledge.

While there have been significant improvements in water quality monitoring methods, advances in regional scale water quality modelling remain a priority. Such advances would effectively imply a reduction in vulnerability owing to the implied increase in adaptive capacity and, ultimately, improved adaptive water quality management.

To ensure that adaptive water quality management is as effective as possible, it is highly critical that catchment processes are investigated in a holistic manner which recognises the interactions between people and their physical and biological environment (Bennet *et al.*, 2005; Lynam *et al.,* 2009). Such an approach is critical in linking environmental and socio-economic systems in order to create a broader understanding of sustainability and the integrative nature of water quality management and socio-economic dynamics. Figure 2.1 cited social, human and financial capital as one of the key determinants of adaptive capacity (Gbetibouo *et al.,* 2010). Therefore, by linking environmental and socio-economic systems (social, human and financial capital) a framework is somewhat automatically created, in which the interactions between the two are recognised and adaptive capacity in water quality management is increased. Such a "framework" would effectively be in the form of a policy, legislature or a regulatory arrangement (Gourbesville, 2008).

The main aim of this section was to highlight the differences in the understanding and application of the terms "vulnerability" and "adaptation", in the contexts of both policy development and water quality management. In essence, vulnerability and adaptation in policy development are concerned with how well a particular policy is formulated and implemented such that it effectively protects environmental resources, in order to reduce vulnerability, increase adaptive capacity and allow for effective adaptation. In the context of water quality management, however, vulnerability and adaptation are more concerned with the "end-pipe" factors. While policy development is more concerned with the conceptualization of rules and regulations which govern water quality management, water quality management is more concerned with the actual, physical execution of those rules and regulations. For instance, the monitoring of pollutant discharge from catchments is a physical activity but the requirement for monitoring would be informed by a policy aimed at ensuring that the water quality of receiving waters is protected. In essence, effective and adaptive water quality management relies on effective and adaptive policy development and furthermore, implementation.

Having reviewed the concepts of vulnerability, adaptation and adaptive capacity and highlighted the differences in the terminology and application of these concepts, the following section presents a review of the contemporary issues central to water quality management in the context of South African water resources management. The adaptation and vulnerability concepts detailed in the preceding section will also be factored into the following discussion.

2.2   Contemporary Issues in Water Quality Management

2.2.1   Introduction

Owing to increased socio-economic pressures such as population growth and economic development, the requirement for a constant freshwater supply of adequate quality has been a subject of increased concern over the last few decades (Huang and Xia, 2001; Smeti *et al.,* 2009). In particular, challenges associated with water quality management have received an increasing amount of attention, due to the apparent close alignment of water quality related issues with sustainable development (Ouyang *et al.,* 2006; Mahjouri and Ardestani, 2011). For example, not only is access to safe drinking water considered a basic human right but is also recognised as one of the key Millennium Development Goals (Kundzewicz *et al.,* 2007). Global and local change issues such as population growth, economic development, urban sprawl and land use change have intensified the debate of whether or not the current global freshwater resources status will radically change over the next few decades (Falkenmark and Rockström, 2006; Kundzewicz *et al.,* 2007; UNESCO, 2009).

Further concerns also abound on whether the continued pressure being placed on water resources will lead to a change in water productivity (adequacy of water for productive use) and ultimately a change in agricultural and industrial productivity (Rockström *et al.,* 2003). It is at this water resource availability and water productivity interface that water quality becomes an issue of concern. In order to further clarify this topic, this section presents a brief discussion on contemporary water quality management issues as a basis for adaptive water resources management. The arguments presented in this discussion are generic in both the international and local water resources management contexts.

2.2.2   Water Quality Management in Context

Water quality management, aligned with principles of sustainable development has become increasingly topical in the last few decades (Pegram and Bath, 1995; Turton, 2008; Cook *et al.,* 2009). This has been especially true in South Africa under the current conditions of economic growth and social transformation (Du Toit *et al.,* 2009). One of the reasons for the elevated concern over water quality management is the increased introduction of pollutants in surface water and groundwater through agricultural, urban and industrial activities and the consequential human health concerns (Honisch *et al.,* 2002; Ouyang *et al.,* 2006; Zhang *et al.,* 2009). As alluded to in the introductory section, increased social and economic pressures on water resources provide the sole basis for the deterioration of water quality in many local Catchments. Figure 2.2 illustrates that socio-economic development and the quality of water resources and the environment are all closely-related aspects. If one compartment changes, then by deduction, the other two also change. In effect, the vast majority of problems associated with water quality management are far less of a technological issue than they are social, political, economic and institutional issues (Novotny, 2003). This is especially true in South Africa, considering the capacity to generate ingenuity which this country possesses (Turton, 2008).
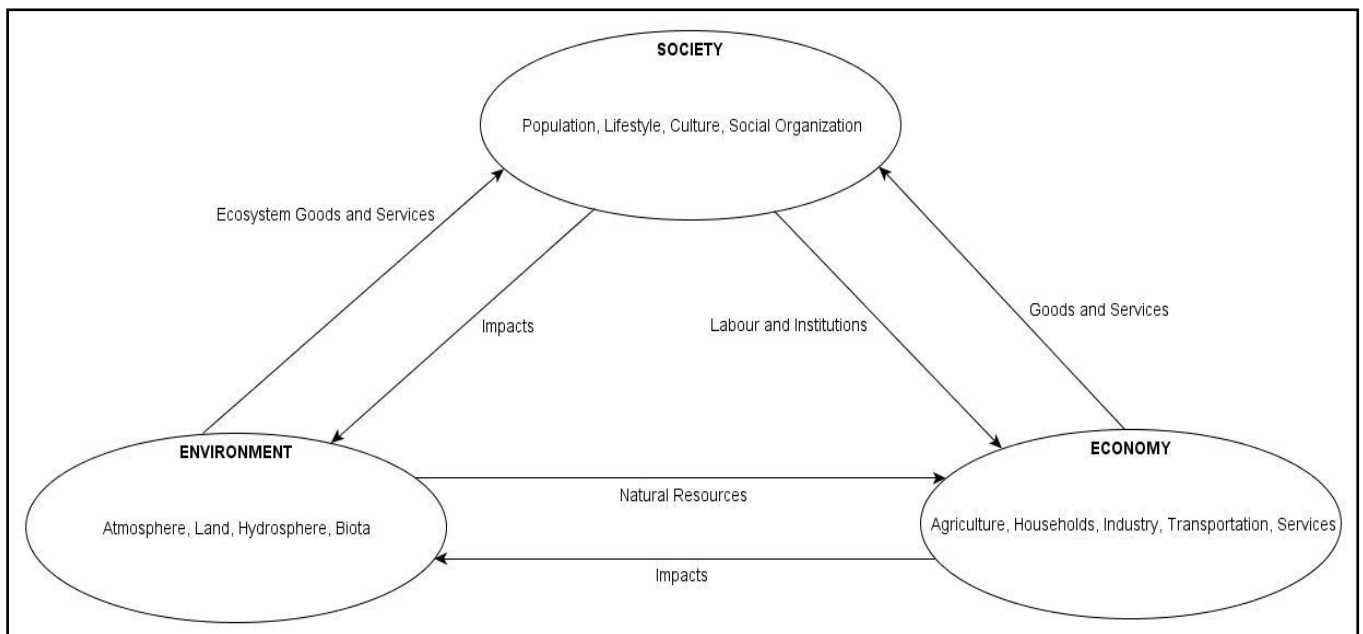
Figure 2.2   Causal chains highlighting socio-economic causes of environmental and water pollution (Novotny, 2003).

Local population growth and economic development have resulted in increased food, fibre, forage and energy demands, which have consequently encouraged the agricultural and commercial production sectors to use increasing amounts of toxic chemicals, soil ameliorants and nutrients to enhance production rates and meet consumer market demands (Foley *et al.,* 2005; Dabrowski *et al.,* 2008; Statistics South Africa, 2009). This consequently leads to the increased introduction of pollutants into the environment through non-point sources (NPS) and increased environmental and human health impact concerns (Foley *et al.,* 2005; Haines *et al.,* 2006; Leigh *et al.,* 2010; Bryan and Kandulu, 2011). Furthermore, the reduced ability of natural ecosystems to provide goods and services such as the regulation and immobilisation of pollutants, results in increased wastewater treatment costs which have undesirable long-term economic implications, especially for developing nations (Jewitt, 2002; Fischlin *et al.,* 2007; Kundzewicz *et al.,* 2007).

Considering the increased human interventions in natural ecosystems in the past century, the currently observed changes in water quality standards are not particularly surprising. Historically, humankind has a long-standing tradition of radically altering vast segments of natural environments in pursuit of economic and social security without necessarily considering the environmental impacts and/or the inevitable feedbacks (Bouma *et al.,* 2002; Pittock, 2009). Nilsson and Renöfält (2008) state that compared to pristine conditions, numerous global rivers, streams and lakes have doubled their nitrogen and phosphorus content as a result of human interventions. The Mgeni Catchment, for example, located in the KwaZulu-Natal Midlands of South Africa, was once a relatively pristine catchment (*i.e.* mid-1800s to early 1900s), with numerous undisturbed ecological regions (Water Research Commission, 2002). Increased urbanisation, agricultural land expansion, population and economic growth and development have led to the alteration and, in some cases, complete destruction of ecosystems and a rapid increase in water pollution, leading to water quality deterioration (Schulze *et al.,* 2004; Turpie *et al.,* 2008; Van Wilgen and Biggs, 2010). This catchment now requires highly incisive water quality management principles, which ensure that freshwater resources are protected and that adequate freshwater standards are maintained (DWAF, 2003).

Providentially, water quality management in this catchment is carried out through intensive monitoring programmes applying principles from the National Water Resource Quality Monitoring Programme, Integrated Water Resources Management (IWRM) principles and water resources modelling tools (DWAF, 2003; DWAF, 2004). This example shows that modern challenges associated with water quality management require not only the reinforcement of established principles, but also the extension of those principles to ensure future sustainable use of water resources (Huang and Xia, 2001; Cook *et al.,* 2009). Furthermore, the importance of information generation and dissemination in water quality management cannot be over-emphasised, since decision-making is highly dependent on relevant and updated information (Chowdary *et al.,* 2004).

Thus, the application of experience-based management, using historical information in conjunction with current information and management systems is an important aspect in local water quality management, since it characterizes adaptive water quality management (Kundzewicz *et al.,* 2007; Bates *et al.,* 2008). The aim of adaptive water quality management is to recognize the impacts of human interventions on freshwater systems and offer novel management ideas, policies and promote institutional commitment to effectively manage water quality issues (Harrison, 2007; Sadoff and Muller, 2007; Mwenge-Kahinda *et al.,* 2010). Prior to considering *adaptive* water quality management, the main issues behind water quality management are crucial aspects to consider since they define the path towards the development of adaptation strategies. The following section is an introduction to the most critical water quality management related challenges.

2.2.3   Challenges in Water Quality Management

Water quality management across all different scales is primarily concerned with making decisions which seek to prevent the progression of pollution (Unami and Kawachi, 2003). However, owing to increasing pressures on water resources from climate change, population growth and economic development, global and local water quality management is far from satisfactory, particularly in developing countries (Huang and Xia, 2001; IPCC, 2007). One of the major reasons for this is that the most rapid growth, with regard to economic development and population growth, occurs primarily in low income countries (*e.g.* in the so-called developing national economic blocs such as BRICS) where water and wastewater

infrastructure is, by global standards, generally substandard. Furthermore, water quality management in these countries is usually carried out in a conservative, non-adaptive manner and many decisions are based on historical trends rather than on current observations (World Bank, 2010). This limits the flexibility of water quality management and creates a state of policy redundancy which can, ultimately, cause policy failure (as detailed in Section 2.3). Bennet *et al.*, (2005) and Lynam *et al.,* (2009) note that water quality management has to be carried out in a holistic manner which recognises the interactions between society and the physical and biological environment. Therefore the dynamism of both society (*e.g.* population growth and migration) and the physical and biological environment (*e.g.* climate change) has to be factored into water quality management and planning, such that policy redundancy and failure is avoided.

For many developing and transitional countries such as South Africa, the rapid growth of urban centres facilitates the deterioration of water quality due to the increased generation of diffuse or non-point source (NPS) pollution (Edwards and Withers, 2008). Other sectors related to economic development in these countries including agriculture, deforestation and mining (acid mine drainage) also contribute significantly to water quality deterioration. Developing countries are subject to high levels of exposure and vulnerability (IPCC, 2007) and this consequently elevates their susceptibility to the effects of diffuse pollution (Novotny, 2003; World Bank, 2010). Novotny (2003) cites the following major reasons for the high susceptibility of developing countries to diffuse pollution and water quality deterioration:

a) Global change pressures (*i.e.* climate change, population growth, economic development and land use change) are largest in developing countries.
b) Many urban centres in developing countries have poorly functioning or non-existent sewer systems and wastewater infrastructure.
c) Surface water contaminated by diffuse pollution is often used as a source of potable water by households in rural communities.
d) Surface runoff is the main contributor to flow in these countries and provides the main mechanism for the transport of pollutants.
e) Intensification of the use of contaminants (fertilizer, pesticides *etc.*) in industrial agriculture increases nutrient inputs into surface waters and impairs the water quality of receiving waters.

For the reasons detailed above, it follows that the degradation of water quality is influenced by the interactions between society and the natural environment. It is apparent that although the environment contributes some background contamination, people are, for the most part, responsible for the undesirable changes in the quality of water resources. Therefore, the major challenges in water quality management are anthropogenic in nature and may be classified into 2 groups as follows (Novotny, 2003):

1) "Human alteration of the status of a water body and its habitat that downgrades its integrity and creates pollution" and,
2) "Addition of allochthonous (originating from outside the water body) pollutants to the water body".

Group 1 essentially refers to the alteration or modification of water bodies for the benefit of society. For instance, the construction of dams and impoundments, flow diversion, construction of inter-basin transfer nodes, channel lining, wetland drainage and conversion, invasion of riparian zones by foreign species originally introduced by people and urban development which alters the hydrology of a stream. Group 2 refers to allochthonous point and non-point sources (NPS) of pollution. These include discrete or point sources of pollution such as municipal and industrial wastewater effluent, runoff from solid waste disposal sites, storm drain discharge, runoff from active mines and active construction sites. Non-point sources include return flows from agriculture, runoff from unconfined pastures, failing septic tank systems, wet and dry atmospheric deposition and other unconfined sources of pollution (Novotny, 2003). The concept of non-point source pollution will be further expanded on in section 2.2.5.

Successful water quality management has to recognise the role people play in the fluctuation of catchment water quality (Bennet *et al.*, 2005; Lynam *et al.,* 2009). It is for this reason that water quality management in developing countries has to be as adaptive as possible to ensure that adaptive capacity is increased and external impacts, such as climate change, are well prepared for. It is at this juncture that the importance of understanding the meaning of adaptive management is critical. The following section, therefore, briefly details the concept of adaptive management and its role in water quality management.

2.2.4   Adaptive Water Quality Management

In the introductory section it was noted that being part of the current global change mosaic, climate change could aggravate current water quality problems. Indeed, climate change is anticipated to introduce added complexities that water quality managers will have to contend with. Although decision makers make decisions under uncertainty every day, even in the absence of climate change (World Bank, 2010), a paradigm shift is required in which the compounding set of uncertainties presented by climate change are recognised and included in the decision-making process (Kundzewicz *et al.,* 2007). This essentially constitutes adaptive management (Kundzewicz *et al.,* 2007; Bates *et al.,* 2008).

According to Bennet *et al.,* (2005), adaptive management can be defined as ''a systematic process for continually improving management policies and practices by learning from the outcomes of operational programs''. Figure 2.3 presents a schematic representation of an adaptive management framework developed by the Australian Coastal Cooperative Research Centre (Coastal CRC) and as shown in this diagram, adaptive management is a cyclic learning, application and review process in which the focus is on action and learning and not in preparing to learn (Lee, 1999; Bennet *et al.,* 2005). In this diagram, the components are all linked through a continuous process of learning and participative action. To briefly summarise: *Information collation* refers to the pooling of information collected from research and from stakeholder consultation and is usually the first step in the development of an adaptive management framework, the *core components* of process and facilitation and evolving knowledge are essential in the planning and management cycle and comprise the establishment of healthy relationships amongst catchment stakeholders such that the entire adaptive management cycle proceeds efficiently. *Systems analysis and vision* focuses on identifying and understanding the most important catchment systems in order to clearly define the vision and aspirations for the catchment. *Plan making* involves the setting of clearly defined resource management goals such that impacts on ecological and socio-economic systems are recognised and strategies are developed. *Implementation* involves the actual execution of the goals created in plan making and systems analysis and vision creation. *Monitoring and Review* follows implementation and is the assessment of the effectiveness of the goals set during the initial stages of framework development and of the effectiveness of the implementation process (Bennet *et al.,* 2005).

It is apparent, therefore, that adaptive management is a process that facilitates intervention in the face of uncertainty. For instance, water quality modelling serves as an approach that water resource managers can use to abstract information about the natural environment and synthesise knowledge and make decisions based on that information. However, water quality models are often fraught with input data errors, model errors and inappropriate process knowledge by the users (Bormann, 2009). This does not imply that these models are not appropriate to be used as decision support tools; rather it implies that water quality models should be used as tools that facilitate explicit learning from experiments in order to inform and improve future decisions.
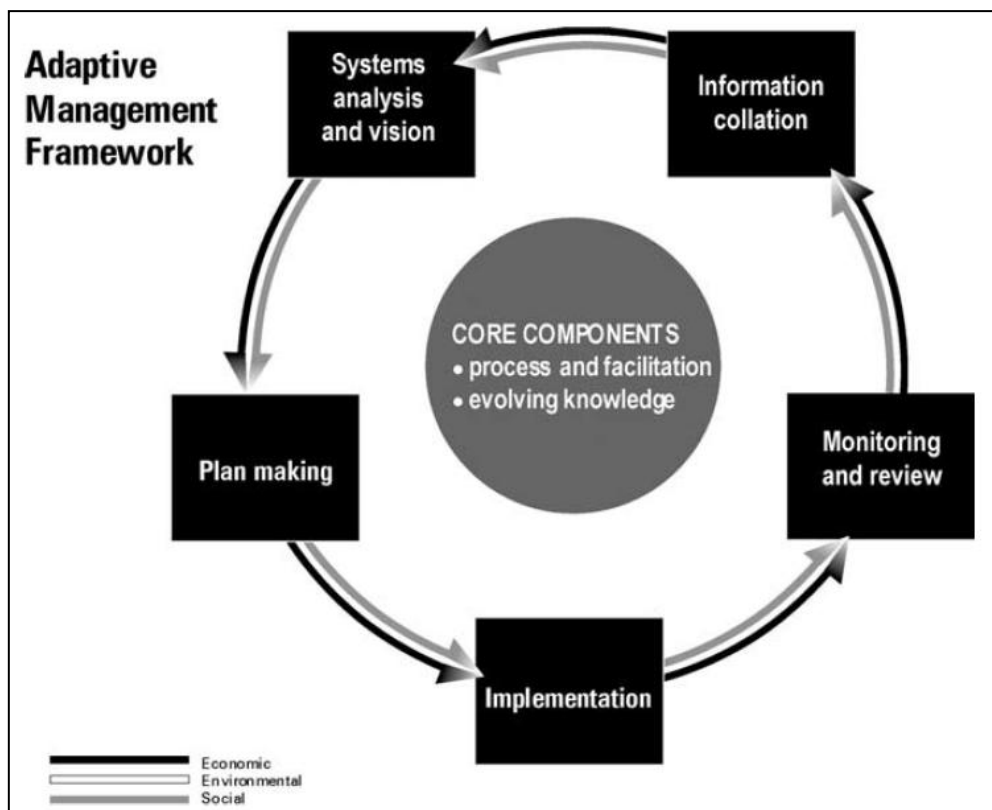
Figure 2.3   Schematic diagram of the Coastal CRC Adaptive Management Framework (Bennet *et al.,* 2005).

Adaptive water quality management, therefore, requires the development of robust strategies that recognize the reality of a world of shifting baselines and intermittent disturbances (Adger and Vincent, 2005; World Bank, 2010; Firman *et al.,* 2011).

This essentially demands a rethink of traditional water quality management practices which assume a predictable future based on past experiences. The World Bank (2010) recognizes four management strategies that are essential in facilitating adaptive (resource) management under climate change. These strategies have been adapted by the author to be more specific to water quality management:

a) Priority should be given to no-regrets options: policy and investment options that maximise benefits related to water quality management even in the absence of climate change *e.g.* improving water and wastewater infrastructure to minimize water quality degradation in receiving waters (Novotny, 2003).

b) Increase resilience of water resource systems by buying "safety margins" in low cost long-term investments *e.g.* increasing water quality awareness education and forming social resource protection schemes (Petermann, 2008).

c) Reversible and flexible options need to be favoured such that in instances of bad decisions being made, the cost of reversing the impacts of decisions is kept as minimal as possible *e.g.* restrictive urban planning due to uncertain flooding trends can be reversed easily and is less expensive than retreat and protection options (Heltberg *et al.,* 2008).

d) Long term planning should be based on forward-thinking scenario analysis and on the assessment of strategies that consider a wide range of possible futures.

A recurring theme in this discussion has been that adaptive water quality management requires a risk-based decision-making model which favours long-term planning and robustness taking into cognisance the dynamic nature of socio-economic and environmental systems. Increasing global change pressures on water resources coupled with the compounding effects of climate change imply that risks related to water quality management cannot be ignored or omitted in the decision-making process. The aforementioned compounding set of uncertainties presented by climate change necessitates the development of robust and adaptive management strategies that will minimize the risk and thus vulnerability of environmental, social, economic and demographic systems. Having detailed the concept of adaptive water quality management and its relation to climate change, the following section provides a brief analysis of the concept of non-point source (NPS) pollution as one of the primary foci in water quality management.

2.2.5 Non-Point Source Pollution

Non-point source (NPS), or diffuse pollution, is now widely recognized as a key agent in the deterioration of water quality, both globally and locally (Carpenter *et al.,* 1998; Hansen, 2002; Novotny, 2003; DWAF, 2003; Edwards and Withers, 2008; Jolly *et al.,* 2008; Oberholster *et al.,* 2009). Although various forms of land-based activities generate NPS pollution, agricultural activities are considered to be the leading cause of surface water quality degradation (Ma and Bartholic, 2003; Liange and Shukai, 2010; Bryan and Kandulu, 2011). Other NPS pollution sources include runoff from pastures, forestry, sewage treatment plants, abandoned mines, industrial facilities, rural livestock feedlots and return flows from irrigated agriculture (Carpenter *et al.,* 1998; Novotny, 2003; Bates *et al.,* 2008). During high flow periods or extreme flood events, vast quantities of contaminants and pollutants may also be exported and transported from various sources such as agricultural catchment areas, landfill sites and from soil erosion (Beven, 2002; Almasri and Kaluarachchi, 2004). This, as shown in Figure 2.4, can lead to numerous water quality related problems ranging from rapid distribution of contaminants and pollutants, pH reduction (acidification), stream sedimentation and increased turbidity and in instances of post-flood standing waters, the introduction of disease carriers (Nilsson and Renöfält, 2008). The effects of NPS pollution on water quality include the introduction of above-normal loads of sediments, contamination of potable water supplies, eutrophication of freshwaters, removal of aesthetic characteristics, increased chemical toxicity and the destruction of ecosystems (Novotny, 2003; Delpla *et al.,* 2009).

Edwards and Withers (2008) suggest that the current global estimate of total nitrogen (63 Tg N yr^{-1}) introduced into water-bodies and other aquatic environments, is double that of the pre-industrial era, while that of phosphorus is estimated to be 20 Tg P yr^{-1}. Haygarth *et al.* (2005) also indicate that annual inputs of phosphorus into water-bodies derived from manure and fertilizer range between 20 and 50 20 Tg P yr^{-1}. Similarly, prior to the introduction of conservation agriculture in the Tertiary Hill of Bavaria, Germany, the total nitrogen and phosphorus fluxes into the adjacent Brook West were found to be 292 kg N yr^{-1} and 4.9 kg P yr^{-1}, respectively (Honisch *et al.,* 2002). Suspended sediment derived from soil-loss has been positively correlated with accelerated watershed land-use practices (Houlahan and Findlay, 2004).

Water quality variables	Low flows	High flows
Pollutants	Concentrations can reach toxic levels	Can be washed out from adjacent, otherwise unflooded uplands; dilution reduces but does not eliminate risk for toxicity
Drugs	PPCP:s (Pharmaceuticals and Personal Care Products) can become toxic; natural estrogens can feminize fish	
Nutrients	Can lead to eutrophication and acidification; N levels can become toxic	Removed from watercourse by downstream transport, uptake by riparian vegetation and denitrification
Salts	Can lead to acidification, mobilization of toxic metals and invasion of salt-tolerant species	
Organic matter and sediments		Considerable addition that increases turbidity, which reduces primary productivity and may increase acidity and threaten fish production. Organic matter can reduce pH. Sedimentation of transported inorganic matter restructures channel
High temperature	Lowers oxygen content, makes contaminants more toxic, lowers productivity	
Low temperature	Surface ice cover leads to reduced oxygen. Open water and low air temperatures can foster excessive formation of frazil ice and anchor ice that damage aquatic biota. Open water and temperatures rising from below to above 0°C lead to melting anchor ice that can jam up and produce local floods and upland ice that damage riparian and upland biota	If high flows occur during periods with low temperatures and surface ice, water can be forced on top of the ice, often leading to floods, or the ice cover may break up and run the risk of jamming

Figure 2.4   Summary of the water quality problems that may arise during extreme discharge conditions (Nilsson and Renöfält, 2008).

These estimates further highlight the importance of understanding and quantifying the effects of NPS in water quality management. Foy and O' Connor (2002) assessed the effects of agriculture on the water quality of two rivers in Northern Ireland. Specifically, this study aimed at "i) examining point source farm pollution and the associated damage to tributary or headwater streams; ii) diffuse nitrogen and phosphorus losses and associated eutrophication; and iii) the sedimentation of spawning redds of the Atlantic salmon (*Salmo salar* L.)".

The Colebrooke and Upper Bann Rivers were the subjects of farm pollution studies for a period of 8 years from 1990 through to 1998. The enrichment of these rivers with nutrients, particularly phosphorus and nitrogen, over this period was attributed to farmyard discharges of manure and silage effluent. Although the government introduced a number of initiatives aimed at reducing water pollution generated from farms, the assessment of the effectiveness of these initiatives proved to be problematic. This was owing to the fact that monitoring sites were located on larger rivers and not on tributaries, and thus water pollution data reflected a large variety of pollutant sources other than farmyards. Therefore, various chemical and biological water quality assessments were undertaken in tributaries to ascertain trends in pollution and define the causes of this pollution. Owing to the extensive use of nitrogen- and phosphorus-based fertilizers in agriculture, this sector was identified as the major contributor to water pollution in these rivers. Additionally, due to the blockage of spawning redds (*i.e.* breeding grounds); the supply of high loads of fine sediment was recognised as another concern that has adverse impacts on the spawning of salmon. However, the high sediment loads were not attributed to agricultural practices, but rather to human interventions. The combination of both nutrient enrichment and sedimentation resulted in a decline in available habitat for salmon spawning and, consequently, a decline in salmon populations for many parts of Northern Ireland (Foy and O'Connor, 2002). The authors concluded that agriculture was primarily responsible for the deterioration of water quality in Northern Ireland and it was difficult to minimise the generation of diffuse pollution from farming activities. Various methods for the reduction of farm-generated diffuse pollution were suggested in this study, ranging from voluntary mitigation measures encouraging farmers to apply nutrient management frameworks, to the introduction of legislative measures that increased fines for pollution. The issue of sedimentation also did not yield satisfactory solutions due to a lack of consensus as to the actual cause of the problem.

To counter increased NPS loads such as suspended solids, nitrates and phosphates, Choi (2008) and Fisenko (2004) suggested preventative management measures such as conservation tillage, soil protection and targeting areas where combinations of land management and landscape factors pose significant NPS pollution generation risks. Although this section has focused on non-point sources of pollution, point sources also exist. However, these sources tend to be continuous and vary little over time and their impacts are therefore considered to be inconsequential.

Various studies in pollution sources *e.g.* Beven (2002), De Vries *et al.* (2002) Hatch *et al.* (2002), Tsujimura (2004), Fisenko, (2004), Deasy *et al.* (2007) and Bryan and Kandulu (2011) concur that the major pollutants associated with water quality are derived from non-point sources. The regulation and monitoring of NPS pollution has recently become central to most government water quality management policies both internationally (*e.g.* Hansen, 2002; Romstad, 2003) and locally (*e.g.* Pegram and Bath, 1995; DWAF, 2003 and 2004).

In South Africa, the rapid developments and land use changes occurring within numerous catchments are responsible for the generation of various forms of diffuse pollution, causing the water quality decline of many local rivers. However, local NPS pollution is yet to be effectively quantified and aligned to the impacts of climate change for the development of adaptation strategies. The most important pollutants in South African waterways are considered to be nitrates, phosphates, sediments, pesticides and salts; all of which are mainly generated from agricultural and urban sources (DWAF, 2004; van der Laan, 2010). An in-depth understanding of pollutant dynamics along local rivers is, therefore, critically important in water quality management. In the last few decades, however, significant advances have been made with intent to reduce impacts on water quality and promote environmental health (Arthington *et al.,* 2006; Rivers-Moore *et al.*, 2007). In spite of these advancements, the continual use of pollutants in agricultural practices implies that the issue of water quality deterioration is going to remain significant in the future (Honisch *et al.,* 2002; DWAF, 2003). Therefore, non-point source pollution and land use change form an integral part of water quality management and will become particularly important under an altered climate. The following section briefly introduces the parameters and processes most critical to South African waterways as recognised by this review.

2.2.6   Critical parameters and processes

As mentioned in the preceding sections, South African catchments are predominantly agricultural catchments and a major component of diffuse (NPS) pollution is generated within these catchments. The increased generation of nutrients such as phosphorus (P) and nitrogen (N) from these catchments due to high rates of manure and fertilizer application primarily leads to eutrophication (Foy and O'Connor, 2002; Deasy *et al.,* 2007).

Both N and P are considered as the main nutrients that drive the fluctuation of water quality in the fluvial systems of agricultural catchments (Withers and Jarvie, 2008). This statement implies that in South African catchments, more focus needs to be directed towards assessing the potential changes in both N and P generation and transport under conditions of climate change. Chapter 3 provides a detailed analysis of the dynamics of nutrient generation, transport and deposition across catchments. Some of the parameters and processes detailed in Chapter 3 considered paramount in nutrient transfer include:

a) surface erosion, entrainment, sedimentation and deposition,
b) catchment connectivity,
c) nitrogen and phosphorus cycling,
d) precipitation and soil moisture content,
e) leaching and runoff, and
f) adsorption.

Another equally important factor in nutrient delivery is sediment conveyance and catchment connectivity. N and P are either transferred in dissolved form (N and P) or attached to sediments (mainly P) (Heathwaite and Dils, 2000), and owing to the connectivity and sediment delivery dynamics characteristic of many catchments, N and P become subject to discontinuous transport and deposition (Avnimelech and McHenry, 1984). Furthermore, the connectivity of landscape compartments affects sediment conveyance processes in response to external disturbances of varying frequency and magnitude (Fryirs *et al.,* 2007). Therefore, under conditions of climate change, the source generation and distribution of sediments and nutrients is highly likely to change due to the anticipated high magnitude and intensity of rainfall events (Heathwaite and Dils, 2000). Deasy *et al.,* (2007) argues that because the "processes of sediment and nutrient transfer are not well understood over the range of scales needed for appropriate modelling and management applications" it is not yet possible to assess the likely impacts of potential changes. However, the issue of scale is somewhat mitigated by the vast amount of work that has been carried out in sediment, catchment connectivity and nutrient transfer dynamics (Haygarth *et al.,* 2005; Owens *et al.,* 2007). These issues will be expanded on in greater detail in Chapter 3.

2.3   Assessing the Impacts of Climate Change on Water Quality

2.3.1   Introduction

It is now a well-accepted notion that some impacts of climate change on water resources are unavoidable (Kundzewicz *et al.,* 2007; Bates *et al.,* 2008; UNESCO, 2009). Projections generated from various General Circulation Models (GCMs) present persuasive evidence that global climate and hydrological systems are going to change despite mitigation actions (Schulze *et al.,* 2005; Bates *et al.,* 2008; UNESCO, 2009). GCM projections that herald increases in temperature and changes in rainfall variability associated with climate change, present sobering implications for, *inter alia*, environmental health and water quality (Lumsden *et al.,* 2009). Regardless of the uncertainty inherent in climate change science (Schulze, 2005; Pittock, 2009), it is important to recognize the potential effects that climate change may have on critical water resources management facets such as water quality (Nelson *et al.,* 2007). This section therefore presents the potential impacts of climate change specifically on water quality and associated processes and constituents.

2.3.2   Climate Change and Water Quality: Impacts and Responses

The anticipated changes in temperature, flow regimes and rainfall variability associated with climate change are expected to exacerbate water quality problems (Ducharne, 2007; Delpla *et al.,* 2009). Increased temperatures will have implications for the chemical and biological integrity of rivers and other aquatic environments. For example, Van Vliet and Zwolsman (2008) presented a case whereby a $2^{o}C$ increase in water temperature during a drought in 2003 resulted in a pH decline, eutrophication, decreased dissolved oxygen and increases in metal and metalloid concentrations in the Meuse River in France. In this example, the combination of low flows and high temperatures resulted in the deterioration of the water quality of this river (Van Vliet and Zwolsman, 2008). In such instances, the consequence of this combination is an increase in the toxicity of contaminants, which increases with temperature and consequently adversely affects aquatic life (Delpla *et al.,* 2009).

Changes in rainfall variability result in changes in flow regimes (flow rates and timing), which has implications for pollutant residence times, pollutant concentrations, salinity levels in arid and semi-arid regions, pollutant transport and stream dilution capacities (Nelson *et al.,* 2007; Turton, 2008). The Meuse River case detailed in Van Vliet and Zwolsman (2008) provides an example that details how combinations of low flows and high temperatures, result in high pollutant concentrations and increased pollutant residence times (eutrophication), which leads to water quality deterioration. A similar but slightly varied trend is observed during high flow periods (during floods or rainy season peaks). Although high flows can result in the dilution of pollutants and in the reduction of pollutant residence times in rivers, the transport of pollutants to other locations which can occur during these events can result in the introduction of foreign contaminants to other aquatic environments (Beven, 2002; Turton, 2008; McCartney, 2009). For example, sedimentation, turbidity and increases in pollutant concentration can occur in rivers and dams following a high intensity rainfall event. Such events usually generate high soil losses and high runoff volumes which can cause pollutants and sediments to be transported from the upper parts of a catchment into downstream water sources (Prathumratana *et al.,* 2008; Neal *et al.,* 2008).

Climate change is not only expected to alter rainfall patterns and, hence, variability, but also the intensity of individual events (Schulze *et al.,* 2005; IPCC, 2007; Bates *et al.* 2008). The high runoff generated from these events can result in the flushing out of faecal coliform bacteria, disinfectant by-products (DBPs), dissolved organic matter (DOM), pathogens, pesticides and various industrial and agricultural pollutants into surface water and groundwater (Neal *et al.,* 2008; Delpla *et al.,* 2009). Groundwater quality has an added dimension when climate change is considered. Pittock (2009) noted that the El Niño Southern Oscillation cycle, which is expected to continue with climate change, will result in extreme high sea levels which can cause salt-water intrusion into aquifers thus impairing groundwater quality. Nelson *et al.* (2007) also indicate that the severe storms predicted to accompany global warming will result in "more polluted runoff" in a climate-altered future. Figure 2.5 summarizes the potential impacts of climate change on water resources and on water quality, as outlined in this discussion. To further summarise the relationship between climate change and water quality, Table 2.1 correlates changes in climatic extremes and the potential resultant effects on water quality variables.
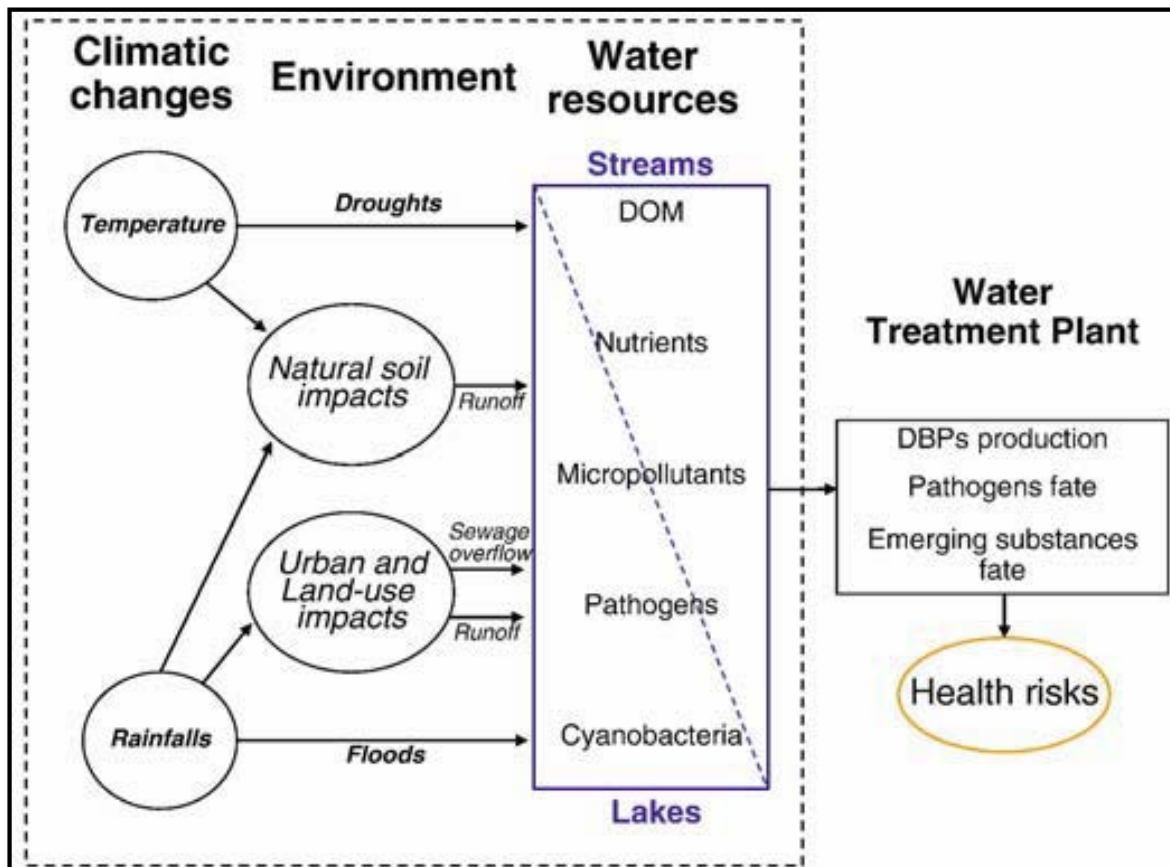
Figure 2.5   Potential impacts of climate change on water resources and drinking water quality (Delpla *et al.,* 2009)

These changes are based on the IPCC (2007) report that details "estimates of confidence" in projected changes for the 21st century. It is apparent from this table that the most serious impacts on water quality are either virtually certain or very likely. This is a cause for real concern regarding the integrity of surface water and groundwater quality. In semi-arid countries such as South Africa, where water resources are already under severe pressure from both quality and quantity perspectives, these projections have especially significant implications. As mentioned before, many uncertainties abound in climate change science (Schulze, 2005; IPCC, 2007; Bates *et al.,* 2008; Pittock, 2009), especially because of its distinctly multi-disciplinary nature. Such projections, therefore, need to be viewed in a context that accepts the inherent uncertainty, but that does not prevent decisions being made. This is especially important in the application of multi-disciplinary concepts such as Integrated Water Resource Management (IWRM).

Table 2.1 Projections of extreme climatic events and associated impacts on water quality variables (IPCC, 2007).

Changes in phenomena and direction of trend	Confidence in projected changes (during 21st century)	Impacts on water quality variables
Higher maximum temperatures and more hot days over most land areas	Virtually certain (>99% confidence)	Higher ambient and water temperatures, reduces dissolved oxygen (BOD and COD), reduces pH (increased acidity) and increases pollutant residence times, adverse impacts on aquatic ecosystems.
Higher minimum temperatures and fewer cold days over most land areas	Virtually certain	Surface ice formation can lead to reduced oxygen levels, disrupts ecological functions (*e.g.* spawning and migration).
Heavy precipitation events with increased frequency over most areas	Very likely (>90% confidence)	Increased flushing of toxic material, faecal coliform bacteria (*e.g. E. coli*), transport of NPS pollutants, disrupts normal flow regime pulses.
Increased areas under risk of drought	Likely (>66% confidence)	Reduced dilution capacities, increased risk of salinity level increases, increased pollutant toxicity.
Increased incidence of extreme high sea levels	Likely (>66% confidence)	Salt-water intrusion, destruction of coastal riparian ecosystems.

In view of the shift in emphasis towards environmental protection and water quality improvement under climate change, a subject that requires consideration is the water resources planning that will be increasingly critical in water quality management under future conditions of change. The previous discussion highlighted the importance of judicious decision-making under conditions of uncertainty. Water quality modelling and process-based predictive catchment studies are indispensable water resources management tools that are critical in decision-making under uncertainty (Rajar *et al.,* 2007; Argent *et al.,* 2009; Lorentz *et al.,* 2010; Schellart *et al.*, 2010). The following section presents a brief description of the principles and practices observed in water quality modelling and process-based predictive studies and the application of these concepts in climate change studies.

2.3.3   Managing the Impacts of Climate Change on Water Quality

With the current discussion on global change, there has been an increased requirement for the development of hydrological prediction and mapping tools that support appropriate water quality management and decision-making (Bates *et al.,* 2008; Zimmerman *et al.,* 2008; Kundzewicz *et al.,* 2007). The connection between land use change, climate change and water quality degradation necessitates the development of predictive tools that will provide support for the assessment and analysis of pollutant loads in catchments and offer possible solutions towards improving catchment water quality (Argent *et al.,* 2009; Mannina and Viviani, 2010). To fulfil that objective, a number of predictive tools such as water quality models and other predictive tools (see Leigh *et al.,* 2010 below) have been developed, tested and applied under various instances in the past few decades (Rajar *et al.*, 1997; Falconer and Lin, 1997; Huang *et al.,* 2009; Leigh *et al.,* 2010; Lorentz *et al.,* 2010). In order to effectively manage the impacts of climate change on water quality, it is important to critique the vulnerability assessment tools that will enable the development of appropriate adaptation strategies.

Leigh *et al.* (2010) undertook a study which investigated the vulnerability of reservoirs to poor water quality and cyanobacterial blooms under future conditions of change (climate and land use change), in southeast Queensland, Australia. During the summer months, this region experiences high ambient and water temperatures and high rainfall frequencies, both of which facilitate stronger stratification and increased inflow rates respectively.

The result of strong stratification is the release of bio-available nutrients from anoxic sediments and high inflow rates increase the nutrient supply into reservoirs (Shanmugam *et al.,* 2008; McCartney, 2009). This results in increased incidences of toxic cyanobacterial blooms due to increases in nutrient loads in the reservoirs of this region. The ability, therefore, to assess the vulnerability of these reservoirs to bloom events was considered paramount in providing information for decision-making, hazard prevention and water resources management (Leigh *et al.,* 2010). This statement highlights a crucial step in linking biophysical processes with vulnerability and adaptation in water law and policy.

The study developed an "index of vulnerability" based on catchment characteristics and reservoir management criteria. The vulnerability index (VI) is essentially a measure of a reservoir's vulnerability to poor water quality under future conditions *i.e.* the ratio of vulnerability to poor water quality for a particular reservoir (Leigh *et al.,* 2010). The vulnerability index was tested by using water quality data collected from 15 reservoirs located in and around Queensland. Water quality parameters tested for included total nitrogen and phosphorus (TN and TP), dissolved inorganic nitrogen and dissolved inorganic phosphorus. The VI of a reservoir was assessed by analysing the correlation between index scores and water quality parameters in the 15 reservoirs. For instance, a reservoir with a VI of 0.77 was considered to be the most vulnerable reservoir to poor water quality. This does not suggest that the reservoir had the highest concentration of nutrients over the duration of the study, but it implies that in the future, based on factors that influence nutrient generation and transport, water quality deterioration in this reservoir will be highly probable. A reservoir expected to experience adverse climate change related impacts would also have a high VI. The authors concluded that although improvements can be made to the calculation of the VI, it can still serve as a valuable tool to water authorities and managers to confidently assess the vulnerability of reservoirs to poor water quality under future conditions of change (Leigh *et al.,* 2010).

The study by Leigh *et al.* (2010) highlights an important aspect regarding the vulnerability of systems: vulnerability is a relative property (Ionescu *et al.,* 2009). For example, increased pollutant discharge and extreme events under climate change can potentially lead to increases in vector-borne diseases and, consequently, an increase in human health related problems (Haines *et al.,* 2006).

Leigh *et al.* (2010) also recognised that under future conditions of change, increased nutrient generation and transport in catchments can result in water quality deterioration, which can ultimately affect ecosystem functioning and human health. Therefore, the study by Leigh *et al.* (2010) was able to highlight the critical link between biophysical processes and vulnerability studies.

The use of water quality models is another equally important water resources management aspect that requires attention. The ability of water quality models to predict reaction changes and model the impacts of these changes throughout a system is not only important in enabling water suppliers to select improved operational strategies, but also ensures the delivery of safe drinking water to consumers (Munavalli and Kumar, 2004). This statement carries with it important implications for water quality modelling. Under future conditions of change, the use of models is going to be increasingly important in the management of water resources. The statement by Munavalli and Kumar (2004) indicates that the use of water quality models enables the selection of improved operational strategies such as best management practices or BMPs. This can potentially be translated to improved adaptation strategies, which will take into account the effects of climate change on water quality. Water quality modelling is, therefore, a critical tool which enables the management of existing and future pollution dynamics of receiving water bodies and/or fluvial systems. Application of water quality models in South Africa is also critically important if adaptive water quality management is going to be effectively applied in daily water resources management. Not only does this build adaptive capacity by strengthening already existing predictive tools (*e.g.* design rainfall studies and the *ACRU*-NPS modelling system), but it also creates a new potential decision-making tool that will reduce uncertainty in water resources management.

2.4 Discussion and Conclusions

The above literature review of the impacts of climate change on water quality identified a number of critical parameters, variables and processes related to water quality that will become increasingly important under future conditions of change. It was identified in this review that nitrogen (N), phosphorus (P) and sediment will increasingly become variables of concern under an increasingly changing climate. Furthermore, the review recognised that the increased variability of rainfall and elevated temperatures anticipated under climate change will add further complexity to current water quality management by altering the behaviour of nutrients and sediment. This stems from the fact that the source generation and displacement of these variables is highly influenced by climatic conditions. Consequently, changes in rainfall and temperature are anticipated to result in changes in biophysical processes such as runoff (*i.e.* baseflow plus quickflow), evaporation, sediment and nutrient generation and displacement and finally, river flows.

This review also raised a number of contemporary water quality management issues which were considered paramount to the development of adaptation strategies for local water resources management. For example, the issue of increased human interventions in local catchments, such as the Mngeni Catchment was highlighted as being the primary cause of water quality deterioration. It was, therefore, recommended that adaptive water quality management be applied in order to enable the recognition of the impacts that human intervention has on freshwater systems, and to offer novel management ideas and policies and promote institutional commitment to effectively manage water quality issues in this country. This review also indicated some fundamental problems regarding water quality in South Africa. For instance, owing to the extensive pressure on local water resources, the majority of South African rivers are considered to have lost their ability to dilute effluent generated from point and non-point sources. Increasing concentrations of pollutants such as nitrates, phosphates and sediments are being recorded across many South African waterways and reservoirs. The implications for drinking water quality standards and the sustainability of rivers and dams in the future are, however, yet to be established.

This implies that without the establishment of the links between basic biophysical processes that influence water quality and the impacts of climate change on those processes, local water quality management is going to become increasingly complex and unsustainable. This gap in knowledge has extensive implications for adaptive water resources management in this country.

Increased concentrations of nutrients (N and P) generated from the increased use of agricultural pesticides and fertilizers, has been recognized as one of the main factors that contribute to fundamental local water quality problems such as eutrophication and bloom events. This is an inevitable outcome considering the fact that South Africa is comprised mainly of agricultural catchments and the increasing food demands prompt the agricultural sector to use increasing amounts of soil and crop ameliorants to meet these demands. An added dimension to the issue of nutrient generation and dislocation is that of sediment conveyance and catchment connectivity.

N and P are transported in dissolved states and bound to sediment particles respectively. Considering the increased magnitude and intensity of rainfall events under climate change, an increase in soil erosion and sediment transfer is expected. This implies that the movement of sediment and these nutrients (N and P) from source areas to water resource systems is likely to increase. Depending on the (dis)connectivity of landscape/catchment compartments, the movement of nutrients and sediment, N and P will vary according to how landscapes respond to external disturbances. It is therefore important to assess the relationship between climate change, sediment, N and P dynamics and landscape/catchment connectivity in local water quality management. The above discussion was considered to have significantly contributed to one of main objectives of the review, which was to highlight the links between adaptation in water law and policy and adaptation in water quality management.

The above discussion reveals another key gap in knowledge with respect to water quality management in South Africa: although the impacts of a changing climate on local water resources have been widely studied with a marked emphasis on water quantity, minimal effort has been directed towards assessing water quality issues under climate change. Considering the notion that water quality equally limits water quantity, this gap in knowledge requires due consideration. Even more disconcerting is the fact that such gaps in knowledge

exist in a country considered to be highly vulnerable to the impacts of climate change and one that is characterised by a predominantly low adaptation capacity. In the interest of developing appropriate adaptation strategies in local water resources management, the importance of incorporating water quality into policy development and governance systems cannot be overemphasised. Chapter 6 presents a detailed description of how this may be achieved.

Another equally important topic that was assessed in this review was that of water quality modelling. Although South Africa has a fair amount of experience in hydrological modelling, local water quality modelling appears to still be in its infancy. The review highlighted the necessity of developing water quality models that account for potential changes in biophysical processes under future conditions of change. The capability to develop new water quality models or, if necessary, extend existing models, exists in local water resources management. Harnessing the ability to perform the necessary modelling exercises locally is going to become increasingly important under future conditions of change, as indicated by the literature review. Consequently, the ability to model the projected impacts of climate change on sediment yield and phosphorus is going to form a critical component of the proposed study.

In conclusion, to design and implement effective adaptive water quality management strategies, the relationship between human activities and natural processes was highlighted as an important water resources management dimension in this review. The climate change projections contained in Table 2.1 suggest that further investigation of this dimension is going to be increasingly crucial for the future. This is going to be especially true in South Africa, considering the perpetual pursuit of economic growth, near-exponential population growth and socio-political instability that has become a basic characteristic associated with this nation. To properly ascertain the extent of climate change impacts on water quality and the complex relationship these impacts are expected to create with socio-economic systems, it is imperative that a sound understanding and quantification of biophysical processes be established and the various links be based on that understanding. Following from the preceding assessment of the fundamental issues regarding the relationships between climate change and water quality, the following Chapter provides a detailed discussion into the potential impacts of climate change on specific water quality constituents (nitrogen, phosphorus and sediment).

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CHAPTER THREE

Potential Impacts of Climate Change on Nutrient and Sediment Transfer

Processes

3. POTENTIAL IMPACTS OF CLIMATE CHANGE ON NUTRIENT AND SEDIMENT TRANSFER PROCESSES

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ABSTRACT

The necessity of developing an adequate understanding of the relationships between the potential impacts of climate change on the generation and delivery of sediment and nutrients cannot be over-emphasized. The majority of hydrological processes governing the generation, transfer and deposition of sediment and nutrients have been shown to be highly sensitive to climatic factors. Consequently, changes in climatic variables such as temperature and rainfall are expected to trigger and/or accelerate changes in the transfer dynamics of sediment and nutrients across disturbed catchments. Although in South Africa the relationships between climatic variability, sediment delivery and nutrient transfer are not entirely understood across the full range of scales necessary for management, the development of the necessary adaptation strategies remains a critical part of local water resources management. This paper, therefore, aimed at reviewing the relationships between climate change and sediment/nutrient transport, and the potential implications this will present for locally-relevant and management-specific adaptation. It was concluded that regardless of the impacts of climate change on sediment delivery and nutrient transfer and the consequent impacts on water quality, the development of adaptation strategies requires an approach that recognises both climate variability and climate change to ensure that flexibility and robustness is incorporated in those strategies.

Keywords: Climate Change, Climate Variability, Sediment Delivery, Nutrient Transfer, Adaptation, Water Resources Management.

3.1 Introduction

There is a well-recognised fundamental and applied need to detail the effects of a changing climate on catchment-wide nutrient and sediment transfer dynamics (Edwards and Withers, 2008; Han *et al.,* 2010; Shrestha *et al.,* 2012) (Also see Chapter 2, Section 2.3). Furthermore, the increased introduction of pollutants from non-point sources into freshwater systems has highlighted the urgency for developing effective and integrative water resources management strategies to mitigate water quality deterioration in freshwater systems (IPCC, 2007). This is primarily motivated by the understanding that freshwater resources have finite dilution capacities to process pollutants generated from non-point sources and, consequently, by the dynamic relationships between water quality and water quantity. For instance, during extreme hydrological events, too much water (*e.g.* floods) or too little water (*e.g.* droughts), may cause water quality deterioration by instigating increased loading and transport of pathogens and pollutants or affecting the dilution capabilities of rivers and other water bodies (Mimikou *et al.,* 2000**;** Tsujimura, 2004). Such conditions would effectively result in reduced water productivity and escalating water treatment costs.

The effects of non-point source (NPS) pollution are associated with the generation, transport and deposition of abnormally high loads of sediment and nutrients, over and above that which the natural environment can assimilate. This consequently leads to, *inter alia*, freshwater eutrophication, the contamination of potable water supplies, the deterioration of aesthetic features, increased chemical toxicity and the destruction of terrestrial and aquatic ecosystems (Novotny, 2003; Delpla *et al.,* 2009). It was noted in Section 2.2.3 that the transport or transfer of sediment and nutrients over the landscape is influenced by various factors including surface runoff, erosion, subsurface leaching from soil, point-source emissions, land use management, atmospheric deposition and biogeochemical processes in the freshwater system (Deasy *et al.,* 2007; Rosberg and Arheimer, 2007). With the exception of point-source emissions and land use management, all these processes are strongly influenced by local weather patterns and consequently by the prevailing climate (Rosberg and Arheimer, 2007). It is apparent, therefore, that a changing climate can lead to changes in sediment and nutrient delivery dynamics. Superimposing the impacts of climate change on the effects of other forms of global change (*i.e.* population growth, economic development and land use change)

also illustrates the dramatic consequences that widespread NPS sediment and nutrient pollution may present for the management of freshwater systems.

From a more local perspective, South Africa is classified by the Köppen Global Climate Classification System as a semi-arid country, with over 65% of the country receiving an average of 460mm of annual precipitation, a value significantly below the global average of 860mm.yr^{-1} (Lohmann, 1993; Hewitson *et al.,* 2005; Turton, 2008). In addition, South Africa is characterized as having "a high risk hydroclimatic environment" (Schulze, 2005; Schulze *et al.*, 2005), and is expected to experience the impacts of severe climate change, which will be manifested through an "amplification of the variability of an already highly variable local hydrological cycle" (Schulze, 2005). If accepted, the latter statement implies serious implications for South African water resources management and suggests an urgent need to shift from the current management paradigms, which are mainly focused on water supply and less on water quality, to a more integrated system in which the importance of both quality and quantity are recognised as equally important aspects of water resources management.

Similar to Rosberg and Arheimer (2007), Jennings *et al.,* (2009) and Donohue *et al.,* (2005) also note that the transfer of sediment and nutrients from non-point or diffuse sources is highly sensitive to climatic factors (see Section 2.3.2). In addition to this, the spatial patterns and magnitudes of climatic variables (*i.e.* precipitation and temperature) directly govern the magnitude, as well as the spatial and temporal losses of sediment and nutrients from catchments (Donohue *et al.,* 2005). Considering the notions of Jennings *et al.,* (2009) and Donohue *et al.,* (2005), and the high variability of the South African hydroclimatic environment (Schulze *et al.*, 2005), significant changes in the dynamics of NPS sediment and nutrient transport may be expected under projected climate change. In water resources management, the uncertainties associated with climate change make it critical to continually assess and re-assess the dynamic influence of this phenomenon on the flow, utilisation and treatment of water, as it moves through the hydrological cycle. This paper presents a review of the relationships that exist between climate change, selected nutrients and sediment transport and the potential implications this will present for management-specific adaptation. The review follows a sequence, which initially describes the typical behaviour of each pollutant (*i.e.* nitrogen, phosphorus and sediment) across the landscape and follows with the association of those behaviours with generally accepted climate change projections.

3.2   Nutrient and Sediment Transfer Processes in the Environment

3.2.1   Nutrients

Recent concerns over the increased anthropogenic introduction of nitrogen- and phosphorus-related contaminants into the environment have stimulated numerous investigations aimed at assessing the controls of N and P transport across the landscape (*e.g.* Cirmo and McDonnell, 1997; Withers *et al.,* 2001; Scanlon *et al.,* 2004; Bachmair *et al.,* 2009). Much of this effort has been concentrated on forested and agricultural catchments, where a major proportion of N and P contaminants are considered to originate (Honisch *et al.,* 2002; Edwards and Withers, 2008; Tong *et al.,* 2009). Point sources of N and P inputs into the environment, such as industrial effluent and wastewater from sewage works, can be identified and consequently contained with relative ease, arguably rendering these sources relatively inconsequential (Schärer *et al.,* 2006). However, non-point sources of pollution, such as agriculture, regional and global atmospheric fallouts of harmful compounds, persist as the main contributors to environmental pollution (IPCC, 2007; Schindler, 2006; Pärn *et al.,* 2011). Although nutrient cycling (Figure 3.1) is a natural process, it is intentionally enhanced by agriculturally-oriented activities, in order to increase primary production. Nutrients of anthropogenic origin frequently enter natural ecosystems through various hydrological and atmospheric pathways and consequently induce water quality problems (De Vries *et al.,* 2002; Hatch *et al.,* 2002; Turpie *et al.,* 2008; Van Wilgen and Biggs, 2010). The effective management of environmental pollution as a consequence of diffuse sources of pollution requires a thorough understanding of the processes that govern N and P transport. This section, therefore, presents a brief overview of the processes which govern N and P transport and the relationships that exists between nutrient transport and hydroclimatic processes.
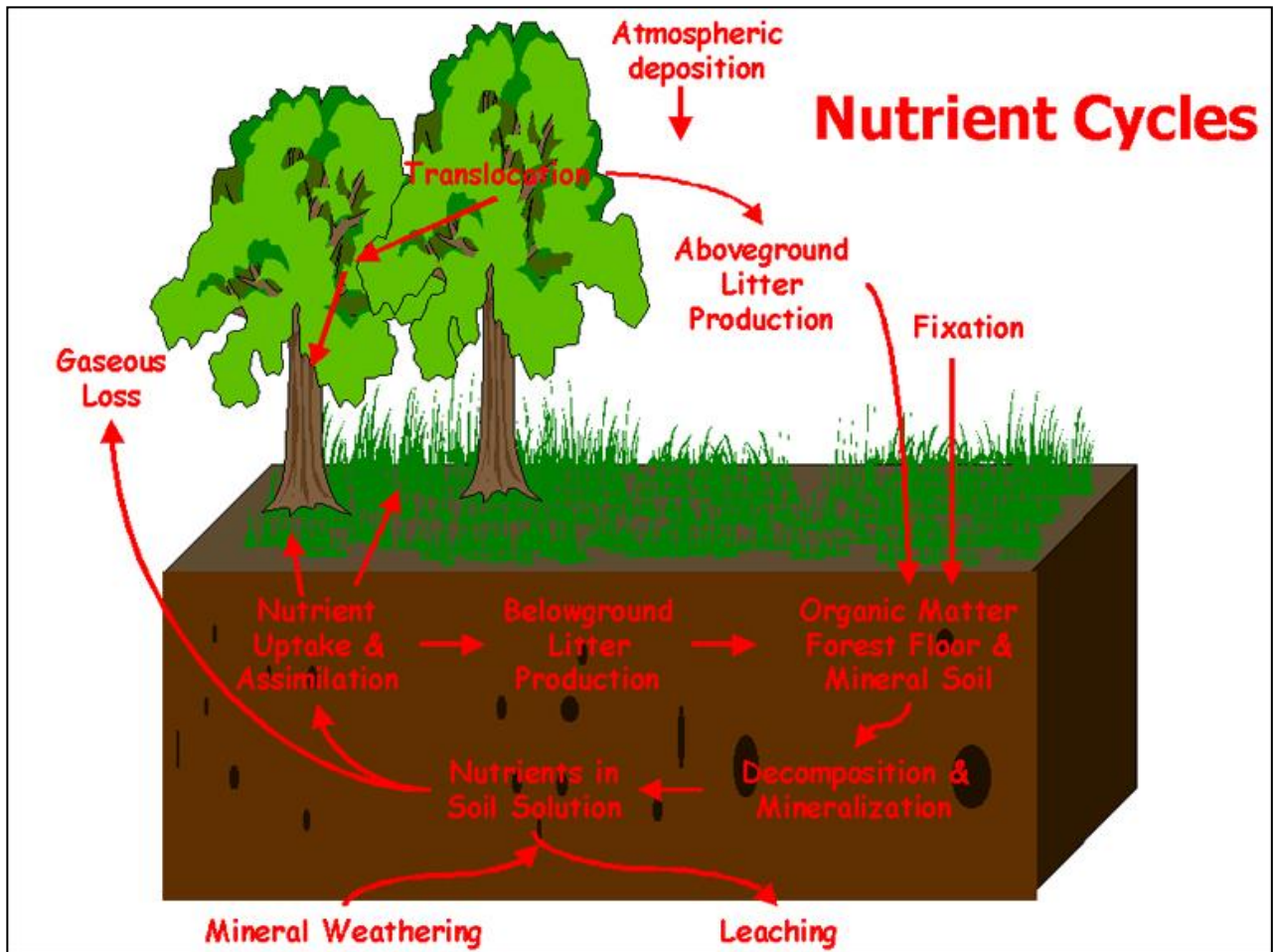
Figure 3.1   Schematic overview of nutrient cycling in terrestrial ecosystems (Van Der Perk, 2006)

3.2.2   Nitrogen

The central role of nitrogen as a limiting nutrient in natural ecosystems and more especially in agriculture is well recognised (Birkinshaw and Ewen, 2000; Almasri and Kaluarachchi, 2004). Nevertheless, at high concentrations, nitrogen in its inorganic aqueous form can be a detriment to water resources and is toxic to animals, plants and humans. It has been shown that nitrogen plays a key role in instigating eutrophication, one of the most common and serious impairments of surface water (Carpenter *et al.,* 1998). The details of how nitrogen contributes to this condition will be outlined shortly. Additionally, the occurrence of elevated concentrations of nitrates or, alternatively, nitrate-nitrogen (NO_3^-N) in drinking water has been shown to induce disorders such as methemoglobinemia or "blue-baby syndrome" (Nelson and Hostetler, 2003; Guay, 2009). Elevated ammonium or ammonium-nitrogen (NH_4^+-N) concentrations have also been shown to be toxic to plants and aquatic organisms

(Carmago *et al.,* 2005). Having introduced the potentially harmful effects of elevated nitrogen concentrations, the following section outlines the nitrogen cycle which describes the movement of nitrogen compounds through terrestrial ecosystems.

3.2.3   The Nitrogen Cycle

Nitrogen transport across the landscape is governed by various processes encompassed in the nitrogen cycle (Figure 3.2). Nitrogen fixation, usually the first process in the nitrogen cycle, is a process whereby atmospheric nitrogen is combined with other elements or with its own derivatives to form useful compounds (Van Der Perk, 2006). Leguminous plants (*e.g.* lucerne, beans and clover) living in symbiosis with bacteria of the *Rhizobium* genus have the ability to capture and fix nitrogen (N_2) directly from the atmosphere. Additionally, massive energy surges such as those generated through lightning discharge also contribute to N_2 fixation (Neitsch *et al.,* 2005). Organic nitrogen is then gradually released through the decomposition of organic matter by heterotrophic bacteria and fungi.
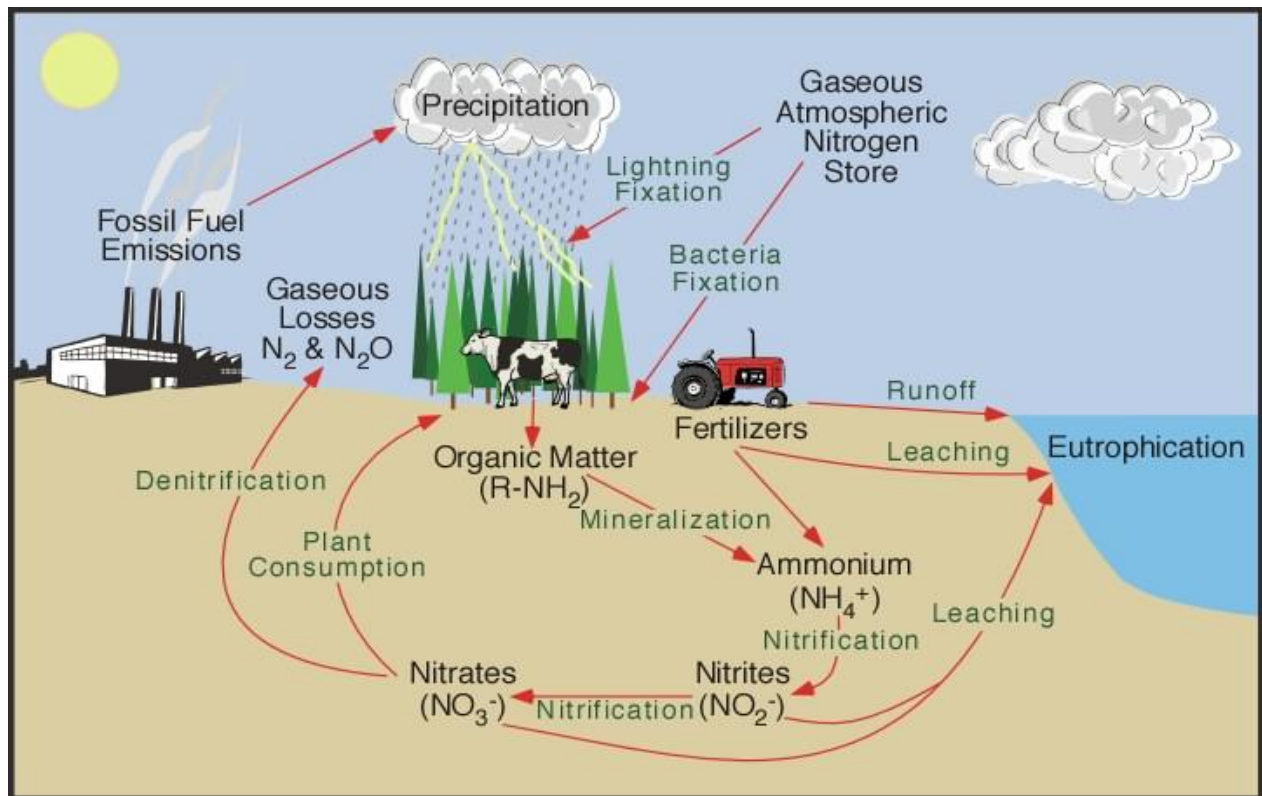
Figure 3.2   Schematic overview of the N-cycle in the natural environment (Van Der Perk, 2006)

This ammonification or mineralization process follows nitrogen fixation and occurs through the oxidation of organic nitrogen into amino acids and ammonium nitrogen (NH_4^+-N). Subsequent to ammonification, autotrophic bacteria belonging to the *Nitrosomonas* and *Nitrobacter* genera oxidise NH_4^+-N to form nitrate-nitrogen (NO_3^--N) and the ephemeral nitrite-nitrogen (NO_2^--N) (Braskerud, 2002). The high reactivity of NO_2^- reduces its residence time in soils, resulting in the primary nitrogen compounds found in soil being NH_4^+-N and NO_3^--N. The oxidation of NH_4^+-N to NO_3^--N and NO_2^--N described above only occurs under aerobic (oxygenated) conditions and is known as nitrification (Carpenter *et al.*, 1998).

NH_4^+-N and NO_3^--N compounds are usually cycled through the system via one of three paths: assimilation, volatilisation and denitrification. Commonly, primary producers and certain microorganisms may assimilate these compounds for utilisation in growth, development and reproduction processes. Alternatively, NO_3^--N and NH_4^+-N compounds may be removed through denitrification and volatilisation processes respectively. Denitrification is the reduction of NO_3^--N to N_2 or N_2O primarily by bacteria. The process occurs under anaerobic or reduced conditions and is dependent on water content, temperature and presence of carbon sources and nitrate. This process is not, however, the opposite of nitrification as intermediaries formed during denitrification such as nitric oxide (NO) and nitrous oxide (N_2O) may be rapidly lost from the system through volatilisation before the denitrification reaction is completed (Carmago *et al.*, 2005; Larsson *et al.*, 2005). Volatilisation, on the other hand, describes the gaseous loss of ammonia (NH_3-N) through the reduction of NH_4^+-N (Van der Perk, 2006).

Inorganic nitrogen may also be assimilated and rendered temporarily unavailable to primary producers through the process of immobilisation. This process is the opposite of mineralization and is influenced by the organic carbon to nitrogen (C:N) ratio prevalent in a particular soil microbial biomass. The typical C:N ratio in soil is 20:1. Therefore, if nitrogen is limiting relative to organic carbon (C:N<20), mineralization is favoured and when the C:N ratio is above 20, net immobilisation is favoured. Although the processes briefly detailed above are considered important in the nitrogen cycle, processes such as nitrogen fixation and ammonium volatilisation are considered relatively inconsequential compared to processes such as ammonification, nitrification, denitrification and assimilation (Neitsch *et al.*, 2005; Van Der Perk, 2006).

It is important to note that all the processes outlined above are influenced, in some way or the other, by the prevalent hydroclimatic conditions, *i.e.* precipitation and temperature variability. Having briefly introduced the chemical processes and fluxes that constitute the nitrogen cycle, the following section will be a detailed assessment of the physical nitrogen transport mechanisms across the landscape.

3.2.4   Nitrogen Migration

Many studies on nitrogen migration tend to be restricted to local catchments where the prevailing hydrological and climatic regimes are well known (Quinn, 2004). Although this may preclude the identification of geographically extensive mechanisms that control nitrogen transfer dynamics (Alvarez-Cobelas *et al.,* 2008), it warrants the isolation and mapping of unique local catchment pulses that govern nitrogen migration (Pellerin *et al.,* 2004). This enables the design and application of management strategies that are both relevant and specific to the catchment in question. The discussion contained in this and following sections will, therefore, be in reference to South African catchments and the prevailing local hydroclimatic conditions will be considered as a backdrop of the overall discussion.

The movement of nitrogen across the landscape is highly dependent on the availability of water (Figure 3.2). Additionally, temperature indirectly influences nitrogen migration by limiting the ability of bacteria to facilitate nitrogen transformation reactions (Carmago *et al.,* 2005). In a study detailing the migration of nitrates across a watershed in Whatcom County, Washington, the highest concentrations of nitrates were primarily found in subcatchments with the highest number of water bodies. In such instances, nitrate concentrations were found to be as high as 39 and 19.7 mg/l in some of the water bodies studied (Almasri and Kaluarachchi, 2004). This study also showed that leaching and runoff are the main transport mechanisms by which nitrogen is transported to downstream areas and water bodies where it is deposited and may, in association with other nutrients and high enough concentrations, trigger eutrophication. Both leaching and runoff are functions of soil moisture content and precipitation and are highly influenced by local hydroclimatic regimes (UNEP, 2010).

Pellerin *et al.* (2004) note that the ability of wetlands to increase water retention times influences the export of nitrogen by streams by promoting nitrogen retention and volatilisation through sedimentation and denitrification respectively. In the study by Almasri and Kaluarachchi (2004) the highest concentrations of nitrates were also found in watersheds with the highest average annual precipitation.

Of the forms of available inorganic nitrogen, nitrate-nitrogen (NO_3^--N) is considered the most mobile anion and migrates easily through terrestrial and aquatic ecosystems (Van Der Perk, 2006), as it is a water soluble anion that is not readily absorbed to soil particles (Felton *et al.,* 2008). As noted above, the ability of NO_3^--N to migrate so easily warrants high levels of concern for environmental pollution and human health. In addition to nitrate-nitrogen, the soluble component of inorganic nitrogen also includes ammonium-nitrogen (NH_4^+-N). Similar to NO_3^--N, NH_4^+-N is also considered to migrate by surface and subsurface leaching and by runoff. However, the environmental and human-related impacts of NH_4^+-N are considered inconsequential relative to those of NO_3^--N. It is perhaps important to note that the migration of nitrogen through terrestrial and aquatic ecosystems is not limited only to its elemental soluble forms. Nitrogen is, in fact, considered to be transported in both dissolved and suspended forms. Particulate nitrogen species (*e.g.* HNO_3) are known to migrate by adsorption onto sediment material generated from upstream erosion or from bank and bed erosion in the stream channel (Viney *et al.,* 2000). Although particulate forms of nitrogen are not transported conservatively (*i.e.* do not remain constant over space and time) as opposed to their soluble counterparts, they still subscribe to processes of surface erosion, entrainment, runoff (baseflow plus quickflow discharge), settling and deposition. Therefore, by deduction, hydroclimatic and biophysical processes which influence these transport processes also influence the transport of particulate nitrogen species. Figure 3.3 is an extended diagram of the processes detailed in Figure 3.2 to include transport processes of particulate nitrogen species. Table 3.1 provides a summary of the various natural and anthropogenic sources of nitrates and their compositional and delivery characteristics.

Table 3.1 Anthropogenic and natural sources of nitrate including general delivery characteristics, chemical compositions and conservation of mass (Adapted from Withers and Jarvie, 2008).

Source	Delivery		Chemical Composition	Conservation of Mass*	Reference
	Discharge	**Rainfall Dependency**			
Fertilizer Applications (Pastures, Feedlots etc.)	Episodic to semi-continuous	Low to Medium	Variable Particulate	No	Larsson *et al.,* (2005); Withers and Jarvie (2008)
Fertilizer Applications (Irrigation, Return flows etc.)	Episodic to semi-continuous	High	Variable Dissolved	Yes	Withers and Jarvie (2008); Pärn *et al.,* (2011)
Industrial	Continuous	Low to Medium	Concentrated Dissolved	No	Edwards and Withers (2008)
Septic Tanks	Episodic to semi-continuous	Low to Medium	Variable Particulate	No	Carpenter *et al.,* (1998)
Landfill Sites	Continuous	High	Variable Particulate	No	Honisch *et al.,* (2002)
Sewage and Wastewater Treatment Works	Continuous	Low	Concentrated Dissolved	Yes	Novotny (2003)
Rainfall Fallout	Episodic	High	Variable Dissolved	Yes	Author
Residential	Continuous	Medium to High	Variable Dissolved	No	Novotny (2003)
Dry Deposition	Episodic	Low	Variable Particulate	No	Han *et al.,* (2010)

*Changes in concentration as nutrient is translocated across the landscape.

Although nitrogen is a critical element in the functioning of terrestrial and aquatic ecosystems, the incidence of this element in abnormally high concentrations can have deleterious impacts. However, these impacts only manifest when nitrogen exists in conjunction with other nutrients. For instance, eutrophication, an increasing water quality management problem in many global and local waterways, is commonly caused by both nitrogen and phosphorus. Since the focus of this section is limited to these two elements, the following section details the cycling and transport of phosphorus in terrestrial and aquatic ecosystems.
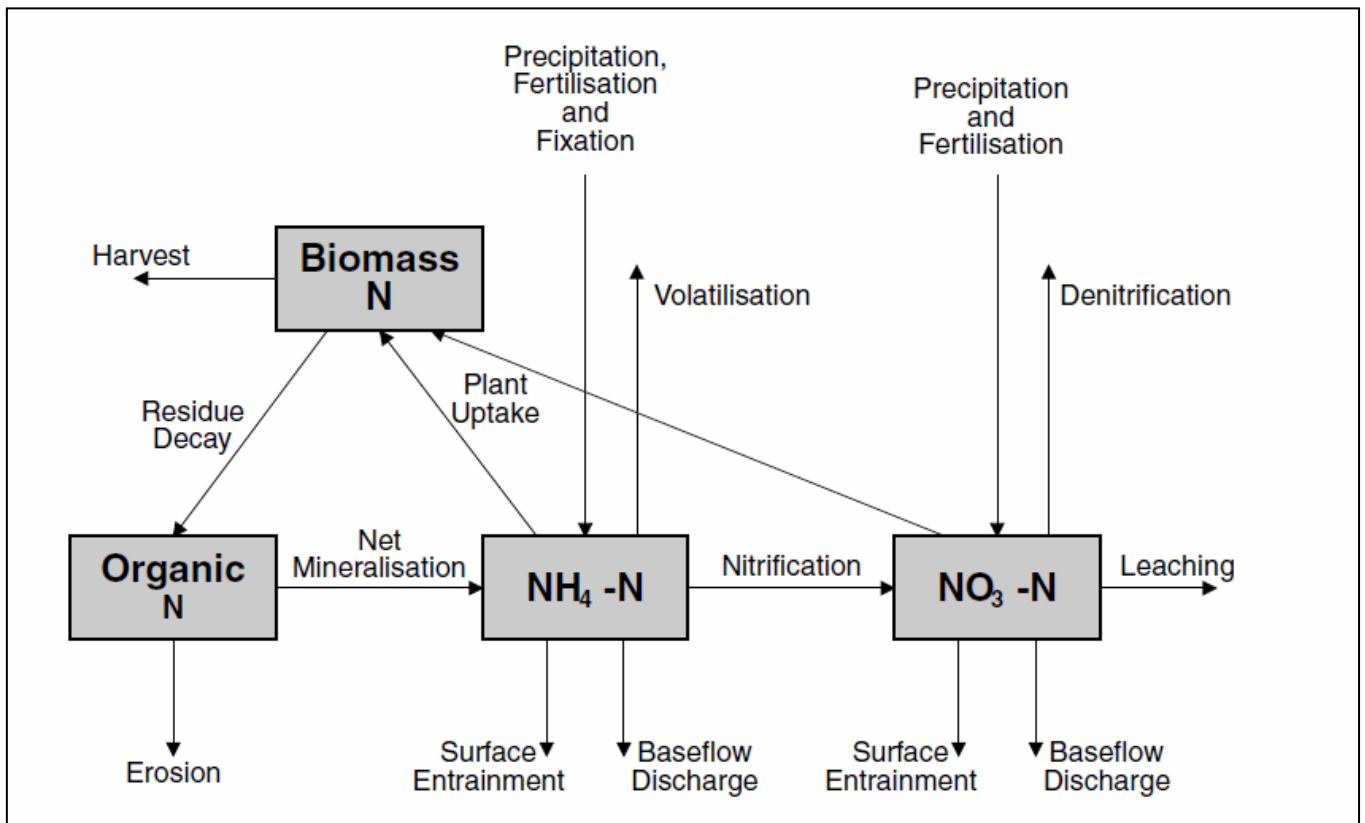
Figure 3.3 Structure of the nitrogen cycle including particulate nitrogen transport processes (Viney *et al.,* 2000).

3.2.5 Phosphorus

Phosphorus (P), akin to nitrogen (N), is an essential nutrient for all organic life forms. It is an essential element critical in various cellular biochemical processes such as energy production and transfer (*i.e.* ATP) and as a constituent of essential proteins such as DNA and RNA (Deasy *et al.,* 2007). In the environment, P primarily occurs as mineral-P, occluded-P, non-occluded P and organic-P. Mineral-P is generally the dominant form of P in the environment and progressive dissolution of mineral-P yields the organic, occluded and non-occluded forms of P (Van Der Perk, 2006). P is subject to the same transport mechanisms as N, in that it is transported in both dissolved and suspended (or particulate) forms. Although nutrient cycling processes account for a large proportion of P migration, catchment connectivity is an equally important factor in P transport. Catchment connectivity essentially describes the ability of landscape compartments to convey matter or energy across one another (Fryirs *et al.,* 2007) and will be discussed in greater detail in subsequent sections.

3.2.6 The Phosphorus Cycle

The terrestrial P-cycle, summarised in Figure 3.4, is relatively less complex in comparison to the nitrogen cycle. This is because unlike nitrogen, phosphorus occurs in fewer forms in the environment and does not have volatile gaseous derivatives. Weathered from bedrock through the dissolution of phosphorus-bearing minerals such as apatite $(Ca_{10}(PO_4)_6(OH,F,Cl)_2)$, P solubilised during weathering is usually available for uptake by plants and other microorganisms (Sims *et al.,* 1998; Van Der Perk, 2006). However, once in the soil solution, P is commonly unavailable for uptake. This is due to the strong sorption of P by various soil constituents, particularly ferric iron and aluminium hydroxides. Although the bioavailability of P in the soil solution is low, plants and other organisms are able to extract small portions through various physiological strategies (*e.g.* ion-exchange and chelation mechanisms) (Barros *et al.,* 2005). The transfer of P across the landscape is significantly influenced by ion-exchange dynamics and gradients within the soil solution (Schindler, 2006). Therefore, by introducing above-normal loads of P into the environment through anthropogenic activities, the bioavailability of P is increased and this can present significant environmental health problems.
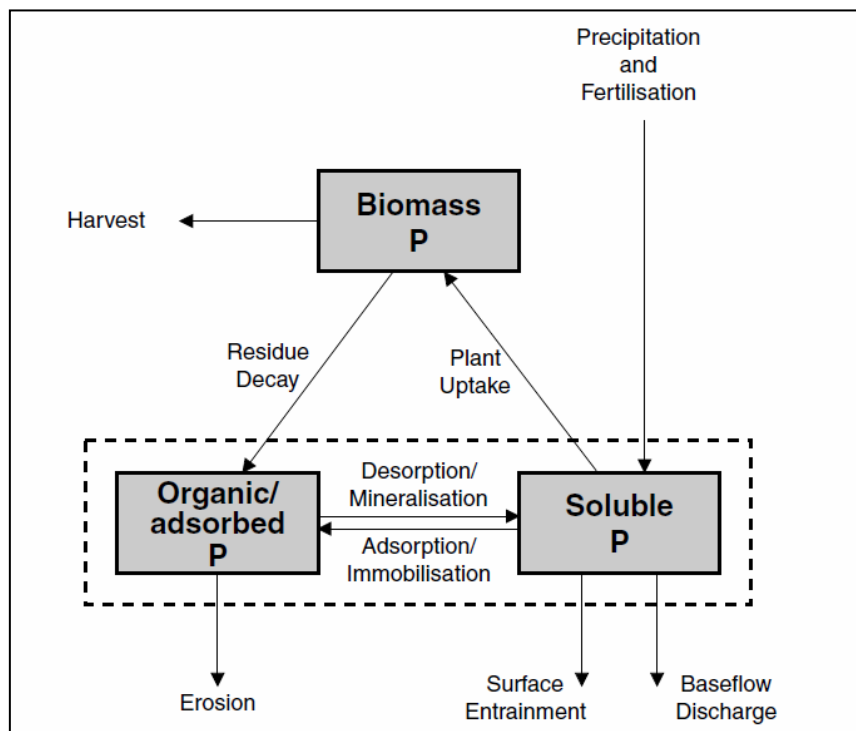
Figure 3.4   Structure of the phosphorus cycle including particulate phosphorus transport processes (Viney *et al.,* 2000)

3.2.7   Phosphorus Migration

P is either transferred in dissolved or soluble form or attached to sediment as particulate or colloidal P (Heathwaite and Dils, 2000). Similar to N, dissolved P is routed conservatively through the catchment via leaching and runoff processes such as surface entrainment, interflow, baseflow and quickflow discharge. The particulate portion of P generally moves through the landscape via erosion and sediment conveyance processes and is not routed conservatively. Figure 3.5 is an example of the various processes through which P migrates through an agricultural catchment. Surface runoff from uncultivated soil or from disjunct and adjunct impervious areas generally carries little sediment and is therefore dominated by dissolved P (Shigaki *et al.,* 2006).
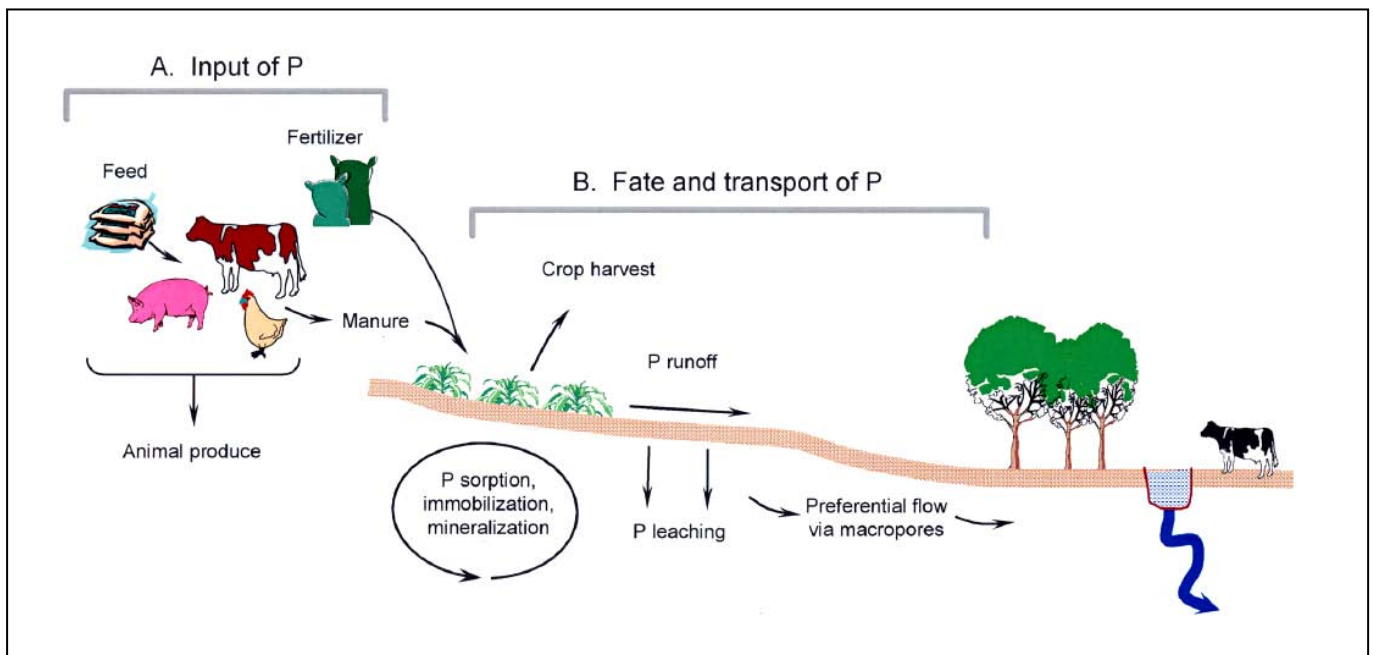
Figure 3.5   Factors affecting the input, fate and transport of P in agricultural catchments (Shigaki *et al.,* 2006).

Mainstone *et al.* (2008) note that particulate P attached to sediment can constitute up to 60% of P lost from agricultural land through surface runoff. This implies that installing runoff and erosion control measures such as contours and embankments is critical in minimizing P loss from agricultural land. P is generally released when incident precipitation or irrigation water interacts with a thin layer of surface soil prior to leaving the field as surface runoff. Although soluble P is usually found in higher concentrations in the environment in comparison to particulate P, the latter can serve as a long term source for algae in waterways and reservoirs (McDowell and Wilcock, 2004).

The extent and degree of catchment connectivity can also significantly affect the migration of P. The connectivity of landscape compartments affects sediment conveyance processes in response to external disturbances of varying frequency and magnitude (Fryirs *et al.,* 2007). For instance, highly urbanized catchments usually display high degrees of connectivity compared to their more rural counterparts. This is due to the high proportion of impervious areas in urban environment which favour better conveyance of matter and energy. Therefore, within these catchments, P can be expected to be transported with relative ease and over larger areas. In rural or agricultural catchments, however, connectivity is usually broken by the incidence of buffers. These buffers include riparian zone strips, wetlands and dams. In catchments where such buffers occur in high degrees, P migration is limited. However, this also presents numerous disadvantages in that the increase in concentration and load of P in these buffers favours eutrophic conditions which results in the deterioration of their water quality. This discussion indicates that the source generation and distribution of P is highly dependent on the magnitude and intensity of rainfall since rainfall drives subsurface leaching and surface runoff. Therefore, under conditions of an altered climate, where the variability of rainfall events is expected to change, the rate and direction of P migration can also be expected to change. Table 3.2, like Table 3.1 for nitrates, provides a summary of the various natural and anthropogenic sources of phosphates discharged to water and their compositional and delivery characteristics.

Table 3.2 Anthropogenic and natural sources of phosphates including general delivery characteristics, chemical compositions and conservation of mass (Adapted from Withers and Jarvie (2008)).

Source	Delivery		Chemical Composition	Conservation of Mass*	Reference
	Discharge	**Rainfall Dependency**			
Fertilizer Application (Pastures, Feedlots etc.)	Episodic to semi-continuous	Low to Medium	Variable Particulate	No	Carpenter *et al.,* (1998); Withers and Jarvie (2008)
Fertilizer Application (Irrigation, Return flows etc.)	Episodic to semi-continuous	High	Variable Dissolved	Yes	Carpenter *et al.,* (1998); Withers and Jarvie (2008);
Industrial	Continuous	Low	Concentrated Dissolved	No	Author
Septic Tanks	Episodic to semi-continuous	Medium	Variable Particulate	No	Carpenter *et al.,* (1998)
Landfill Sites	Continuous	High	Variable Particulate	No	Deasy *et al.,* (2007)
Sewage and Wastewater Treatment Works	Continuous	Low	Concentrated Dissolved	Yes	Novotny (2003)
Rainfall Fallout	Episodic	High	Variable Dissolved	Yes	Author
Wetlands	Episodic to semi-continuous	High	Variable Dissolved	No	Braskerud (2002)
Suspended Sediment	Episodic	Low	Variable Particulate	No	Han *et al.,* (2010)

*Changes in concentration as nutrient is translocated across the landscape.

This section has described, albeit briefly, the processes involved in the migration of nutrients in the environment and the hydroclimatic processes which influence the transport of these nutrients. Since the aim of this review is to assess the relationships that exist between climate change and the transfer dynamics of sediment and nutrients, the following section provides a brief description of the processes influencing catchment-scale sediment delivery.

3.2.8   Catchment Scale Sediment Transfer

The generally accepted theory of catchment scale sediment transfer follows the notion that upstream sources of runoff and sediment are (dis)connected to their corresponding downstream sinks through linkages referred to as hydrological and sedimentological connectivity (Fryirs *et al.,* 2007; Gumiere *et al.,* 2011). Hydrological connectivity refers to "the transfer of water from one part of the landscape to another" while sedimentological connectivity refers to the "physical transfer of sediment and attached pollutants through the drainage basin" (Bracken and Croke, 2007). Erosion generates sediment by detaching and transporting soil particles through the erosive forces of raindrops and surface flow of water. The detached soil particles then traverse the landscape through natural and artificial rills, gullies and channels and progressively move into ephemeral streams (should they exist) and finally into continuously flowing river channels. Depending on the degree of connectivity characteristic of the catchment, sediment particles can be entrained and deposited at any point along the river channel flow path (Neitsch *et al.,* 2005).

Although erosion and sedimentation processes are strongly influenced by environmental factors such as climate, morphology, relief, geology and soil type, it is the extent and type of land uses and land use changes unique to each catchment which are the key controls influencing the generation, transfer and deposition of sediment (Lexartza-Artza and Wainwright, 2011). Additionally, Vericat and Batalla (2005) note that sediment is transferred through the catchment continuously, with the river channel serving as a "conveyor belt" for the transfer of erosional products downstream to the ultimate depositional sites. Therefore, any breaks in catchment continuity through land use will directly influence the rate of sediment transfer. Dams, for instance, are considered to be highly effective in disrupting the continuity of sediment transfer by trapping bedload and a considerable amount of suspended sediment (McCartney, 2009). However, not only does this cause dam sedimentation resulting in the long-term reduction of reservoir storage capacity (Heathwaite *et al.,* 2004), but it also introduces sediment-associated pollutants into receiving waters thus creating serious water quality problems (Ng Kee Wong *et al.,* 2002; Leigh *et al.,* 2010).

Although erosion is a process that occurs naturally; human influences have been shown to accelerate the rate of erosion (Steegen *et al.,* 2001; Bjoneberg *et al.,* 2006). Hence catchments

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with high degrees of human influences coupled with high connectivity (*e.g.* highly disturbed catchments or catchments with limited sediment storage compartments such as dams or wetlands) may be expected to experience greater degrees of sediment related pollution. Furthermore, the connectivity of landscape compartments affects sediment transfer processes in response to external disturbances of varying frequency and magnitude (Fryirs *et al.,* 2007). Therefore, under conditions of an altered climate, the source generation and distribution of sediment is highly likely to change due to, for example, the anticipated increased magnitude and intensity of rainfall events (Heathwaite and Dils, 2000). Soil erosion is usually computed using Modified Universal Soil Loss Equation (MUSLE; Eq. 2) (Williams, 1975). The MUSLE equation is a modified version of the Universal Soil Loss Equation (USLE; Eq. 1) developed by Wischmeier and Smith (1978). According to the Soil and Water Assessment Tool (SWAT) Manual, the USLE equation uses rainfall energy to estimate average annual gross erosion whereas the MUSLE equation replaces this energy factor with a runoff factor. This is considered to improve sediment yield prediction, eliminate the need for sediment delivery ratios and facilitate the application of the equation to individual storm events (Neitsch *et al.,* 2005).

The USLE equation estimates average annual soil loss from:

$$A = R.K.LS.C.S.P \qquad\qquad (1)$$

And MUSLE estimates average annual soil loss from:

$$A = 11.8\ (Q_{surf}.\ Q_{peak}.\ Area_{hru})^{0.56}.\ K.C.P.LS.CFRG \qquad (2)$$

Where, in both equations 1 and 2, *A* is the estimated soil loss per unit area (metric tons), *K* is the soil erodibility factor (0.013 metric ton m^2 .hr/ (m^3-metric ton cm)), *L* is the slope-length factor, *S* is the slope-steepness factor, *C* is the cover and management factor and *P* is the support practice factor. In equation 1, *R* is the rainfall erosivity (or rainfall energy) factor (0.017 m-metric ton cm/ (m^2 hr)) and in equation 2, Q_{surf} is the surface runoff volume (mm H$_2$O/ha), Q_{peak} is the peak runoff rate (m^3/s), $Area_{hru}$ is the area of the hydrological response unit (HRU) (ha) and *CRFG* is the coarse fragment factor (Merritt *et al.,* 2003; Neitsch *et al.,* 2005).

The USLE soil loss model has a number of limitations. The model is not event-based, which essentially implies that it cannot identify events which are most likely to result in large-scale erosion (Merritt *et al.,* 2003). Gully erosion and mass movement are omitted and the model should not be applied outside the United States (where the model was developed) due to data constraints. Therefore, a number of modifications and revisions to the USLE have been proposed. These include the previously discussed MUSLE model, the Revised USLE (RUSLE) model (Renard *et al.,* 1994) and the USLE-M model (Kimmel and Risse, 1998).

This section has briefly described the processes involved in the migration of nutrients and sediment in the environment and the hydroclimatic processes which influence their transport. Since the aim of this review was to assess the relationships that exist between sediment and nutrient transfer and projected climate change, the following section details the implications an altered climate presents for sediment and nutrient transfer.

3.3   Impacts of Projected Hydro-Climatic Changes on Sediment and Nutrient Dynamics

3.3.1   Impacts of Altered Precipitation Variability

Changes in climate variables, including precipitation (depth, duration and frequency), are expected to alter the transfer dynamics of sediment and nutrients worldwide (Jeppesen *et al.,* 2011). Although not well understood over the full range of scales necessary for management, the relationships between precipitation variability, sediment delivery and nutrient transfer have been extensively studied (*e.g.* Viney and Sivapalan, 1996; McNamara and Cornish, 2004; Low, 2005; IPCC, 2007, Bates *et al.,* 2008; Statham, 2011). In South Africa, for instance, an extensive climate change study was conducted in which the projected impacts of climate change on the water resources of the country were assessed through climate scenario development and impact modelling (Schulze *et al.,* 2005). With respect to precipitation trends under climate change, some of the findings of this study were that increases in precipitation, increases in raindays and increases in rainfall event intensities may be expected for eastern and central parts of the country and the opposite is anticipated for western regions of the country (Hewitson *et al.,* 2005).

The statements made by Hewitson *et al.,* (2005), therefore suggest that in countries such as South Africa, in which climate change related increases in precipitation and runoff are anticipated, an increase in the rate at which sediment and nutrients are generated and transferred across catchments located in eastern and central regions of the country may also be anticipated.

The timing and volume of runoff within a catchment is intrinsically linked to seasonal climate variability and change, particularly rainfall variability (Shrestha *et al.,* 2012). Furthermore, the transfer of sediment and nutrients from upstream sources to downstream sinks has been shown to be highly sensitive to climatic factors (Donohue *et al.,* 2005; Jeppesen *et al.,* 2011). Table 3.3, for instance, summarises the relationship between extreme climate change, rainfall variability and sediment and nutrient transfer. Table 3.4, on the other hand, provides a list of locally relevant, climate-sensitive biophysical processes and parameters that are anticipated to be impacted by climate change. Taking into consideration the sensitivity of runoff to rainfall variability, any changes in rainfall can, therefore, be expected to produce considerable changes in the dynamics of sediment and nutrient generation and transfer. For instance, heavy rainfall events (long/short duration, high intensity) result in increased erosion and the generation of high volumes of stormflow and runoff which subsequently leads to high sediment and nutrient generation and transport. Additionally, high intensity rainfall events can lead to the "flash" generation and rapid transport of stored sediment and nutrients through the sheer force of raindrops.

A lot of uncertainties abound in climate change predictive modelling, especially in rainfall-runoff modelling (Hewitson *et al.,* 2005; Bates *et al.,* 2008). However, these uncertainties are mitigated somewhat by the fact that the currently understood relationships between rainfall, runoff and non-point source pollution transport can be used as reliable benchmarks for future predictions (Christiansen *et al.,* 2004). To complete the discussion regarding the impacts of hydroclimatic changes on sediment and nutrient transfer, the following section details the effects of temperature on these parameters.

Table 3.3 Projected changes in precipitation trends and impacts on sediment and nutrient generation, transfer and deposition constructed from a survey of the literature.

i. Changes in climatic phenomena (derived from: IPCC 2001; Hewitson *et al.,* 2005; IPCC, 2007; Bates *et al.,* 2008)	ii. Consequence on hydrologic processes	iii. Impact on sediment	iv. Impact on nutrients (N and P)
Heavy precipitation events with increased frequency (*i.e.* floods).	High stormflow and runoff volumes and increased streamflow (Jeppessen *et al.,* 2011; Hewitson *et al.,* 2005).	Increased transport of sediment from source generation areas (*e.g.* landslides and soil slips) (Heathwaite and Dils, 2000; Fryirs *et al.,* 2007).	Increased flushing of nutrients from source generation areas (EPA, 2009). Increased water renewal of water bodies leading to washout of nutrients (Rosberg and Arheimer, 2007).
High intensity events.	Rapid generation of stormflow and runoff (IPCC, 2001; 2007; Bates *et al.,* 2008).	Increased soil erodibility due to high raindrop energy (Mainstone *et al.,* 2008).	Altered mixing patterns in stratified reservoirs (Tsujimura, 2004).
Increased variability of precipitation.	Increased inter-annual variability of runoff and streamflow (IPCC, 2001; 2007; Bates *et al.,* 2008).	Increased variability in sediment transfer trends (Withers and Sharpley, 2007).	Increased variability in nutrient cycling trends, increased variability in the timing of nutrient delivery (Van Der Perk, 2006).
Reduced precipitation events with increased frequency (*i.e.* droughts).	Low volumes of stormflow and runoff and reduced streamflow (Hewitson *et al.,* 2005).	Higher deposition of sediment in sink areas (*e.g.* floodplains and estuaries) (Fryirs *et al.,* 2007).	Reduced dilution capacities, increased pollutant toxicity (*e.g.* nitrate toxicity) (Carpenter *et al.,* 2008).
		Reduced transport of sediment from source to sinks (McKergow *et al.,* 2006).	Reduced transport of nutrients from sources to sinks but increased storage of nutrients (Mainstone *et al.,* 2008).

Table 3.4   Selected climate-sensitive processes linked to climate change and their impacts on water quality*. The probable direction of change of these processes under climate change is indicated by the arrows**. Processes and trends in a particular row are not connected.

SEDIMENTS	NUTRIENTS	BIOCHEMICAL PROCESSES
Particle detachment/Erosion (↑)	Fertilizer, manure and crop residue application (timing and rates) (↔)	Organic matter decomposition (release of N and P) (↑)
Overland flow (↑)	Fixation (↑)	Mercury mobilisation (caused by a build up of benthic anoxic layers) (↑)
Instream sediment transport/Bed-load transport (↑)	Ammonification (↔)	Denitrification (e.g. in wetlands and riparian buffers) (↔)
Flow types (Laminar vs Turbulent) (↔)	Mineralization (↑)	Acidification (increased deposition of N and P and releases of H ions) (↑)
Attenuation of sediment conveyance (↓)	Conversion of Organic N and P to Mineral N and P (↔)	Solubility of gases (high temp. reduces solubility of oxygen) (↓)
Sedimentation (↑)	Wet and Dry deposition (↑)	pH fluctuations (↔)
Particle settling (i.e. rates) (↓)	Leaching (↑)	N and P transformation (↑)
Suspension and Resuspension (influence on Turbidity and light pen.) (↑)	Hydraulic conductivity (as related to how easily nutrients move through soil) (↑)	Eutrophication (as the culmination of the impacts of NPS pollution of water resources) (↑)
Shear stress (influence on detachment) (↑)	Subsurface flow (inclusive of g/water flow and recharge) (↑)	Formation of hypoxic zones (↑)

Deposition **(↑)**	Surface runoff (excess N and P) **(↑)**	Increased residence times (Increased growth of algae and cyanobacteria) **(↑)**
Riverbank scouring **(↑)**	Dilution (capacity of stream to dilute nutrients) **(↑)**	Solubilization of nutrients **(↑)**
Phosphorus adsorption by very fine sediments **(↑)**	Washout during extreme events **(↑)**	Chelation **(↔)**
Transport of adsorbed nutrients **(↑)**	Salinisation **(↑)**	Mineralization-immobilization turnover (MIT) **(↑)**
Lagging of downstream conveyance **(↓)**	Volatilisation/Evaporation **(↑)**	Heterotrophic nitrification **(↑)**
Tributary transport capacities **(↓)**	Effluent seepage **(↑)**	
Breaching capacity of buffers **(↓)**	Preferential flow via macropores **(↑)**	
Selective size segregation **(↓)**	Plant uptake **(↑)**	
Sediment transport through overland flow **(↑)**	SOM formation (contributing to N and P retention in soil) **(↑)**	

* References: Novotny, 2003; Van der Perk, 2006; Heathwaite and Dils, 2000; Fryirs *et al.,* 2007; Carmago *et al.,* 2005; Withers and Jarvie, 2008; Withers and Sharpley, 2007; Smithers and Schulze, 2004; McDowell and Wilcock, 2004; Deasy *et al.,* 2007; IPCC, 2001; IPCC, 2007; Bates *et al.,* 2008; UNESCO, 2009.

** ↑ implies a highly probable increase, enhancement or exacerbation of the process under climate change.

↓ implies a highly probable decrease, retardation or impairment of the process under climate change.

↔ probable direction of change under climate change not known or not sufficiently documented in the literature to fully ascertain direction of change.

3.3.2   Impacts of Temperature Changes

Temperature is perhaps the most important climatological parameter in the climate change discussion. Explicitly or implicitly, temperature directly influences the supply of energy necessary for the initiation and catalysis of critical physicochemical reactions and climatological processes (Warburton *et al.,* 2005). Not only does this ensure the continued functioning of terrestrial and aquatic ecosystems, but it also limits the rate at which both hydrological and biophysical processes proceed. In the context of this review, the implication of the previous statement is that any changes in temperature may be expected to have cascading effects on the hydrological processes which influence the transfer of sediment and nutrients. For instance, sediment is considered as a major transport medium for nutrients such as nitrogen and phosphorus (Slattery and Burt, 1997).

Consequently, since the generation and transfer of sediment and nutrients is highly sensitive to climatic and land use factors (Donohue *et al.,* 2005; Jeppesen *et al.,* 2011), particularly rainfall-runoff relationships (Bates *et al.*, 2008), changes in rainfall (influenced by changes in temperature and, thus, evaporation) resulting in changes in runoff processes can be expected to trigger changes in the generation and rate of transfer of sediment and thus nutrients (see Chapter 5). The relationships between temperature and rainfall have been well studied (*e.g.* Gleick, 2000; Schulze and Maharaj, 2004; Pittock, 2009). Temperature is a major driver of evaporation and condensation processes which ultimately drive the propagation of precipitation (Warburton *et al.,* 2005; IPCC, 2001; IPCC, 2007). Therefore, the anticipated increases in temperature associated with climate change may result in increased evaporation rates which may lead to increased precipitation. Increases in rainfall will, ultimately, result in increased soil erosion and runoff generation and this, as aforementioned, may lead to increased rates of sediment and nutrient generation and transfer.

Although erosion has increased both globally and locally largely owing to anthropogenic land-use change, there is limited data supporting or opposing past climate-related changes in erosion and, thus, sediment transport (Water Research Commission, 2002; IPCC, 2007). However, the anticipated increases in rainfall intensity would necessarily lead to increased rates of soil erosion and, thus, increased sediment generation and transfer (see Chapter 5).

As shown in Section 3.2, phosphorus is a sediment-associated nutrient and is usually transported bound to sediment (McDowell and Wilcock, 2004; Bjoneberg, 2006). Owing to the reduced dissolved oxygen concentrations in fluvial systems initiated by rising temperatures, increased releases of phosphorus bound to sediment are anticipated (IPCC, 2007). This presents numerous implications for catchment water quality management.

Temperature does not directly influence the generation, transfer and deposition of sediment and nutrients. However, it is an important driver of the processes which facilitate the generation and transfer of nutrients. For instance, nitrogen retention and volatilization in wetlands is highly dependent on the ability of the wetland(s) to retain water, thus facilitating anaerobic conditions which promote volatilization (Pellerin *et al.,* 2004). Additionally, temperature indirectly influences nitrogen migration by driving bacterial activation and deactivation temperature thresholds, thus affecting the ability of the bacteria to facilitate nitrogen transformation reactions (Carmago *et al.,* 2005). Similarly, the influence of temperature on rainfall and consequently on runoff processes, influences the transfer of sediment and sediment-bound phosphorus. Evidently, the influence of temperature on the generation, transport and deposition of nutrients and sediment is equally important as that of rainfall. The development of a complete understanding of the potential impacts of climate change on water quality, therefore, requires due consideration of the critical influence that temperature has on the biophysical processes that govern the behaviour of nutrients and sediment.

3.4   Discussion and Conclusions

As part of the overarching aim of this work, recognizing and characterizing the relationships that exist between climate change, sediment and nutrient generation, transfer and deposition was considered critical in the development of adaptation strategies for local water resources management (see Chapters 4, 5 and 6). Furthermore, since the main aim of this work was the development of management specific adaptation strategies based on hydrological and climate modelling, it was important that a sound scientific background be developed in order to inform the modelling. This literature review served to provide an understanding of the impacts of climate change on biophysical processes governing the transfer of sediment and nutrients. For instance, the majority of processes governing the transport of nutrients from source areas require the presence of water as a transport medium. This review showed that since these processes are highly sensitive to climatic factors, including precipitation, the projected changes in temperature and precipitation variability (see Section 3.3) will most probably alter the transfer dynamics of nutrients. The same argument applies to sediment. Based on these findings, it is concluded that the anticipated temperature and rainfall changes will most likely increase the rates at which the processes that govern the generation and transport of nutrients and sediment proceed (Tables 3.3 and 3.4), which will consequently increase the rates at which these WQ variables move across the landscape.

By way of example, it was shown in this review (*e.g.* Mainstone *et al.,* 2008, Section 3.2) that the physicochemical behaviour of phosphorus in fluvial systems is highly sensitive to temperature changes. High water temperatures facilitate reduced dissolved oxygen concentration conditions, which trigger the release of sediment-bound phosphorus. Considering the fact that phosphorus is a limiting nutrient in many fluvial systems, increased phosphorus concentrations in these systems can lead to serious water quality problems, such as eutrophication and algal blooms. Similarly, the numerous transformation reactions that occur throughout the nitrogen cycle are carried out or facilitated by temperature-sensitive bacteria. For instance, the release of nitrate through the nitrification process is carried out by bacteria belonging to the *Nitrosomonas* and *Nitrobacter* genera and significant increases in temperature (Table 3.4) can deactivate these bacteria, thus reducing the release of nitrates from their sources.

Although a reduction in the release of nitrates may be favourable in the water quality management context, in the agricultural food production context it can be a highly negative consequence to increased temperature since the same bacteria are critical in releasing essential nutrients for utilisation by crops.

Projected increases in rainfall intensity are anticipated to lead to increased particle detachment (higher kinetic energy of raindrops), erosion and, consequently, increased sediment generation and transport. Not only will this result in major soil loss in agricultural catchments but it will also increase reservoir sedimentation and pollutant discharge. This will present numerous challenges for water quality management both globally and locally. Table 3.4 presented a summary of the most probable directions of change with regard to climate-sensitive processes. In most cases, the anticipated increases in temperature and rainfall intensity are expected to result in an increase or exacerbation of the rate at which these processes are going to occur. The implication of these changes is that in South Africa, the expected amplification of the variability of an already highly variable hydroclimate will require a radical shift of the current water quality management paradigms. This will ensure better preparedness for the water quality related consequences of extreme events.

This review was carried out from a perspective of a highly variable and dynamic climate regime and a perspective that climate change will exacerbate these patterns; that is, climate change that favours increases in the variability of both temperature and rainfall. The reason behind this was that the arguments presented herein were based on available climate projections specific to South Africa. These climate change projections are consistent in suggesting increased temperature and rainfall variability for most parts of the country, particularly the eastern and central parts (see Hewitson *et al.,* 2005). The opposite, however, is also possible. The western regions of the country, for instance, are expected to experience reduced rainfall and increased temperatures. Reduced rainfall would not only limit the downstream transfer of sediment and nutrients, but it would also result in reduced dilution capacities for fluvial systems, which would increase the toxicity of pollutants and present water quality problems. The consequences of these conditions would cascade throughout terrestrial and aquatic ecosystems and would create even more complex problems for water resources management in the western regions of South Africa.

Therefore, regardless of whether climate change results in "positive" impacts (*e.g.* increased runoff from high rainfall events) or "negative" impacts (*e.g.* increased risks of floods and droughts), the development of the necessary adaptation strategies requires an approach that recognises both ends of the spectrum (*i.e.* "positive" and "negative" consequences of climate change) in order to ensure that flexibility is incorporated in those strategies.

3.5 Acknowledgements

3.6 References

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CHAPTER FOUR

Projected Impacts of Climate Change and Mitigating Effects of a Perennial

Wetland on Selected Water Quality Constituents in the Mkabela Catchment,

South Africa

4. PROJECTED IMPACTS OF CLIMATE CHANGE AND MITIGATING EFFECTS OF A PERENNIAL WETLAND ON SELECTED WATER QUALITY CONSTITUENTS IN THE MKABELA CATCHMENT, SOUTH AFRICA

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ABSTRACT

The projected impacts of climate change have increased concerns over the supply of adequate quality freshwater. There is an inadequate body of knowledge pertaining to linking the basic hydrological processes which drive water quality (WQ) variability with projected climate change. Incorporating that research into policy development and governance with the intention of developing adaptive WQ management strategies is also largely overlooked. This paper assesses projected climate change impacts on selected WQ constituents (sediment, nitrogen and phosphorus) in the context of agricultural non-point source pollution. This assessment was carried out in the form of a case study in the Mkabela Catchment near Wartburg in KwaZulu-Natal, South Africa. The research involved the application of various climate change projections derived from downscaled Global Circulation Models (GCMs) with the *ACRU*-NPS water quality model, to assess the impact on selected WQ constituents. Results indicated positive correlations between WQ related impacts and contaminant migration as generated from agricultural fertilizer applications. GCM projections indicate increases in rainfall, runoff and associated changes in WQ variable generation and migration from upstream sources. Through the research presented in this paper, it is motivated that ascertaining the links between biophysical WQ related processes and adaptive water resources management should be a key focus in efforts to adapt to the projected impacts of climate change.

Keywords: Water Quality Modelling, Climate Change, Non-Point Source Pollution, Global Circulation Models, Water Quality Management.

4.1 Introduction and Background

Increased global change pressures which include, *inter alia*, climate change, have increased concerns over the supply of adequate quality freshwater (Huang and Xia, 2001; IPCC, 2007; Smeti *et al.,* 2009). In particular, challenges associated with water quality management have received an increasing amount of attention due to the close alignment of water quality related issues with sustainable development (Ouyang *et al.,* 2006; Mahjouri and Ardestani, 2011). Global and local change issues, such as population growth, economic development and land use change have intensified the debate over whether or not the current global freshwater resources status will radically change over the next few decades and, if so, what would be the implications for policy development and governance (Falkenmark and Rockström, 2006; Kundzewicz *et al.,* 2007; UNESCO, 2009). Further concerns also abound on whether the continual pressure being placed on water resources will lead to a change in water productivity (adequacy of water for productive use) and, ultimately, a change in agricultural and industrial productivity (Rockström *et al.,* 2003). It is at this water resource availability and water productivity interface that water quality becomes an issue of concern.

Since the continued functioning of both natural and socio-economic systems relies heavily on the constant supply of freshwater of an adequate quality (Gleick, 2006; Nangia *et al.*, 2008), the rapid and almost unprecedented changes in ecosystem behaviour observed over the past few decades have resulted in the decline of fluvial water quality globally and locally (Deasy *et al.,* 2007; Edwards and Withers, 2008). The marked and almost sole influence of anthropogenic activities on water quality deterioration has been noted by numerous scholars and organisations (*e.g.* IPCC, 2001; Hewitson *et al.,* 2005; Schulze, 2005; Schulze *et al.*, 2005; IPCC, 2007; Bates *et al.,* 2008; Vairavamoorthy *et al.,* 2008; Pittock, 2009; UNESCO, 2009; World Bank, 2010). In addition to the apparently unmitigated and unabated anthropogenic impacts on water quality, climate change will aggravate water quality problems and further compound the complexities involved in water quality management (see Chapter 2). This presents significant water quality management implications, particularly for transitional countries where land use change is rapid and population growth is high, such as in South Africa.

Schulze (2005) notes that South Africa is a country characterized by a high risk hydroclimatic environment and that the impacts of severe climate change will be manifested through "an amplification of an already highly variable local hydrological cycle". With this anticipated increase in variability, the impacts on water quality, assurance of supply, food production, human health, energy production, environmental sustainability and economic efficiency will be far reaching and potentially economically and socially destructive (Descheemaeker *et al.,* 2010). Therefore, for transitional countries, such as South Africa, climate change is anticipated to compound the complexity of socio-economic development and environmental sustainability in an already complex water resources management background (UNESCO, 2009; Descheemaeker *et al.,* 2010; Mahjouri and Ardestani, 2011).

This enhanced complexity will not only amplify the exposure and vulnerability of water resource systems to external adverse effects, but it will simultaneously undermine the adaptive capacity of these systems. Vulnerability was defined in Chapter 2, Section 2.1, as the degree to which a particular system is likely to experience harm due to exposure to an internal or external hazard (Füssel, 2006). The ability or preparedness of a system to adapt or to reduce its vulnerability defines the adaptive capacity of the system. Although substantial work has been accomplished in both the fields of climate change related adaptation (*e.g.* IPCC, 2001; Adger and Vincent, 2005; IPCC, 2007; Vincent, 2007; Paavola, 2008) and water quality management based on catchment processes (Novotny, 2003; Van Der Perk, 2006), there appears to be a disconnect between the two. In other words, there is an inadequate body of knowledge to directly link basic hydrological processes which drive water quality (WQ) variability with climate change projections. There is also a well-recognized fundamental and applied need to detail the effects of changing climate on catchment-wide nutrient and sediment transfer dynamics (Edwards and Withers, 2008; Han *et al.,* 2010; Shrestha *et al.,* 2012). Consequently, incorporating such knowledge into policy development and governance with the intention of developing adaptive WQ management strategies is also overlooked. As discussed in Chapter 2, Section 2.3, establishing these links will be a critical step in building adaptive capacity. In that regard, it is important that the primary processes and parameters which influence water quality are understood. In the scope of this paper, these are:
   a) processes influencing sediment generation, transport (or transfer) and deposition and,
   b) processes influencing nitrogen and phosphorus generation, transport and deposition in the context of agricultural non-point source pollution.

Building on this understanding, the potential impacts of climate change on water quality through, for example, possible increases in the severity or frequency of extreme events can then be assessed with the help of modelling and climate change projections. This is particularly important in the context of extreme events whose potential impacts on sediment, nitrogen (N) and phosphorus (P) dynamics have not been adequately assessed in South Africa (see Sections 2.3.3 and 3.2 for references) and is especially relevant in the predominantly agricultural and rural catchments of this country, where non-point source pollution (NPS) is widespread. The mechanisms that govern sediment yield, N and P distribution are anticipated to change under conditions of higher temperature and changes in rainfall but the magnitude and direction of that change is still not fully understood.

Furthermore, biophysical or catchment processes and linkages that are essential in understanding how NPS pollution and land use change influence water quality have not been reconciled with adaptive water resources management, both in management and in policy and governance structures. Therefore, the assessment of the links between biophysical processes, climate change and adaptation is of significant importance in the pursuit of reducing vulnerabilities and building adaptive capacity (see Chapter 6). In this paper, an assessment of projected climate change impacts on selected WQ constituents is undertaken using the Mkabela Catchment (near Wartburg) in KwaZulu-Natal, South Africa as a case study. Additionally, the effects of a single wetland system located in the Mkabela Catchment in mitigating the aforementioned impacts of climate change on the selected WQ constituents are outlined in this paper.

This paper reports on the various simulations carried out in this study, using data derived from historical observations and downscaled General Circulation Models (GCMs) and the results obtained from each of those exercises. It includes a description of the selected catchment, the selected water quality model, the selected wetland system, the acquisition and treatment of input data, the GCM-derived climate change projections considered, the types of simulations performed and the results of the simulations of the catchment, and finally, offers an analysis of the results highlighting the merits and possible improvements of this type of modelling application.

4.2   Site Description

The water quality modelling exercise presented in this study was conducted in the Mkabela Catchment ($42km^2$) located approximately 1km east of the town of Wartburg, near Pietermaritzburg, South Africa (Coordinates: 29.34' 57.00" S, 30.36' 48" E) (Figures 4.1-4.2). The Mkabela catchment is a sub-catchment of the Nagle Water Management Unit (WMU) which forms part of the Mgeni Tertiary Catchment in KwaZulu-Natal. The locations of both the Nagle WMU and Mkabela Catchment within the Mgeni Catchment are indicated in Figures 4.1 and 4.2. A more detailed illustration of the Nagle WMU (showing the Mkabela Catchment) is shown in Figure 4.2. Commercial agriculture is the most dominant land use activity in the Mkabela Catchment. The proportions of the various agricultural production systems in the catchment are shown in Table 4.1. Irrigated sugar cane is the most dominant land use, followed by commercial afforestation, with land uses such as vegetable plots and dairy covering minor portions of the catchment (Table 4.1). Various structures, which act as hydraulic controls to the movement of pollutants, are found in the catchment, including an assortment of farm dams, wetlands and riparian buffer strips. Synthetic fertilization only occurs in sugar cane, vegetable and dairy (pastures) farming systems.

The Mkabela Catchment falls within the summer rainfall region of South Africa and experiences a warm subtropical climate with distinct dry and rainy seasons. The altitude in the catchment ranges from 965 m.a.s.l from the eastern escarpment to 755 m.a.s.l at the catchment outlet. The mean annual precipitation (MAP) of the catchment averages 835 mm per annum. The baseline vegetation is classified by Acocks (1988) as the Southern Tall Grassveld and the catchment relief ranges from open hills, low relief to open hills, high relief.

For modelling purposes, the Mkabela Catchment was further subdivided into smaller subcatchments with similar hydrological characteristics (Figure 4.3). These subcatchments, alternatively referred to as Hydrological Response Units (HRUs) in this text, were delineated using various geomorphological, pedological and hydrological reference factors. These factors included land use and land cover types, soil types, catchment slope, topography and the location and distribution of hydraulic controls (*i.e.* dams, wetlands and streams).

Delineation of the catchment in this manner allowed the isolation and observation of the pathways and processes that govern the generation, transport and deposition of agricultural pollutants across the Mkabela Catchment (see Lorentz *et al.,* 2010 for further details on the delineation of this catchment).
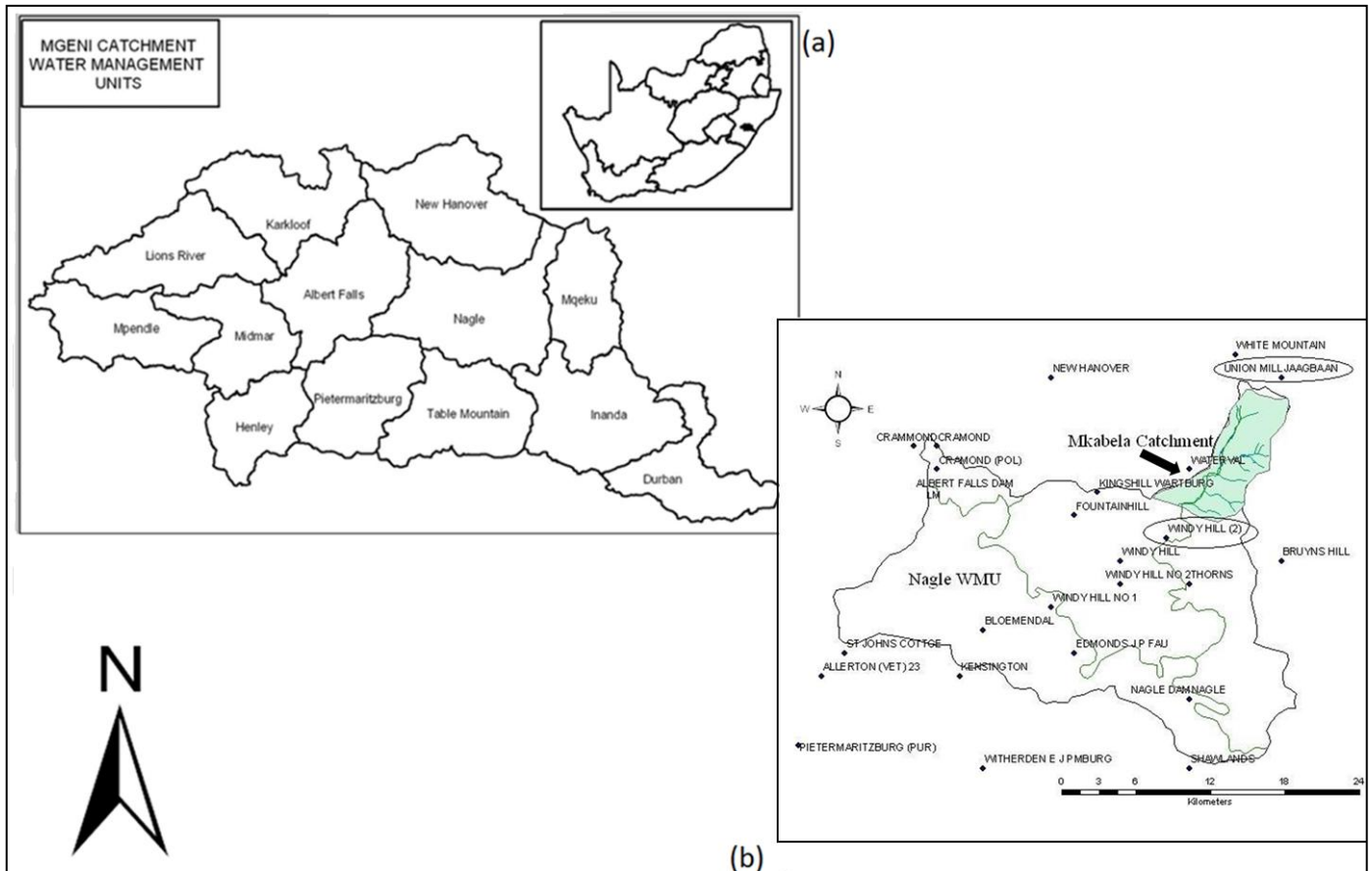
Figure 4.1 Location of the Nagle WMU within the Mgeni Quaternary Catchment in (a) and the Mkabela Research Catchment within the Nagle WMU in (b). Also shown in (b) are the selected rainfall gauging stations (circled) and other rainfall stations and towns located in and around the Nagle WMU.
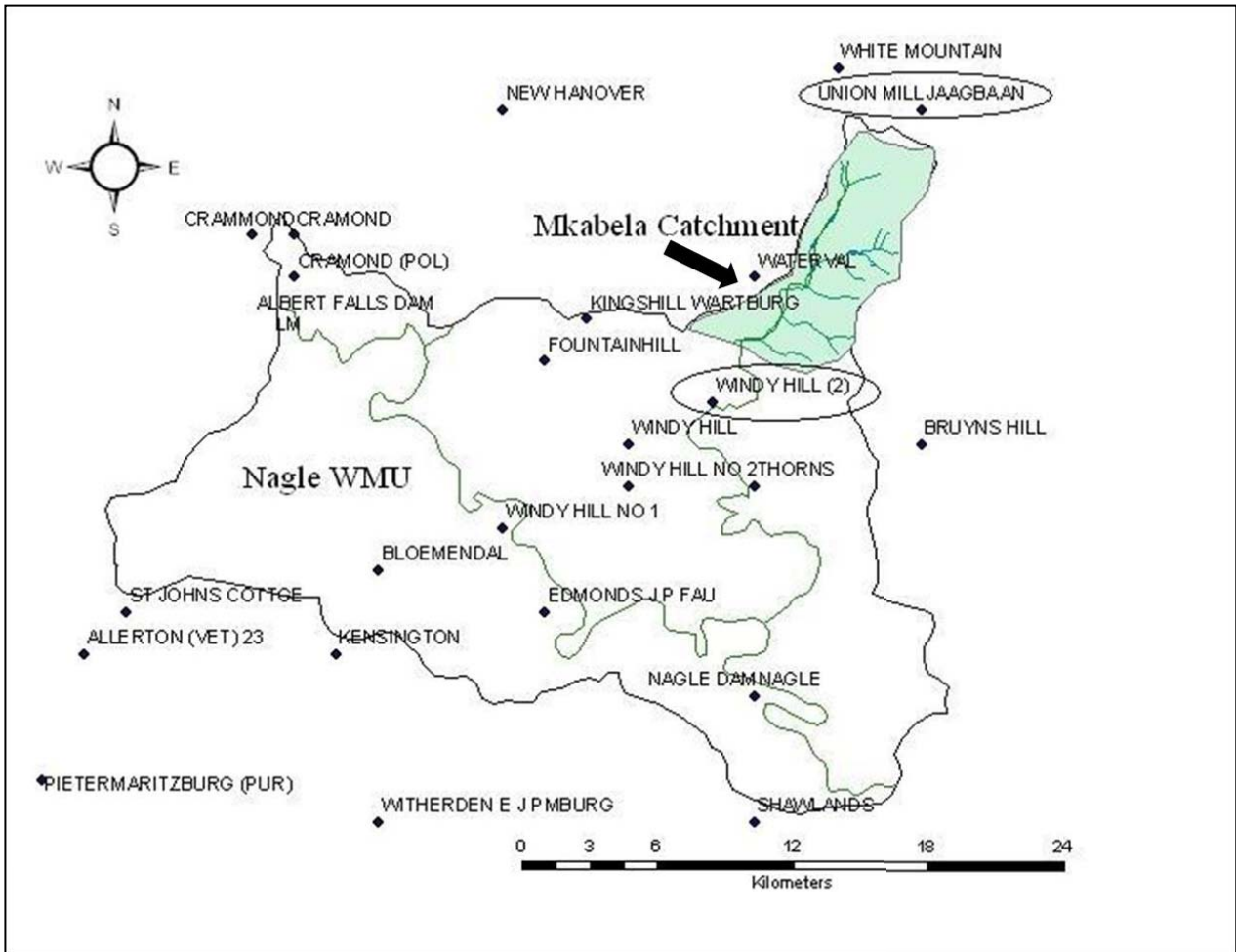
Figure 4.2 A more de tailed image of the Nagle W MU indicating the location of the Mkabela catchment, surrounding rainfall stations and towns. Also indicated in this diagram are the Windy Hill Number 2 and Noodsberg-Jaagbaan stations (circled) selected as driver rainfall stations.

This also enabled source-pathway-response modelling of the Mkabela Catchment, with the intention of understanding the impacts of agricultural NPS pollutants on the water quality of hydraulic controls across the catchment. The simulation of runoff and streamflow processes (from the rainfall measured within the catchment), was then carried out for the individual HRUs. Figure 4.3 indicates the delineated Mkabela HRUs. Also indicated in Figure 4.3 is the land use distribution of the Mkabela catchment and model relevant subcatchments numbers. The *ACRU*-NPS water quality model was selected as the primary model for use in the simulations. A description of this model and the rationale behind its selection are detailed in the following section.

Table 4.1   Mkabela Catchment land use distribution

Land Use (km^2)	Area (km^2)	%*
Sugar Cane	26.40	63.00
Commercial Afforestation	3.09	7.36
Maize	2.69	6.40
Vegetables	1.56	3.71
Dairy	1.50	3.57
Grassland	2.56	6.10
Riparian/Dams/Wetlands	3.75	8.93
Total	42.00	100.00

*Values have been rounded-off.
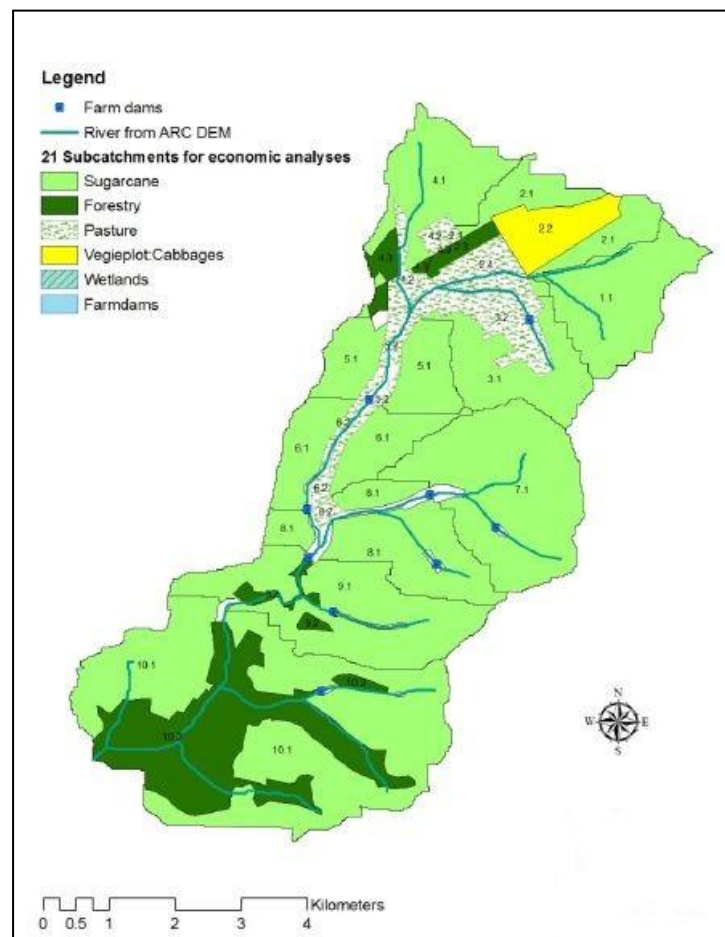
Figure 4.3   Map of the Mkabela Catchment showing land uses, hydraulic controls, and subcatchments (Lorentz *et al.,* 2011).

4.3   Description of the *ACRU*-NPS Model

ACRU-NPS is a water quality module of the physical-conceptual agrohydrological *ACRU* model*,* developed at the University of KwaZulu-Natal, South Africa. The *ACRU* model is a multi-purpose, multi-level daily time-step model which has been applied in numerous contexts including design hydrology, crop yield estimation, reservoir yield simulations, irrigation water demand and supply simulations, climate change assessment and in land use and management impacts (Schulze, 1995; Warburton *et al.,* 2010). The *ACRU* model has been applied both in South Africa and internationally. The water quality routines of the *ACRU*-NPS model are based on the Groundwater Loading Effects on Agricultural Management Systems (*GLEAMS*) model. The *GLEAMS* model is a root zone water quality model which describes the transport and transformation of nutrients across surface boundaries (Leonard *et al.,* 1987; Knisel and Davis, 1999). The *ACRU*-NPS model, therefore, describes the impacts that land use and land management interventions have on the translocation of non-point source (NPS) pollutants. Specifically, the *ACRU*-NPS model is designed to simulate (Lorentz *et al.,* 2011):

a) N and P losses in surface runoff, sediment and leaching,

b) N and P cycling in the soil-water-plant-animal system, and

c) N and P mass balances in the watershed system.

This model was, therefore, selected owing to its ability to effectively link hydrological parameters such as rainfall and runoff with sources of nutrients, which include fertilization, irrigation and plant and animal wastes to describe or represent management impacts on N and P transport and transformation. The model also allows the routing of nutrients and sediment generated from upstream sources, or HRUs, through the various control structures (wetlands, dams and riparian buffer strips) allowing for the evaluation of the effect these controls have on the downstream displacement of these WQ variables.

The influence of temperature on the generation of nutrients and sediment is factored into the *ACRU*-NPS model. Although not directly responsible for the generation and translocation of NPS pollutants, temperature still assumes an important role in the initiation and catalysis of critical physicochemical reactions and climatological processes (Wartburton *et al.,* 2005) (Chapter 3, Section 3.3.2). Temperature influences total evaporation, which consequently influences condensation processes, which influence precipitation. As mentioned in Section 3.3.2, changes in precipitation (influenced by changes in temperature and, thus, total evaporation) resulting in changes in runoff processes can be expected to trigger changes in the generation and rate of transfer of sediment and, thus, nutrients. These processes are included in the *ACRU*-NPS model.

The *ACRU*-NPS model was set up for three separate spatial units or HRUs located in the headwaters of the Mkabela Catchment. The HRUs are located upstream of a perennial wetland, termed "wetland1". The combined runoff and streamflow from each of these HRUs form the inflow into this wetland. Owing to the effects of the wetland in retarding the downstream translocation of nutrients and sediment, a set of algorithms were developed to route daily water discharge, sediment, N and P loads through the wetland (Lorentz *et al.,* 2011). The reader is referred to Lorentz *et al.* (2011) for a complete description of these algorithms. The simulated daily discharges, sediment, N and P loads are read into a spreadsheet which is configured to route the resultant output discharges and loads from each HRU through the wetland. The algorithms used to calculate the variable amounts or loads entering and exiting the wetland contain parameters which are specified by the user in the spreadsheet. The most crucial of these parameters are alphaQ and betaQ which control daily discharges and loads entering and exiting the wetland. AlphaQ and betaQ were specified as 0.001 and 1 respectively. Both parameters do not have units. These parameters control the rate at which the wetland gains or loses water based on the following water balance:

$$V_i = V_{i-1} + V_{in} - V_{evap} - V_{seep} - V_{out}$$

Where V_i is the wetland volume on day i, V_{i-1} is the wetland volume on day $i-1$, V_{in} is the inflow volume on day i, V_{evap} is the evaporation volume on day i controlled by an area-volume relationship for the wetland, V_{seep} is the seepage volume from the base of the

wetland on day i controlled by an effective hydraulic conductivity and the wetland area, V_{out} is the outflow volume on day i controlled by the storage volume in excess of the full volume. The seepage volume percentage is specified by the user and is added to the outflow volume. All variables in the water balance are in m^3 (Lorentz *et al.,* 2011). AlphaQ and betaQ are adjusted according to the rate at which the wetland loses water. If the wetland drains too rapidly, for instance, these two parameters may either be increased or reduced until a favourable daily drainage rate is achieved. Since the wetland can never be allowed to run completely dry (*i.e.* V_i can never equal zero), the aforementioned values of 0.001 for alphaQ and 1 for betaQ were specified to ensure that this condition is never reached.

The MUSLE equation (Williams, 1975) was selected for the estimation of sediment yield. In *ACRU*, stormflow is estimated using a modified form of the SCS stormflow equation (Schulze, 1995). Generated stormflow is released over time by specifying a value for the variable *QFRESP, i.e.* the fraction of the total stormflow store that runs off from the catchment on a particular day. In the simulations performed a value of 0.60 was assumed. Water that infiltrates the intermediate or groundwater store is released over time as baseflow at a rate controlled by the baseflow response coefficient (*COFRU).* A value of 0.001 was assumed for *COFRU*. In both cases, these are based on best practices as reported in the *ACRU* model user manual (Smithers and Schulze, 2004). Daily runoff is the sum of baseflow and stormflow for a particular day. Peak discharge, which is required for the estimation of sediment yield, is simulated using the SCS peak discharge method. Catchment lag is required for the simulation of peak discharge and was estimated using the Schmidt/Schulze lag equation (Smithers and Schulze, 2004). This equation requires as input the 2-year return period 30-minute rainfall intensity (*XI30*) in mm.hr^{-1}, which was derived from the four rainfall intensity distribution zones and the 2-year return period one-day rainfall depth maps of southern Africa also given in Smithers and Schulze (2004). A value of 58.4mm.hr^{-1} was calculated for *XI30*. In the absence of an objective method to estimate this variable in a future climate, the variable was not adjusted for future WQ projections The A-Pan is used in *ACRU* for reference potential evaporation and was estimated using the Hargreaves and Samani (1985) daily temperature-driven equation (Samani, 2000).

4.4   Input Data Acquisition and Processing

The simulations outlined in this paper were performed using observed climate data and climate data derived from selected downscaled GCMs. The acquisition and treatment of these climatic data is described in the sections below. The last section (Section 4.4.3), provides a description of other (non-climatic) input data also used as input in the *ACRU*-NPS model. Each HRU was modelled for separately within the *ACRU*-NPS model using datasets from both the observed records and downscaled GCMs. For each HRU, two separate simulations were performed; namely, one simulation using observed data and a second simulation using data derived from the downscaled GCMs (see Section 4.5).

4.4.1   Observed Climate Data

Daily observed climate data were acquired from two rainfall stations located in and around the Mkabela Catchment. These stations were identified as having the longest and most reliable records of those available. The two stations, Windy Hill No. 2 and Noodsberg-Jaagbaan (marked as "Union Mill Jaagbaan"), are indicated in Figures 4.1 and 4.2. The records from these stations had data available over different periods and were combined to form a single composite record for the period 1950 to 2011. These datasets were combined for two reasons: firstly, it was to minimise or eliminate possible errors in either one of the records and, secondly, it was to ensure the continuity of the newly created composite record.
The Windy Hill Number 2 rainfall station had data from 1950 to 2000, whereas the Noodsberg-Jaagbaan rainfall station had data from 1971 to 2011. The Noodsberg-Jaagbaan dataset was, however, quality controlled and, thus, more reliable compared to the Windy Hill Number 2 dataset. Therefore, combining the two datasets would ensure that the composite record was as extensive and error free as possible. The limitation of the Noodsberg-Jaagbaan dataset was that it only commenced in 1971, which meant that it could not be directly comparable with GCM-derived datasets, which commenced in 1961. This was particularly important in the estimation of mean annual precipitation and in the initialization (*i.e.* set-up) of the *ACRU*-NPS model. It was, therefore, necessary that the dataset from the Noodsberg-Jaagbaan station be combined with the dataset from the Windy Hill Number 2 station to ensure that the final record, from 1950 to 2011, included the period from 1950 to 1970.

The daily maximum and minimum temperature estimates for the Mkabela Catchment were sourced from the gridded daily temperature database of Schulze and Maharaj (2004). The maximum and minimum temperature estimates were used to calculate daily evaporation using the Hargreaves and Samani daily temperature-driven equation (Samani, 2000).

Although daily rainfall data was obtained from two stations, data from the Windy Hill Number 2 station was not directly representative of the Mkabela Catchment. Therefore the rainfall data from this station had to be adjusted to ensure that it represented the Mkabela Catchment in its entirety, more realistically. The Noodsberg-Jaagbaan was considered to be close enough to the Mkabela Catchment to permit the use of its data without the necessity for adjustment (see Figures 4.1 and 4.2). The adjustment of the Windy Hill Number 2 station rainfall data was carried out using the *ACRU* model rainfall adjustment or *CORPPT* function. Median monthly rainfall data were used to determine month-by-month adjustment factors, which were applied to the record to adjust daily rainfall (see Smithers and Schulze, 2004 for reference). Essentially, the aim of the adjustment was to best estimate the rainfall in the Mkabela Catchment (and, thus, the focal HRUs) using available data over the period of interest (*i.e.* 1950-1970). In adjusting the records from the Windy Number 2 station to better represent the catchment rainfall, the data from the two selected stations were, consequently, made to be more comparable.

4.4.2 Climate Change Projections Considered

The climate change projections used in this study were derived from seven downscaled global circulation models (GCMs) employed in the Intergovernmental Panel on Climate Change (IPCC) Fourth (AR4) Assessment Report (IPCC, 2007). The downscaled climate change projections were obtained from the Council for Scientific and Industrial Research (CSIR) and from the Climate Systems Analysis Group (CSAG) based at the University of Cape Town (UCT). The CSIR GCM projections were dynamically downscaled to a 0.5 degree horizontal resolution grid across southern Africa (Engelbrecht *et al.,* 2009) and the CSAG GCM projections were empirically downscaled to regional scales (Hewitson, 2012, pers. comm.), also encompassing all of southern Africa.

The differences between these downscaling techniques are detailed in Table 4.2, which also includes a summary of the relevant information regarding the selected GCM projections and the downscaling institutions.

Table 4.2   Information on selected downscaled GCMs, the downscaling institutions and projected trends in mean annual precipitation.

Downscaled GCM	Downscaling Institute	Time Periods Considered	MAP Trend
GDFL2.1	CSIR	1971-1990	Wetting
		2046-2065	
MIROC	CSIR	1971-1990	Drying
		2046-2065	
CSIRO	CSAG-UCT	1971-1990	Wetting
		2046-2065	
ECHO	CSAG-UCT	1971-1990	Wetting
		2046-2065	
IPSL	CSAG-UCT	1971-1990	Wetting
		2046-2065	
ECH5	CSAG-UCT	1971-1990	No Appreciable Change
		2046-2065	
MRI	CSAG-UCT	1971-1990	Wetting

The selection of the downscaled GCMs was based on projected changes in mean annual precipitation (MAP) and mean annual runoff (MAR) described by each downscaled GCM projection. An increasing trend in MAP and MAR between the present and the future essentially indicates a wet climate change projection or wetting pattern of change, whereas a declining trend in MAP and MAR suggests a dry climate change projection or drying pattern of change. The GFDL2.1 and MIROC GCMs downscaled by the CSIR represented wet and dry climate change projections respectively. With the exception of the ECH5 GCM, all GCMs downscaled by CSAG represented wet climate change projections, with variations in the degrees of change.

Owing to time constraints, not all GCMs downscaled by the CSIR could be included in this study. Therefore, based on projected changes in MAP, only the "wettest" downscaled GCM (*i.e.* the GFDL2.1 GCM) and the "driest" downscaled GCM (*i.e.* the MIROC GCM), were selected from the ensemble of CSIR GCMs (see Engelbrecht *et al.*, 2009). Further, the majority of the GCMs used in this study are GCMs downscaled by CSAG. These particular projections represent regional/point scales, a condition which makes them more suitable for application in hydrological modelling. All GCMs used in this study were originally derived from coupled GCM (CGCM) projections that contributed to the Intergovernmental Panel on Climate Change (IPCC) Fourth Assessment Report (AR4) (IPCC, 2007). It is important to note that these projections represent a range in global models (including their various sensitivities, parameterizations, *etc.*), downscaling methodologies and institutions and, therefore, reflect the uncertainty that is inherent in climate change projections at present. This was considered critical since using projections from a single combination of GCM-downscaling institution runs the risk of obtaining a biased view of the future.

The GFDL2.1 and MIROC GCM projections were dynamically downscaled by the CSIR using the high-resolution conformal-cubic atmospheric model (CCAM), developed by the Commonwealth Scientific and Industrial Research Organisation (CSIRO) in Australia. This was performed by forcing the CCAM model using bias-corrected sea-surface temperatures and sea-ice fields of CGCMs to produce regional scale climate change projections (Engelbrecht *et al.*, 2009). The CSAG GCM projections were empirically downscaled by using observed data to derive relationships between synoptic scale climates and local climates and applying the resulting relationships to GCM output to generate higher resolution local scale climate change projections (Hewitson *et al.,* 2005).

It is critical to note at this juncture that this study used *GCMs* to provide an understanding of the likely behaviour of point specific catchment processes. It is recognised that GCMs are inherently limited by their spatial resolutions. A single GCM generally represents a spatial grid of ~300km (Hewitson *et al.,* 2005). This means that a particular GCM will provide one average value that theoretically represents a 300km by 300km grid pixel. At this resolution, this average value is of little value in the investigation of point specific (*i.e.* local) catchment processes.

Therefore, the use of downscaled GCM data was considered useful in understanding the likely changes in water quality responses to future changes in rainfall and temperature regimes through modelling exercises, rather than representing a precise simulation of Mkabela Catchment itself. The GCM projections used in this study were downscaled to "regional" scales, which in this case was at the scale of the Nagle WMU (Figures 4.1 and 4.2). The ability of the downscaled GCM projections to sufficiently reproduce regional scale climatic data has been verified elsewhere (Engelbrecht *et al.,* 2009; Hewitson *et al.,* 2005) and these projections were considered to be credible for their application in this study.

The spatial resolution limitation of GCMs mentioned above implies that when compared to actual point specific measured data, GCM-derived data are not infallible and must be applied with some caution (see Chapter 5). This can be attributed to a number of issues ranging from the effects of natural variability, which may not be entirely captured by the downscaled GCMs and land use-climate feedback mechanisms which may also influence local scale climates and thus be potentially omitted in the downscaled GCMs. These issues introduce some uncertainty with respect to the application of downscaled GCM output. This discussion is expanded on in Section 4.6.4 and Chapter 5.

The climate change projections used in this study considered present (1971-1990) and future (2046-2065) time periods. The projections are based on the Special Report on Emission Scenarios (SRES) A2 storyline and emission scenario (Nakićenović *et al.,* 2000), which assumes that global efforts to reduce greenhouse gas emissions are relatively ineffective. The SRES scenarios are considered to be plausible alternative futures based on current emission trends rather than specific predictions of the future (Woznicki and Nejadhashemi, 2012). The A2 scenario used in this study assumes a "business as usual" approach in which developing countries continue to use ever-increasing quantities of fossil fuels and developed countries make little effort in altering their energy consumption patterns or developing efficient fuel technologies. By deduction, the A2 scenario assumes conditions which favour increased anthropogenic pressure on environmental resources. Climatic data and, in particular, rainfall data, obtained from the downscaled GCMs for the Nagle WMU was not adjusted or post-processed in any way for the Mkabela Catchment, since the catchment was considered to be located in relatively close enough proximity to the points of interest of the downscaled GCMs (*i.e.* the Nagle WMU).

4.4.3 Additional Input Data

The *ACRU*-NPS model requires various other (non-climatic) spatial and hydrological datasets for use as input in the model setup (see Appendix A for example HRU input file). These datasets include soils and land use/cover data, catchment locational information, evaporation and agronomical data. The sources of input data used in this study are summarised in Table 4.3. The following section provides a description of the simulation performed in this study.

Table 4.3   Sources of input datasets used in the *ACRU*-NPS model setup, including climate variables considered.

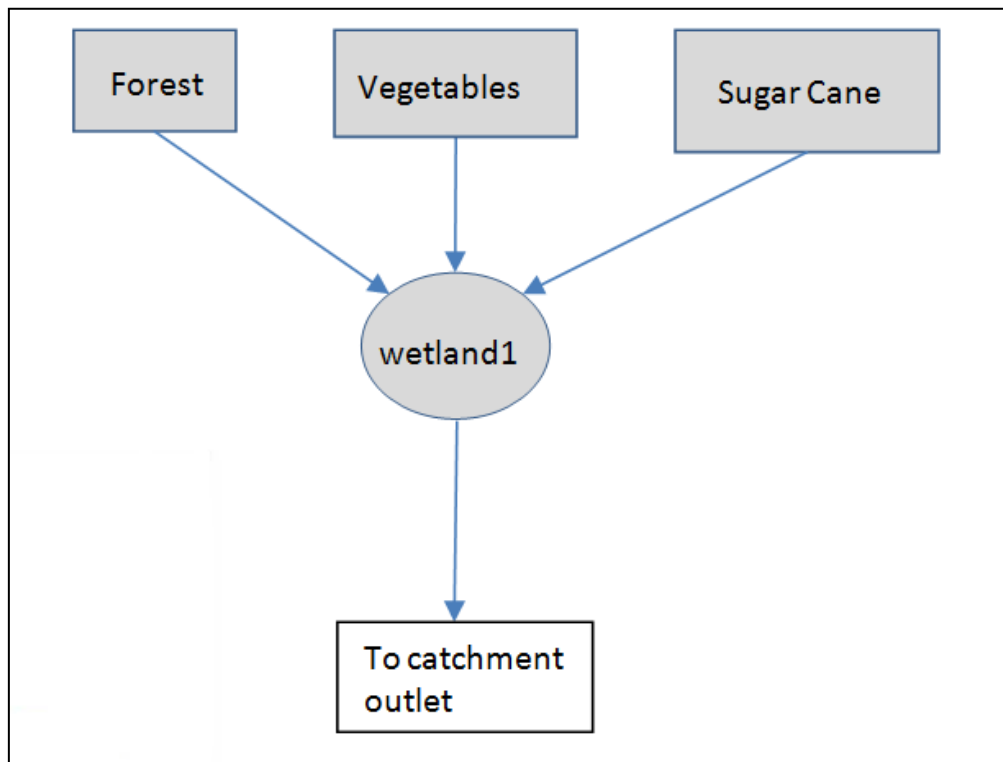| Input Data	Data Source	Variable
Observed Climate	Rainfall Extraction Utility Tool which interrogates the rainfall database developed by Lynch (2003)	Observed Rainfall
	South African Sugar Research Institute (SASRI)	Observed Temperature and Rainfall
	Mkabela Research Station	Observed Temperature and Rainfall
	Schulze and Maharaj (2004)	Temperature
Soils	Le Roux *et al.,* (2006) (Detailed Mkabela Catchment Soil Survey)	
Land Use and Cover	In-situ observations and Acocks baseline land cover database (Acocks, 1988)	
Topography	21m x 21m Digital Elevation Model (DEM) (Lorentz *et al.,* 2011)	
	1: 10000 Maps from the Surveyor General's Office	

4.5 Simulations Performed

As alluded to in Section 4.4, the focal HRUs were modelled for separately within the *ACRU*-NPS model using datasets from both the observed records and downscaled GCM projections. It is, therefore, important at this juncture to differentiate between the simulations performed based on the different datasets in the context of this study. Both modes of simulation were performed using the *ACRU*-NPS model for the HRUs considered. The 1950 to 2011 simulations (encompassing the 1971-1990 period) in the *ACRU*-NPS model were based on observed climate data whereas the 1961-2100 simulations (encompassing the 1971 to 1990 and 2046 to 2065 periods), also in the *ACRU*-NPS model, were based on downscaled GCM-derived climate data. In the results section, these simulations are differentiated based on these criteria.

The *ACRU*-NPS model was set up for three separate spatial units or HRUs located in the headwaters of the Mkabela Catchment. The general characteristics of each of these HRUs are detailed in Table 4.4. The HRUs are located upstream of a perennial wetland, marked as "wetland1" in Figure 4.4. The combined runoff and streamflow from each of these HRUs form the inflow into this wetland as indicated in Figure 4.4.

Table 4.4   General characteristics of the 3 (three) upstream Hydrological Response Units.

HRU Name	Area (km^2)	Mean Elevation (m.a.s.l)	Slope (%)
Sugar Cane	6.31	965	3.5
Commercial Afforestation	0.61	965	5.5
Vegetables	1.56	965	1.5
Total	8.48	-	-

Figure 4.4   Location of HRUs relative to the wetland. Also indicated in this diagram is the flow direction from each HRU in the Mkabela catchment headwaters into the wetland and finally the catchment outlet.

4.6   Results

4.6.1   Verification of the *ACRU*-NPS Model

A number of verification studies were conducted to ensure that the *ACRU*-NPS model adequately represented the observed behaviour of the Mkabela Catchment with regard to the WQ variables of concern *i.e.* sediment, nitrogen and phosphorus. Model simulations were verified against observed WQ variable data from the Mkabela Catchment and results from these exercises indicated that the model was representing the hydrological system satisfactorily. Results from those exercises are presented below for runoff. The *ACRU*-NPS model was able to consistently reproduce runoff satisfactorily across the verification period (Figure 4.5). Additional verification results for nutrients and sediments were also performed and these results, similar to runoff, also indicated that the *ACRU*-NPS model is able to adequately reproduce the system of the Mkabela Catchment adequately.
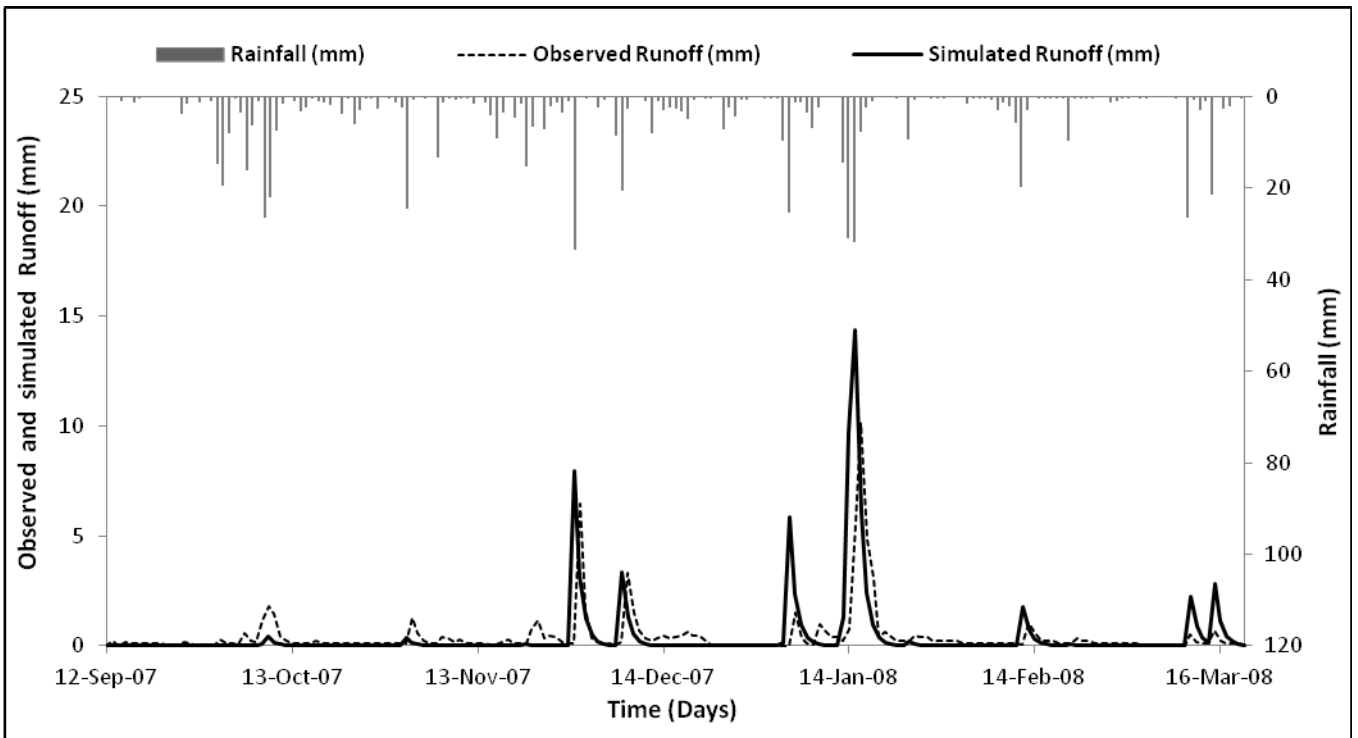
Figure 4.5 Runoff verification results for the Mkabela catchment across the verification period (Lorentz, 2012, pers. comm.).

4.6.2 Impact of the Wetland on the Transfer of NPS Pollutants

As highlighted in Chapter 3, Section 3.2, wetlands and other buffers play an important role in the movement of nutrients through the catchment. Based on the simulations performed using observed input data, the influence of the single wetland system in the catchment on runoff and on the transfer of nutrients and sediments was assessed by analysing the changes between variable amounts entering the wetland (Wetland1-"variable" IN) and amounts exiting the wetland (Wetland1-"variable" OUT). These changes are indicated in Figures 4.6 for daily runoff and in Table 4.5 for all WQ variables considered. Table 4.5 presents mean annual estimates of the variables entering and exiting the wetland and the percent changes between variable quantities entering the wetland and amounts exiting the wetland for the period between 1971 and 1990. These changes are based on user specified values of alphaQ and betaQ (see Section 4.5). Figures 4.7 to 4.9 indicate the behaviour of sediment, nitrogen and phosphorus before and after the wetland. These variables follow the runoff trend with respect to changes in the amounts or loads entering and exiting the wetland.

Table 4.5   Simulated mean annual estimates of water quality variables entering and exiting the wetland based on observed input for the present period.

| Variable	Wetland1-IN	Wetland1-OUT	%Change
Runoff (mm)	185.15	54.22	-70.72
Sediment (t)	297.75	8.69	-97.08
Nitrogen Loads (kg)	69579.00	19258.27	-72.32
Phosphorus Loads (kg)	22101.31	6602.58	-70.13

Figure 4.6 indicates the effect of the wetland on runoff generated from upstream HRUs. Mean annual runoff decreases by an average 70.72% subsequent to being routed through the wetland (Table 4.5). This simulation also highlights the high effectiveness of the wetland to mitigate floods, judging by the reduction in exit flow in the September 1987 floods by over 97% (Figure 4.6). Sediment, being sensitive to runoff, also displays a similar attenuation trend to that of runoff as indicated in Table 4.5 and Figure 4.7. Following a rainfall event, the amount of sediment generated from upstream sources generally increases with an increase in runoff. The sharp decline by 97.08% in sediment between wetland entry and exit can be attributed to the settling effect of sediment when routed through the wetland (see Figure 4.7). The factors affecting sediment transfers across water bodies have been outlined elsewhere (Section 3.2.8). Subsequent to wetland routing, a similar reduction trend observed for both runoff and sediment was also observed for nutrients. Changes in quantitative nutrient transfer before and after the wetland are also shown as mean annual estimates of N and P loads in Table 4.5.

The mean annual estimates of both N and P appear to follow the runoff trend with regard to being retained in the wetland (Table 4.5 and Figures 4.8 and 4.9). The reason for this is that since the Mkabela catchment is a predominantly agricultural catchment, crop fertilization is administered using primarily N- and P-based fertilizers and these nutrients have been shown (*e.g.* Donohue *et al.,* 2005; Lorentz *et al.,* 2010; Lorentz *et al.,* 2011) to migrate easily with runoff. Chapter 3, Section 3.2 detailed the factors affecting the behaviour of nutrients across hydraulic controls and it was shown that these nutrients have a high dependency on runoff-generating mechanisms such as rainfall-events and frequent irrigation.

The decline in nutrients subsequent to being routed through the wetland (Figures 4.8 and 4.9) can be attributed to the hydropedological and biochemical characteristics of wetlands. The ability of wetlands to retain water for prolonged periods of time promotes anaerobic conditions which facilitates the retention and loss of both N and P through volatilisation, mass adsorption and immobilisation. The simulations detailing the migration of both N and P through the wetland followed expected trends, as outlined in Chapter 3, regarding the interactions of nutrients with hydraulic controls such as wetlands and riparian buffers.
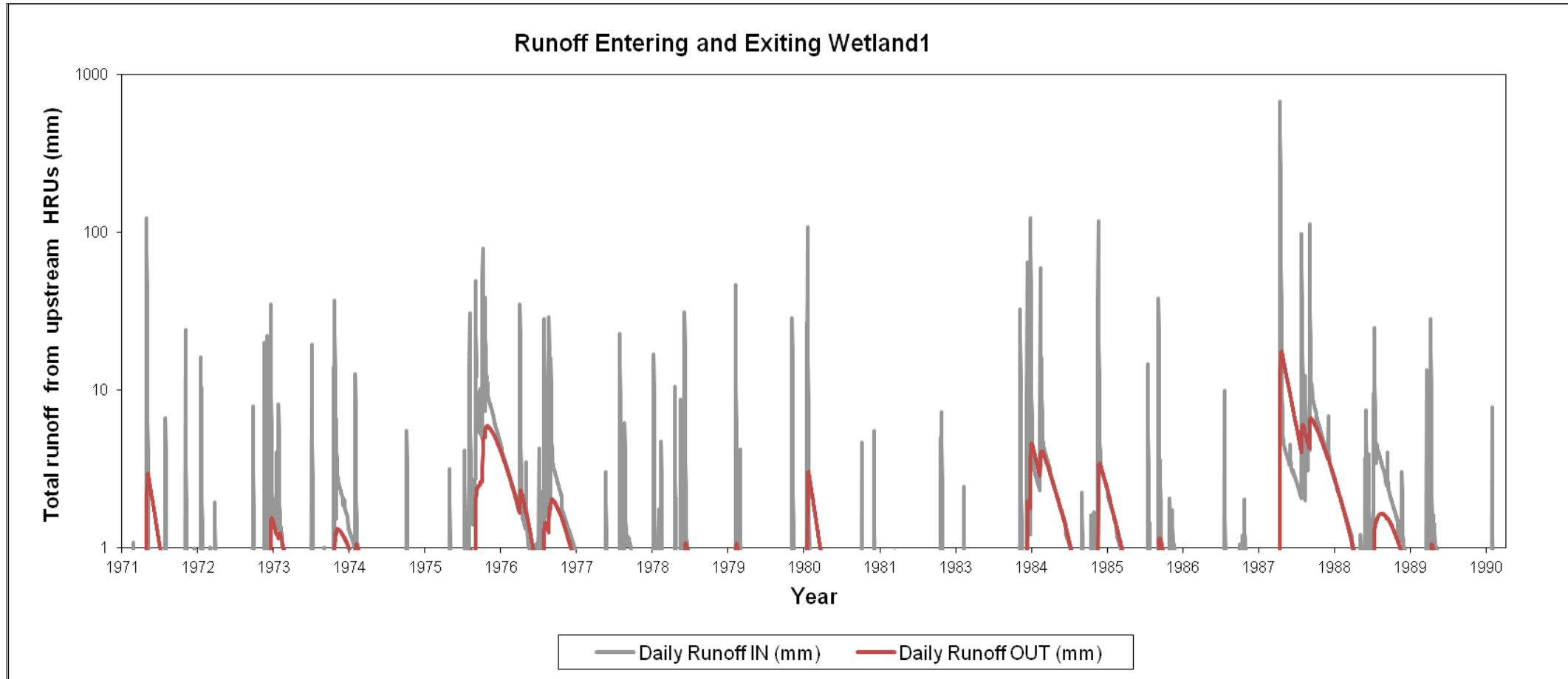
Figure 4.6 Simulated daily runoff entering and exiting the wetland for the period 1971 to 1990.
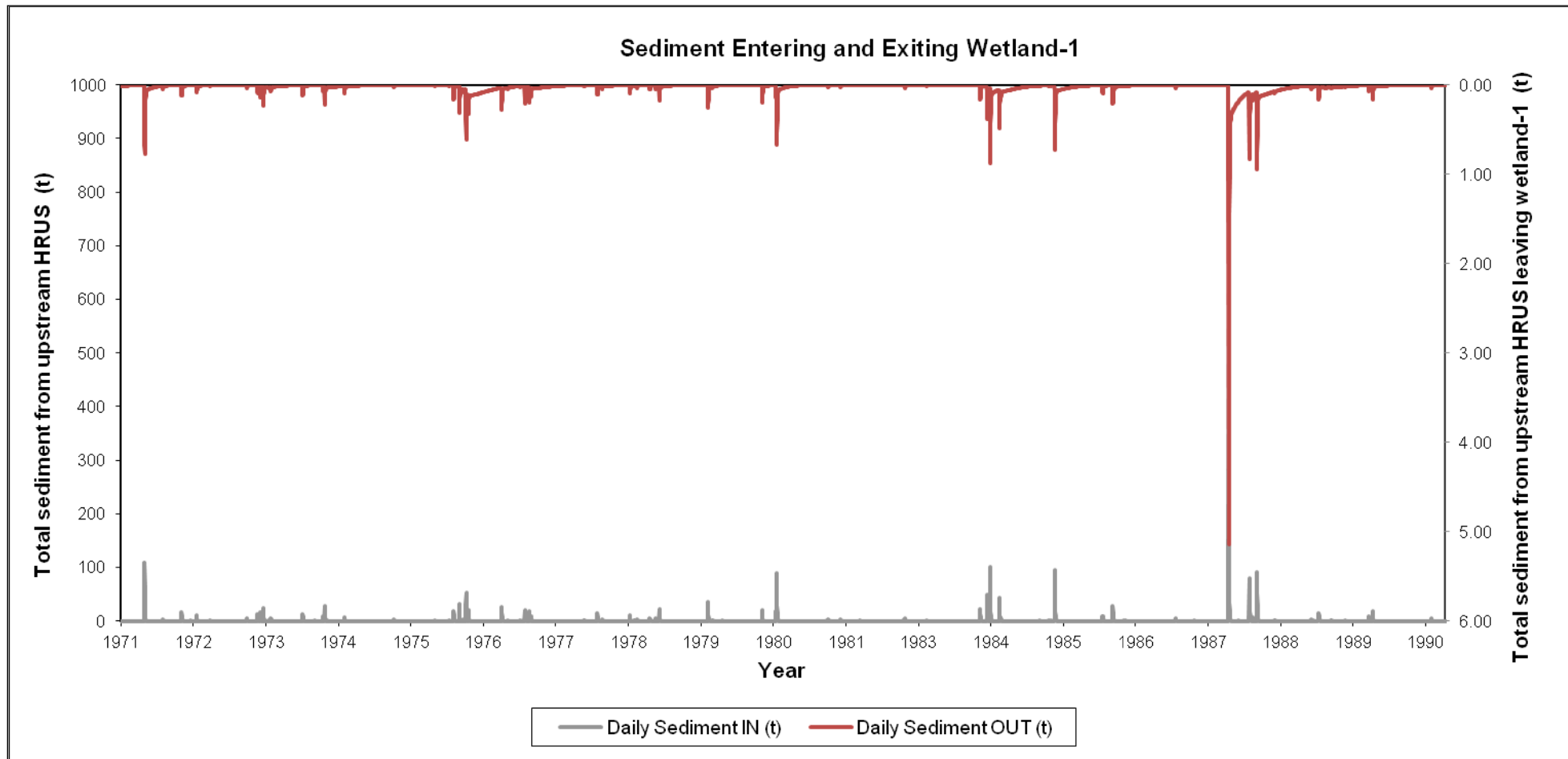
Figure 4.7   Simulated daily sediment loads entering and exiting the wetland for the period 1971 to 1990.
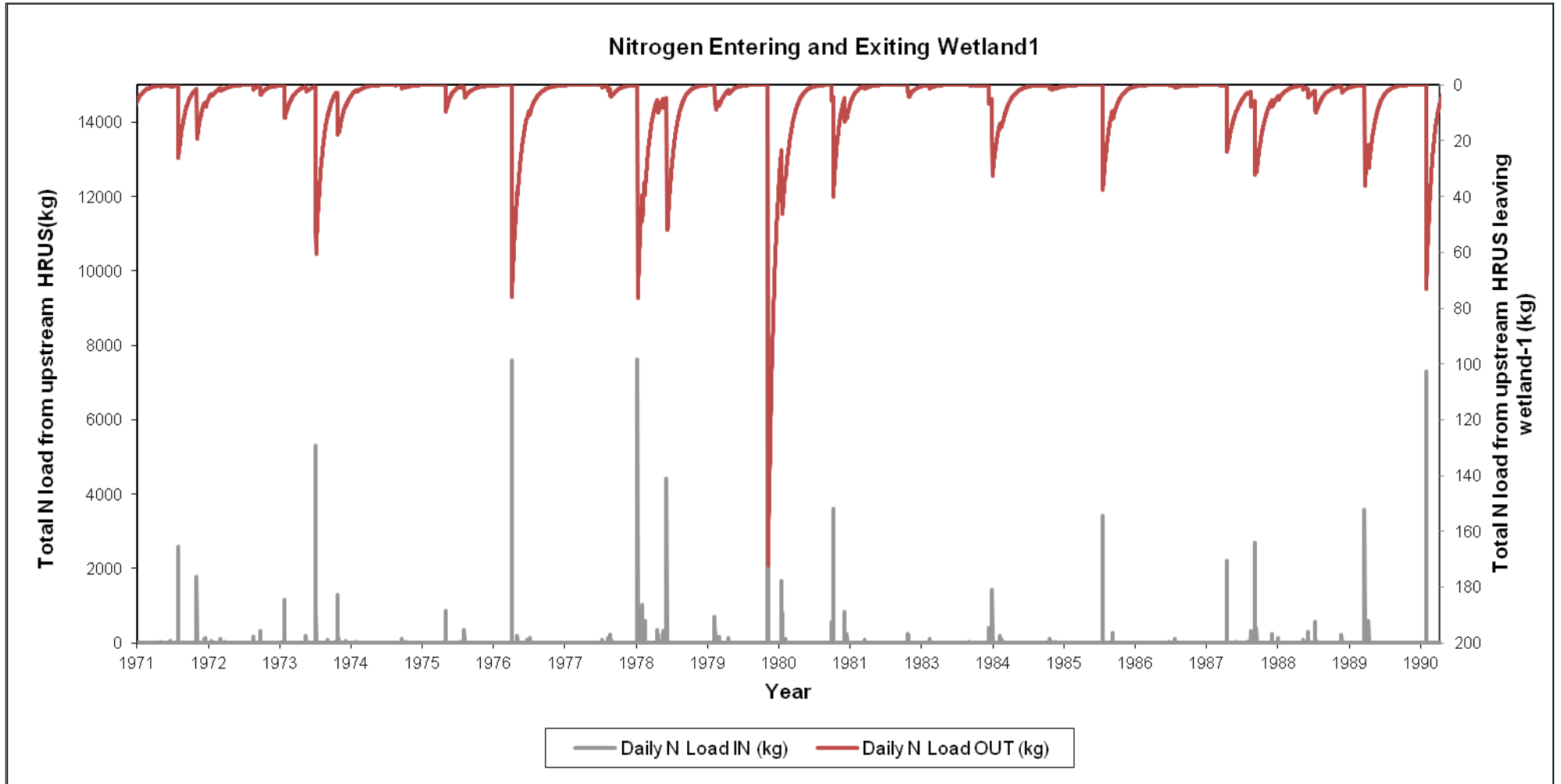
Figure 4.8 Simulated daily N loads entering and exiting the wetland for the period 1971 to 1990.

Figure 4.9   Simulated daily P loads entering and exiting the wetland for the period 1971 to 1990.

4.6.3 Comparison of Present GCM Climate with Observed Climate

As mentioned before, the modelling exercises conducted in this study were performed using observed climatic data derived from *in-situ* observations and climatic data derived from a variety of downscaled GCM projections. Since the overall aim of this study was to understand and detail the impacts of future climate change on water quality constituents, the ability of the downscaled GCM projections to adequately reproduce present conditions with regard to hydrological response processes such as runoff (baseflow plus stormflow) and streamflow was paramount. This was considered important owing to the fact that the fluctuation of fluvial water quality is highly sensitiv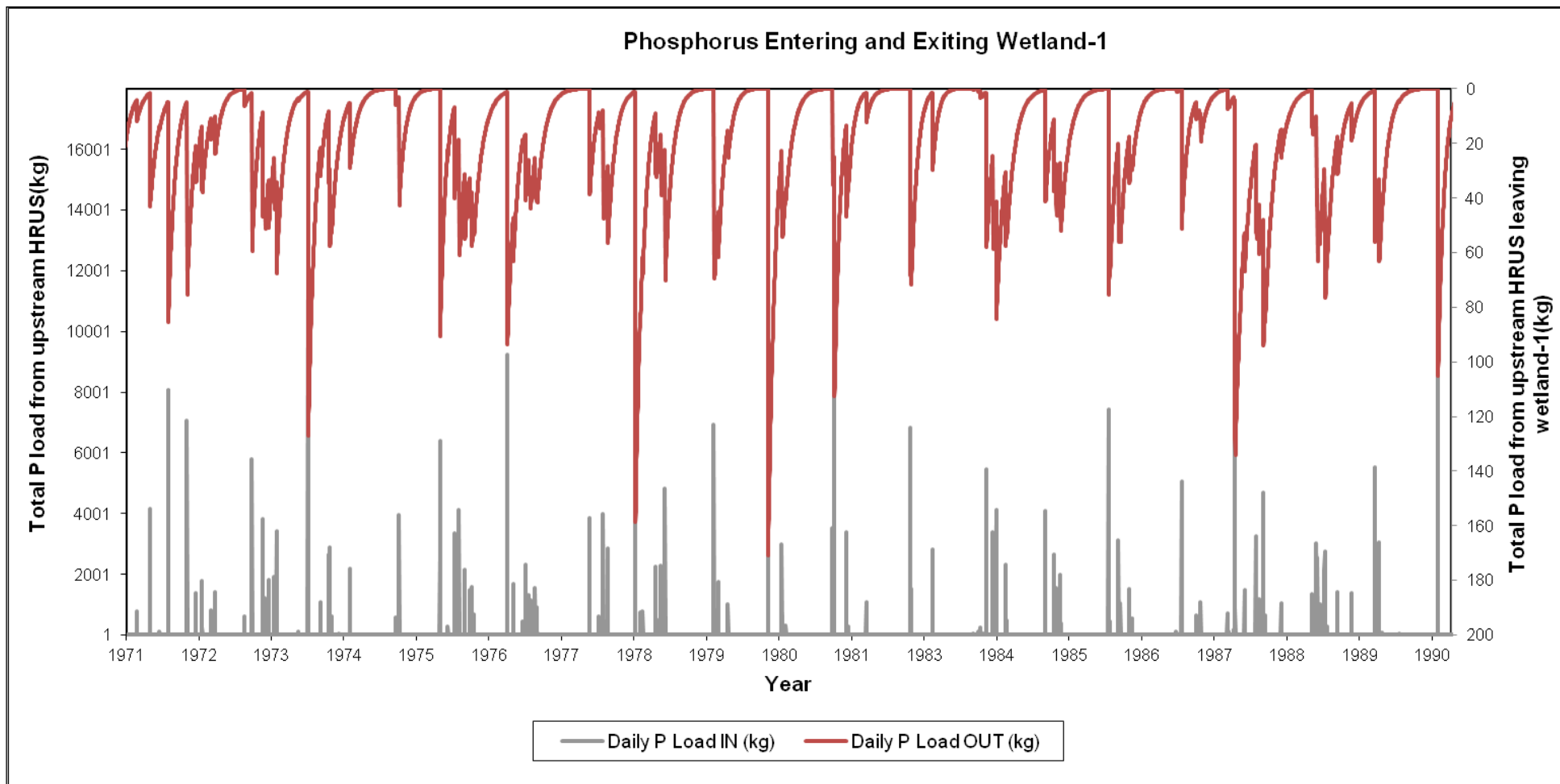e to the behaviour of the aforementioned hydrological response processes. To verify the ability of the downscaled GCM projections to adequately simulate present climatic and thus hydrological response conditions, the simulation output obtained from input data derived from the projections was compared with the simulation output obtained from input data derived from catchment observations.

Although GCM projections are designed to assess climatic changes over long periods of time, the 20 year period between 1971 and 1990 was considered to be a representative period for comparison of model output from the GCM-derived present climate with that of the observed. The statistical analysis from the long term (20 year) *ACRU*-NPS modelling showed that all GCMs under-simulate present (1971-1990) runoff entering the wetland (Table 4.6 and Figure 4.10). The reasons for this trend were attributed to the spatial resolutions to which the GCM projections were downscaled to (*i.e.* regional scale) and to the apparent lack of representation of the major September 1987 flood event (responsible for a significant portion of the observed MAP and MAR), by all the downscaled GCM projections. It is generally accepted that downscaled GCM projections do not necessarily reproduce the exact time series variations of point scale rainfall (Hughes, 2012) and, consequently, they may not reproduce the exact time series variations of local scale runoff. It was therefore, highly critical that the uncertainty introduced by the output from both the CSAG and CSIR downscaled GCM projections, be recognized and factored into the analyses of this study (see Chapter 5 for detailed analyses of downscaled GCM climatic output).

Table 4.6   Comparative s tatistics of mea n a nnual estimations of rainfall a nd runoff entering the wetland for simulations ba sed on observed c limate and downscaled GCMs.

	VARIABLE	
	MAP	**MAR**
Observed Climate	835.01	185.15
Downscaled GCM:		
CSIRO	803.00	73.94
ECHO	856.65	164.98
IPSL	990.45	105.45
MRI	817.04	107.85
GFDL2.1	1301.06	116.70
MIROC	1310.45	109.94
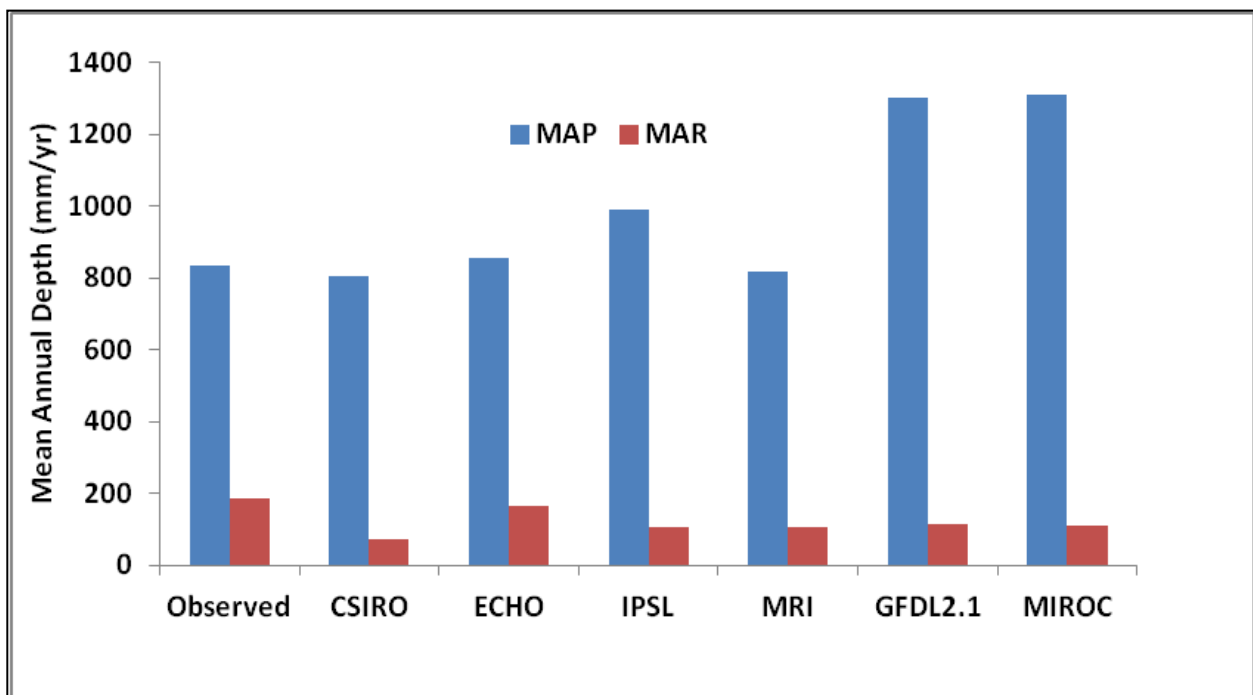
Figure 4.10   Mean a nnual estimations of   rainfall a nd runoff entering th e we tland for simulations based on observed climate and downscaled GCMs.

Temperature has been noted to indirectly influence precipitation (Section 4.3). Thus, increases in temperature anticipated under climate change may be anticipated to accompany, or influence, increases in precipitation also anticipated under climate change (Section 4.6.4). The indirect relationships between temperature and runoff precluded the representation of the relationships between nutrients, sediment and temperature in these results. Temperature was only used as input in the *ACRU*-NPS model to initialize evaporation and crop yield calculations within the model. However, the changes in rainfall outlined in this study were considered to be comparable to changes in temperature, albeit indirectly.

The potential impacts of climate change on water quality in the Mkabela Catchment were evaluated with and without the impact of the wetland on the response of WQ variables. This was done in order to ascertain the relative impacts of climate change on these variables between the present and the future. The procedure and results of these analyses are detailed in the following section.

4.6.4   Projected Impacts of Climate Change

With regard to the present (1971-1990) and future (2046-2065) GCM projections, variable changes between the present and the future were presented as ratios of change and percentage changes. A ratio value above 1 indicates an increasing trend in the simulated variable, a value between 0.9 and 1 indicates a negligible change in the variable and a value below 0.9 indicates a decreasing trend in the simulated variable. The ratios represent qualitative rather than quantitative changes in the simulated WQ variables. Quantitative estimates of these variables were considered to be less appropriate owing to the uncertainty presented by future GCM projections with regard to rainfall and the apparent large variations in the runoff outputs generated by the *ACRU*-NPS model using GCM-derived input (Table 4.6 and Figure 4.8). Therefore, qualitative analyses were deemed more appropriate as they give a more holistic representation of the potential future changes in simulated variables and highlight relative changes better than quantitative assessments which are, admittedly, only as accurate and relevant as the modelling assumptions applied. To add further clarity to the analyses, percentage changes, calculated by subtracting the future value of a variable from the present value of the same variable and dividing by the present value of the variable, were also included in these analyses.

Unlike the ratio-based approach, in the percent change approach a positive percentage change suggests an increasing trend in the variable while a "negative" percentage change suggests a declining trend in the variable.

The potential impacts of climate change on mean annual runoff, nutrient loads and sediment yield are indicated in Table 4.7 for all downscaled GCMs considered and in Figures 4.9 and 4.10 for the CSIR and CSAG downscaled GCMs, respectively. Table 4.7 presents the ratios of change, as described above, between the future and the present for each water quality variable considered. Figures 4.9 and 4.10 show the potential impacts of both climate change and the potential impacts of the wetland under climate change (*i.e.* under future conditions) on the generation and transfer of the WQ variables considered. In Figures 4.9 and 4.10, the impacts of climate change ("Impact CC") are represented by the future versus present changes in wetland inflows. The combined impacts of climate change and the wetland ("Impact CC and Wetland) are represented as future wetland outflows versus present wetland inflows. Table 4.7 and Figures 4.9 and 4.10 show that 4 out the 7 downscaled GCMs considered project increases in runoff, nutrients and sediment going into the wetland (ratios above 1 and positive percentage changes). These were the GDFL2.1, MRI, IPSL and CSIRO GCMs. However, 3 of these GCMs *viz.* the MIROC, ECH5 and ECHO GCMs, project decreases (albeit small decreases) in runoff, nutrients and sediment.

For the GCMs downscaled by the CSIR, the GFDL2.1 GCM projects increased runoff going into the wetland (positive percentage change) while the MIROC GCM projects decreased runoff going into the wetland. As a consequence of the combined impacts of climate change and the wetland, a general decreasing trend (negative percentage change) in wetland outflow was observed for the MIROC GCM. Under climate change, the GFDL2.1 GCM indicates positive but minimal change with regard to nutrients and sediment. The MIROC GCM, conversely, shows decreasing trends with regard to nutrients and sediment generated from upstream HRUs. In all instances, however, the role of the wetland is much greater than the impact of climate change and results in overall decreases in nutrients and sediments (Figure 4.11). Although the simulations project increases in runoff for most of the GCMs under climate change and also point to the potential increase in the generation of sediment and nutrients, the downstream transfer of these variables is mitigated to a high degree by the wetland.

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Most of the CSAG downsc aled GCMs indi cated posi tive c hanges with regard to runoff, nutrients and sediment (Figure 4.12) under future conditions. The exceptions to these trends were the ECHO and ECH5 GCMs which indicated negligible decreases in runoff (5.44% and 2.5% respectively) between the future and the present. These GCMs also indicated decreases in nitrogen and sediment and negligible change in phosphorus. Ratios of change greater than 1 and positive percentage changes were observed for all other GCMs (Table 4.7 and Figure 4.12). The va rious GCMs indi cated large v ariations in projected run off, nutrients and sediment. For instance, the IPSL GCM suggested increases in runoff of up to 95%, while the MRI GCM suggested i ncreases of only 22%, and in the sa me sense the C SIRO GCM suggested incr eases of up to 71%. This, as it is evident, r epresents a lar ge a mount o f disagreement between these GCMs.
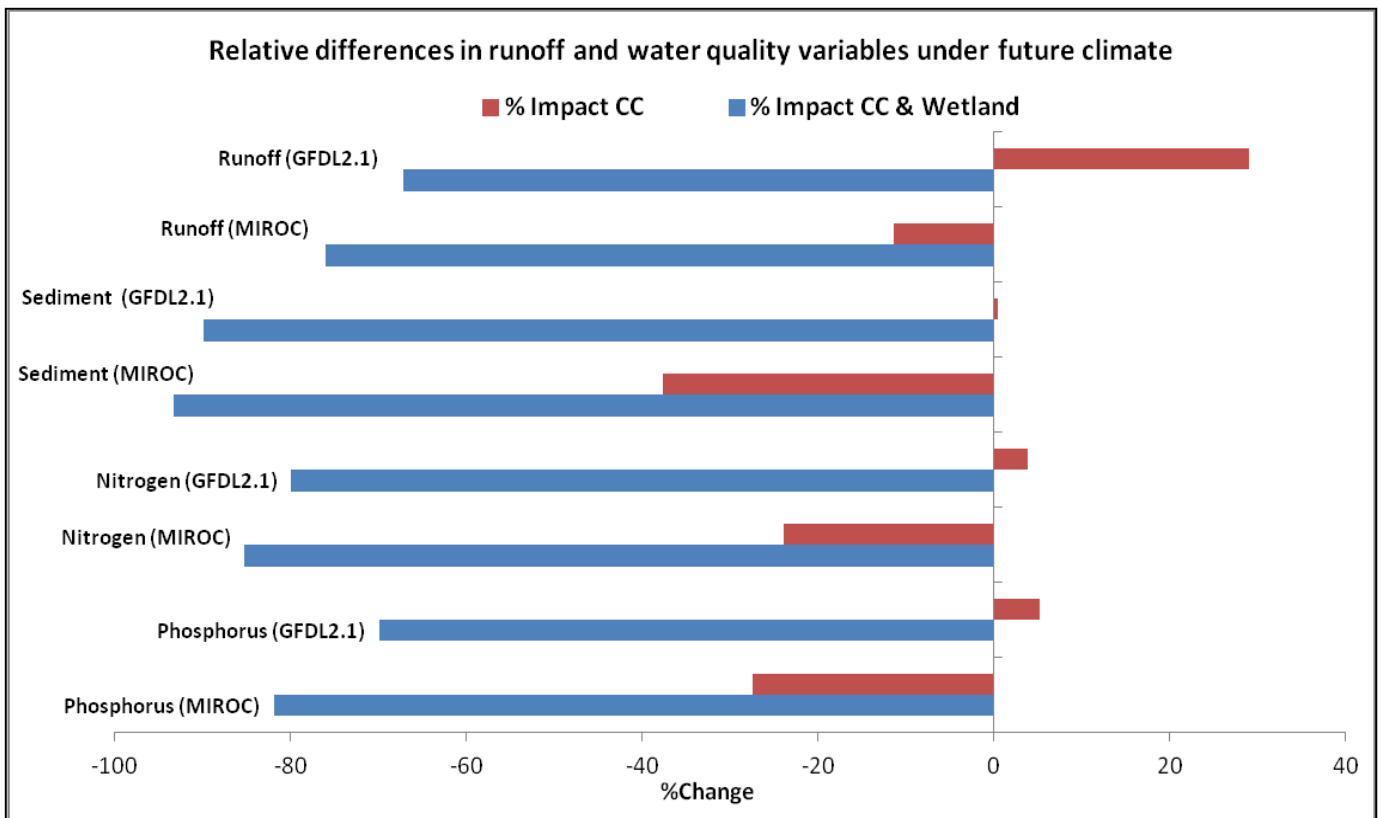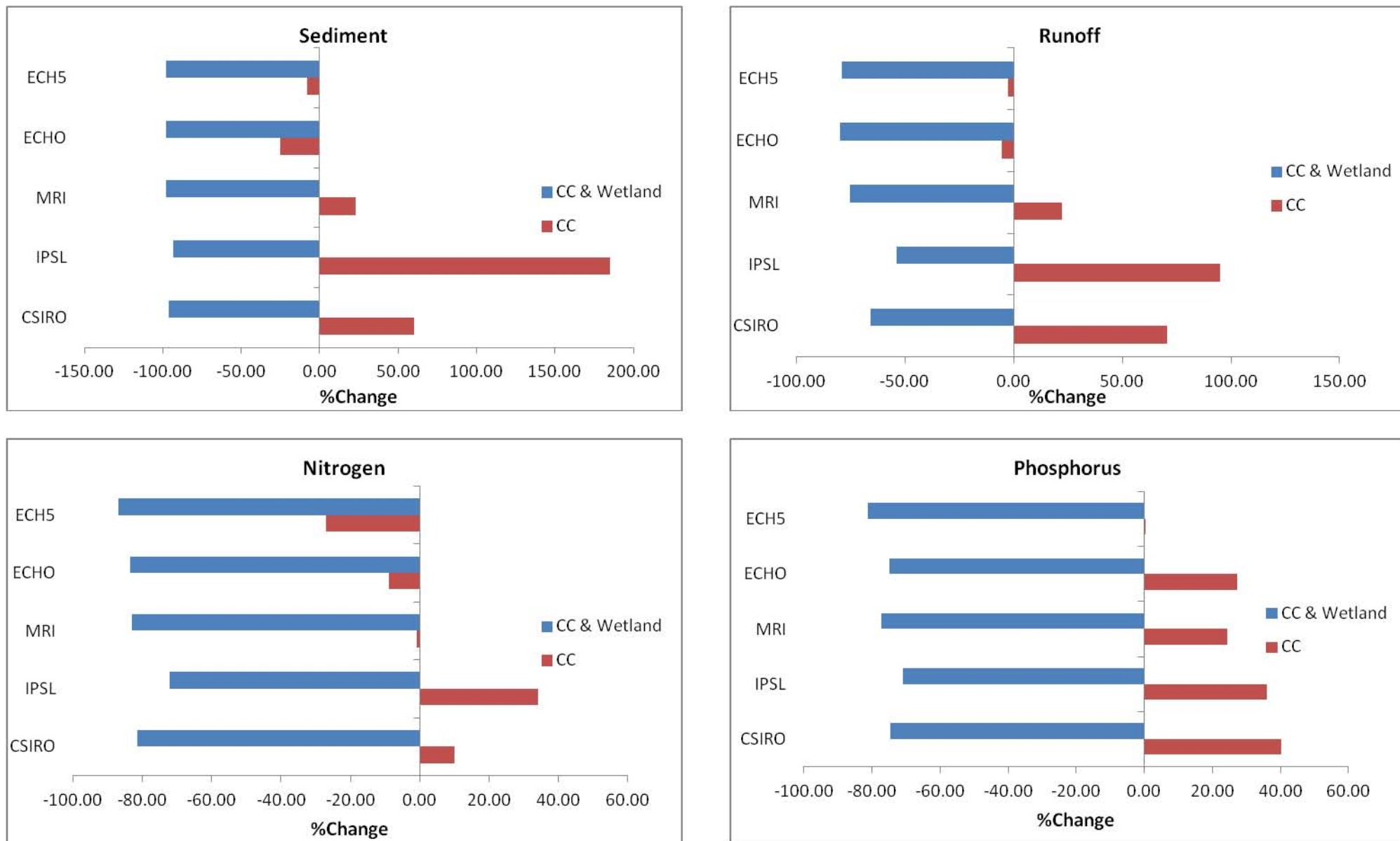

Figure 4.11 Impact of c limate c hange and c limate change c ombined with the wetland on mean annual runoff, sediment yield, nitrogen load and phosphorus load for the CSIR downscaled GCMs.

Regardless of these variations, the majority of the CSAG downscaled GCMs indicated the same direction of change, which was a generally increasing trend in the generation of runoff, nitrogen, phosphorus and sediment under climate change. It has been mentioned before that GCMs are highly uncertain and they are not always expected to explicitly reproduce the exact time series variations of point scale rainfall and, consequently, that of local scale runoff. It was, therefore, considered highly critical that the focus of these analyses be on the variability and relative changes presented by the downscaled GCM projections rather than on the absolute (*i.e.* quantitative) estimates that they project. Although there was consensus amongst the CSAG GCMs regarding the direction of change in WQ variables (*i.e.* nutrients and sediment), there was limited agreement between these GCMs as to the magnitude of change of these WQ variables (Table 4.7).

Nearly all CSAG GCMs show that the generation of runoff and associated WQ variables will increase under future conditions of change, but there are significant variations between the GCMs regarding these increases. A closer inspection of mean annual precipitation was undertaken in an attempt to isolate and describe these trends. MAP changes indicated neutral to slight increases, yet runoff changes range from neutral to large increases (Table 4.7). Downscaled GCMs projecting large runoff increases, thus, indicate a change in the distribution of rainfall (*e.g.* at seasonal or daily levels) which results in a lot more runoff from the same total rainfall. Some GCMs (*e.g.* ECHO, ECH5 and MRI) show reductions in sediment and nitrogen. These are GCMs that also project minimal change in annual runoff (save for the MRI GCM) – again this suggests changes in the distribution of the rainfall, this time in the opposite manner (less concentrated/intense rainfall). These variations were considered critical in these analyses primarily for the fact that the CSAG downscaled GCM projections were considered to best represent the Mkabela Catchment with respect to climatic variability. To gain a better understanding of these variations in runoff and WQ variables, it is important that the nature of the changes in daily rainfall (as the main "driver" of these trends) under climate change be fully detailed. Chapter 5 presents a more detailed analysis of the correlations between observed and GCM-derived rainfall.

Table 4.7 Ratios of future to present mean annual precipitation, runoff, nutrients and sediment for all downscaled GCM projections.

	RATIOS OF CHANGE*				
	MAP	RUNOFF	SEDIMENT	NITROGEN	PHOSPHORUS
DOWNSCALED GCM					
GDFL2.1	1.05	1.29	1.00	1.04	1.05
MIROC	0.89	0.89	0.62	0.76	0.73
CSIRO	1.08	1.71	1.60	1.10	1.40
ECHO	1.04	0.95	0.75	0.91	1.27
IPSL	1.01	1.95	2.85	1.34	1.36
ECH5	1.00	0.97	0.92	0.73	1.00
MRI	1.04	1.22	1.23	0.99	1.24
		*As ratio of future to present			

Figure 4.12   Impact of climate change and climate change combined with the wetland on mean annual runoff, sediment yield, nitrogen load and phosphorus load for the CSAG downscaled GCMs.

4.7 Discussion and Conclusions

This paper investigated the impacts of climate change on the behaviour of selected water quality constituents *viz*. nutrients (N and P) and sediment. This was done by assessing the changes in these water quality constituents under present and future climate change conditions while also taking into account the influence of a wetland in limiting their downstream transfer. For the variables considered, *i.e.* runoff, nutrients and sediment, the general trend observed was a significant reduction between the values of the variables incident to the wetland and values exiting the wetland. This was true for both present and future simulations. Similar reduction trends were observed in a constructed wetland where between 21-44% of P input was retained from an average daily input load of 0.7-1.8m (Braskerud, 2002). Similarly, 3-15% of N input was retained in the same constructed wetland from a similar average daily input load (*i.e.* 0.7-1.8m) (Braskerud, 2002). Mean annual statistics of runoff were considered as a means of obtaining a general overview of the impact of climate change on the selected WQ variables and for assessing the ability of the wetland to limit the downstream transfer of nutrients and sediment. Simulations based on observed data for the present (1971-1990) period indicated that the wetland under study was highly competent in attenuating runoff and limiting the downstream transfer of nutrients and sediment (Table 4.5 and Figures 4.6 to 4.9). These were expected trends considering the hydropedological, geomorphological and biochemical nature of wetlands. McKergow *et al.* (2006), notes that riparian buffers, including wetlands, can be used by farmers and catchment managers to achieve water quality improvements. Wetlands are able to reduce the kinetic energy of incident variables (*e.g.* flow, nutrients and sediment) and through their ability to retain vast amounts of water, allow the settling and restraint of nutrients and sediment limiting their downstream transfer.

This study made use of 7 different dynamically and empirically downscaled GCMs. Two of these GCMs were dynamically downscaled by the CSIR and five were empirically downscaled by CSAG-UCT. The selection of these downscaled GCMs in this manner proved useful in detailing the potential impacts of climate change on water quality from different climate change projection perspectives, as presented by the various GCMs. The different techniques used in downscaling GCM projections were anticipated to yield equally different outputs.

This would, necessarily, result in varied modelling outputs when the downscaled projections were used as input into the *ACRU*-NPS water quality model to generate runoff, nutrients and sediment estimates. In essence, although downscaled GCMs are expected to reproduce prevailing regional climates with confidence, they are nonetheless models and as such, are subject to the same uncertainty constraints and boundary conditions that are inherent to all mathematical models.

It is important to note that downscaled GCM projections are not necessarily expected to explicitly reproduce the exact time series variations of point scale rainfall. This was indicated by the variations in MAP shown by the different downscaled GCMs when compared to the observed MAP (Table 4.6, also see Chapter 5). Similarly, simulated runoff (MAR) indicated large variations between the various downscaled GCMs and when compared to MAR simulated from observed records. The same was true when potential future changes in runoff were assessed. The different downscaled GCMs indicated large variations in potential changes in runoff going into the future (Figures 4.11 and 4.12). While there was a general consensus among the downscaled GCMs that runoff will increase in the future, there was little agreement between these GCMs regarding the magnitude of that change. Some downscaled GCMs projected significant changes while others projected little or no change. In the same sense, more than half of the downscaled GCMs projected increases in nutrients and sediment but there was little agreement as to the magnitude of those changes. Similar to runoff, some downscaled GCMs projected significant increases in these variables (*e.g.* GDFL2.1, MRI, CSIRO and IPSL) while others indicated no change or insignificant changes (*e.g.* MIROC, ECH5 and ECHO).

These large variations in output highlight a critical aspect regarding the application of downscaled GCMs in the assessment of possible changes in WQ variables: GCMs, downscaled or otherwise, are uncertain. This is vital to note considering the fact that this study was using regional-scale GCM data (at the highest resolutions) to try and describe point scale processes. Although the simulations conformed to the initial expectations (*e.g.* increases in rainfall will potentially result in increases in runoff and potential increases in the downstream transfer of agricultural pollutants), the large variations in the output highlighted the absolutely crucial need to take uncertainty and natural variability into cognisance.

Further, these variations highlighted the importance of viewing downscaled GCM projections in a more critical light and perhaps directing more emphasis toward the variability of the natural climate rather than focusing on absolute estimates of change which cannot be verified. Therefore, focus needs to be directed more towards assessing robust patterns of change that are consistently shown by downscaled GCM projections and in the literature *e.g.* increases in temperature and rainfall variability. Furthermore, although these are anthropogenically induced changes, natural variability will always be present and will constantly remain a challenge.

With respect to the actual impacts of climate change, this study has shown that climate change will potentially result in rainfall and runoff increases in the study catchment, regardless of the variability inherent in the various downscaled GCMs (Table 4.7). It was also demonstrated by this study that, with an increase in runoff, the generation and transfer of nutrients and sediment is also highly likely to increase, as indicated by most of the downscaled GCMs, particularly those that show significant trends of wetting going into the future. However, the wetland appeared to have an overriding effect on these changes. This was ascertained from the apparent high competency of the wetland to attenuate runoff and limit the downstream transfer of nutrients and sediment (Figures 4.11 and 4.12). Regardless of the increase in magnitude of a particular variable (*i.e.* increase in generation), the wetland consistently retarded the movement of the WQ variables from upstream to downstream sources. The reasons for this behaviour have already been outlined.

The influence of temperature on the generation and translocation of runoff, nutrients and sediment was not overlooked in this study. Temperature is an important driver of the processes that influence water availability in a catchment. For instance, increased temperatures influence increased evapotranspiration (total evaporation) which ultimately influences regional rainfall patterns (depending on other biophysical aspects such as land use and aspect). In a study of regional impacts of climate change on water resource quantity and quality, Mimikou *et al.* (2000) found that increased temperatures complemented by reduced rainfall had negative impacts on stream water quality by reducing runoff and consequently reducing the dilution capacities of receiving waters.

Since the generation of nutrients and sediment is highly sensitive to climatic factors, not limited to rainfall, changes in rainfall influenced by changes in temperature may be expected to trigger changes in the generation and rate of transfer of sediment and thus nutrients (as shown by Mimikou *et al.,* 2000). In this study, the influence of temperature on water quality was, therefore, taken into account solely from the point of view of the influence on evapotranspiration. Other temperature influences, such as the influence on water temperature, chemical reactions and settling rates were not taken into account. Downscaled GCM projections generally give adequate representations of observed temperatures owing to the fact that temperature is influenced by fewer biophysical factors than rainfall (see Hughes, 2012). Therefore, no significant anomalies were anticipated in the time series distribution of daily temperature records described by the various downscaled GCMs. The same was not true for rainfall with regard to biophysical influences. This explains the focus this study assumed on rainfall as a direct driver of the generation and transfer of WQ variables.

It is generally accepted that many uncertainties abound in climate change predictive modelling, especially in rainfall-runoff modelling. The results presented in this study also highlighted this notion. The results indicate that the uncertainties presented by downscaled GCM projections when attempting to reproduce present hydrological conditions and responses must be considered in decision-making and adaptive water quality management based on future predictions. It is important to reiterate that the results obtained in this study do not necessarily imply that the downscaled GCM projections are not adequate for the simulation of future hydrological conditions, only that the uncertainty they display will be an important factor in the development of adaptive water quality management strategies.

To fully explain the variations in rainfall data between the downscaled GCMs, it is critical that the variability and patterns of change shown by the downscaled GCMs be fully detailed and assessed. Rainfall, as one the primary drivers of catchment processes, should be assessed in terms of potential changes in the frequency distribution of daily depths and in the changes in certain defined rainfall thresholds. The statistics relevant in such analyses include: MAP changes, number of days in which various runoff thresholds are exceeded, coefficient of variation (CV) of annual precipitation, total number of raindays and total number of rainless days. The results of those analyses are detailed in a subsequent paper (Chapter 5).

In summary, this paper evaluated the ability of seven downscaled GCMs to simulate present climate conditions and the behaviour of runoff, nutrients and sediment for 3 HRUs located at the headwaters of the Mkabela Catchment over two 20 year periods, encompassing the present (1971-1990) and the future (2046-2065). Additionally, the projected impacts of climate change on water quality constituents were assessed while also taking into account the ability of the wetland to attenuate and retard the downstream displacement of runoff, nutrients and sediment. Results showed that 4 out of 7 downscaled GCMs project increases in each WQ variable under future conditions and that the wetland maintains its ability to limit the transfer of nutrients and sediment regardless of changes in the generation of these variables. It is believed that this paper has shown the potential of the methodology to be applied to develop improved future water quality projections and, therefore, to assist in developing appropriate and informed climate change adaptation strategies.

The scope of the analyses presented in this paper was relatively limited and there is potential for refinements to be made to the methodology. It was therefore recommended that the following be investigated in future research:

a) the exact nature of the changes in rainfall, especially with regard to variability, intensity and extreme events,

b) ensure that the above changes are all incorporated in future modelling methodology to the best of current understanding,

c) similarly, the changes in temperature need to be characterized and represented in the modelling methodology (temperature effects are currently only represented in total evaporation and need to be extended to possibly include nutrient cycling, migration and depositions),

d) projections for other CSIR GCMs need to be evaluated to assess the evenness of the spread in results between the selected downscaled GCMs, and

e) the impact of climate change on the remainder of the catchment needs to be investigated (*i.e.* at larger scales).

4.8 Acknowledgements

4.9 References

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CHAPTER FIVE

Assessing Potential Changes in Daily Rainfall Distribution under Climate

Change for the Mkabela Catchment

5. ASSESSING POTENTIAL CHANGES IN DAILY RAINFALL DISTRIBUTION UNDER CLIMATE CHANGE FOR THE MKABELA CATCHMENT

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ABSTRACT

As part of a broader study, which was to detail the potential impacts of climate change on water quality using the daily-time step water quality model *ACRU*-NPS and seven downscaled Global Circulation Models (GCMs), it was deemed necessary to fully detail the probable changes in daily rainfall distribution between the present and the future as described by selected downscaled GCMs. Hydrologically relevant rainfall statistics of seven different downscaled GCMs were analysed in order to detail changes in the frequency of pre-defined rainfall thresholds. Results from these analyses indicated limited consistency between the GCMs with respect to probable changes in rainfall frequency distribution between the present and the future. There was also high variation between the downscaled GCMs regarding changes in defined rainfall event intervals with some GCMs indicating significant increases and others indicating minimal changes and some indicating no changes. It was concluded that in the development of adaptation strategies, focus should be directed more towards the uncertainty and variability presented by these projections rather than on absolute quantitative estimates of future climatic conditions.

Keywords: Rainfall, Climate Change, Global Circulation Models, Uncertainty, Variability, Adaptation.

5.1 Introduction

Climate change is anticipated to result in changes in the frequency of daily rainfall distributions for most catchments in South Africa, particularly those located in the eastern and central parts of the country (Hewitson *et al.,* 2005). This presents numerous implications not only for runoff and streamflow regimes, but also for the generation and translocation of agricultural non-point source (NPS) pollutants within these catchments (Nilsson and Renöfält, 2008; Lorentz *et al.,* 2011). It is therefore important that the potential impacts of climate change on water resources be assessed in order to ensure the judicious and adaptive management of these water resources (Kundzewicz *et al.,* 2007; IPCC, 2007). One way of achieving this is through daily time-step hydrological modelling. However, previous studies (Chapter 4; Hewitson and Crane, 2006; Hughes *et al.,* 2011; Hughes, 2012) have highlighted several uncertainties in the daily rainfall generated from downscaled Global Circulation Models (GCMs) and used as input in these hydrological models. Therefore, it is important to detail the exact *nature* of the input rainfall data in order to understand the characteristics of the simulated runoff and consequently those of the simulated NPS pollutants.

The majority of climate change studies rely on the output generated from various GCMs developed at various climate research institutes around the world (Chapter 4; IPCC, 2001; IPCC, 2007; Bates *et al.,* 2008). It was noted in Chapter 4, Section 4.4.2 that GCMs are limited by their spatial resolutions. A single GCM generally represents a spatial grid of ~300km (Hewitson *et al.,* 2005). This means that a particular GCM will provide one average value that theoretically represents a 300km by 300km grid pixel. This average value generated by a GCM is of little value in the investigation of point specific catchment processes or local impact assessments. Therefore, the output from these GCMs needs to be downscaled in order to provide better representations of regional or local scale climatic regimes (Engelbrecht *et al.,* 2009; Hewitson *et al.,* 2005; Hewitson and Crane, 2006). The use of downscaled GCM data is, therefore, considered useful in understanding the likely changes in biophysical responses to future changes in rainfall and temperature regimes through modelling exercises. The climate change projections used in this study were derived from 7 (seven) downscaled GCMs employed in the Intergovernmental Panel on Climate Change and Fourth (AR4) Assessment Reports (IPCC, 2007).
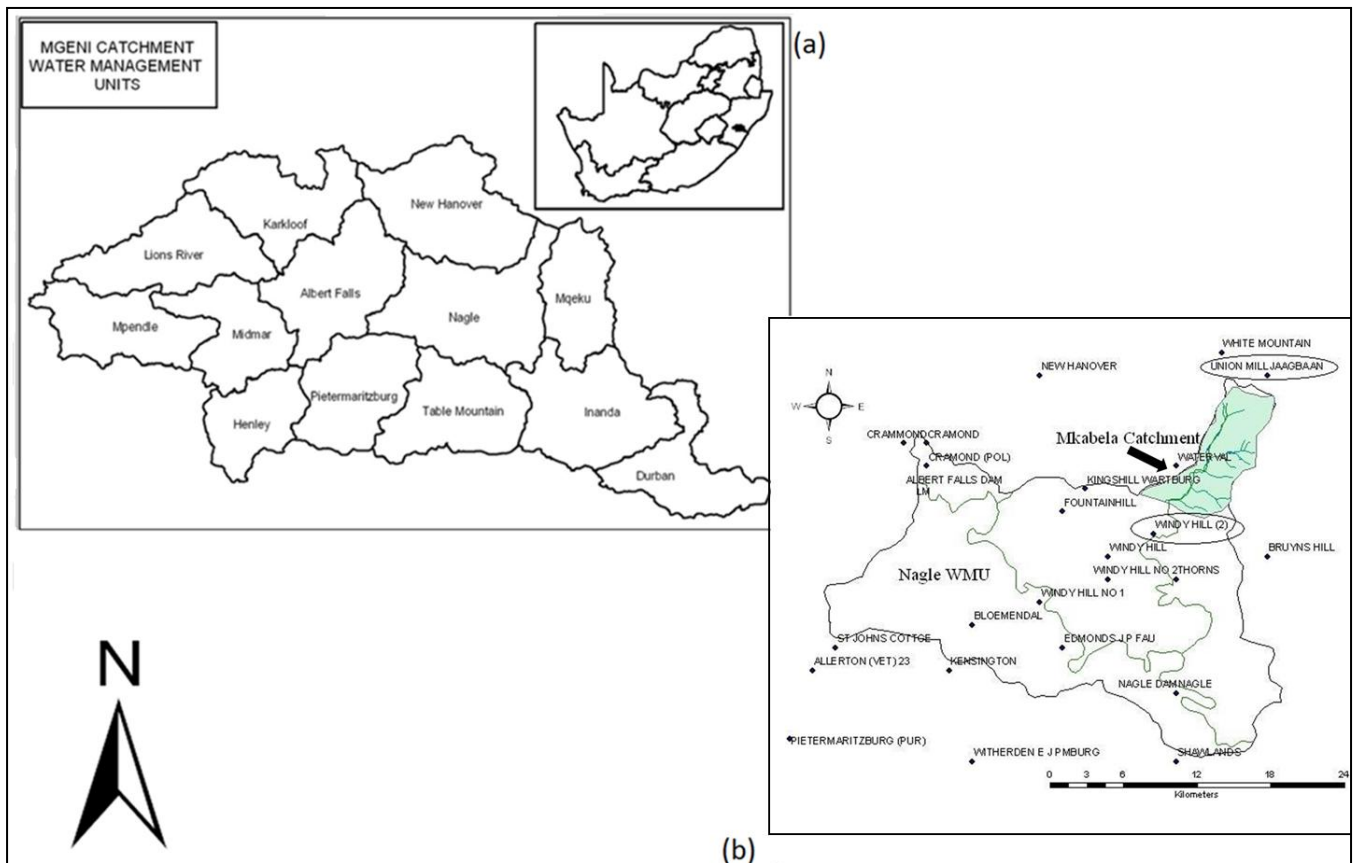
The downscaled climate change projections were obtained from the Council for Scientific and Industrial Research (CSIR) and from the Climate Systems Analysis Group (CSAG) based at the University of Cape Town (UCT). The CSIR GCMs were dynamically downscaled to a 0.5 degree horizontal resolution grid over southern Africa (Engelbrecht *et al.,* 2009) and the CSAG GCMs were empirically downscaled to point scales across southern Africa (Hewitson, 2012, pers. comm.). Daily rainfall data obtained from historical observations and from the downscaled GCMs was assessed at a daily time-step resolution. Owing to the techniques applied in downscaling GCM rainfall data, some differences in daily rainfall data were expected between the GCM-derived time series and observed/historical time series (the terms "observed" and "historical" are used interchangeably in this text). This stems from the fact that GCMs are models that attempt to mimic the rainfall characteristics of a catchment using a fairly coarse spatial scale, whereas the observed records assessed in this study were localised, point measurements (see Section 4.4.2). As will be shown in this study, downscaled GCMs do not necessarily capture the exact nature of the rainfall typical of a *specific point* within a particular catchment. This presents important implications for the translation of rainfall to runoff within any hydrological model such as the one applied in Chapter 4 and, thus, for the interpretation of output obtained from such hydrological modelling exercises.

It has been noted elsewhere that downscaled GCMs are not entirely infallible with respect to reproducing local scale climates, although they are designed to reproduce regional scale variables with similar statistical frequency(-ies) to what is actually observed (Hewitson *et al.,* 2005; Hughes, 2012). The reason behind this is that although the downscaled GCMs attempt to reproduce *regional* rainfall records, the resolutions used in the downscaling exercises are inherently coarse and will not necessarily capture the exact nature of the rainfall of a specific *point* of interest within a catchment. This presents significant implications for the analysis of rainfall time-series generated by GCMs intended to provide climate change output. It is also important to assess the ability or skill of a particular downscaled GCM to represent present climate before evaluating future climatic changes. In this paper hydrologically relevant statistics of rainfall are assessed with the aim of providing a holistic view of the differences between the nature of observed and GCM-derived rainfall data. In addition to assessing the differences between observed and GCM-derived rainfall, through the analyses undertaken, changes in rainfall distribution for the downscaled GCMs between present (1971-1990) and future (2045-2065) periods are characterised.

## 5.2	Methodology

### 5.2.1	Observed Rainfall Data Acquisition and Treatment

Daily observed rainfall data were obtained from two rainfall stations located in and around the Mkabela Catchment, located approximately 1km east of the town of Wartburg, near Pietermaritzburg, South Africa (29.34' 57.00" S, 30.36' 48" E) (Figure 5.1). The two stations, Windy Hill No. 2 and Noodsberg-Jaagbaan, (marked as "Union Mill Jaagbaan") are also indicated in Figure 5.1. The records from these stations had data available over different periods and were combined to form a single composite record for the period 1950 to 2011. An adjustment of daily rainfall data from the Windy Hill Number 2 station was carried out in order to ensure that it represented the Mkabela Catchment in its entirety, more realistically. Rainfall data from the Noodsberg-Jaagbaan station was not adjusted since this station was considered to be close enough to the Mkabela Catchment to permit the use of its data without the necessity for adjustment. The adjustment of the Windy Hill Number 2 station rainfall data was carried out using the *ACRU* model rainfall adjustment or *CORPPT* function. As mentioned in Chapter 4, median monthly rainfall data were used to determine month-by-month adjustment factors, which were applied to the record to adjust daily rainfall data (Smithers and Schulze, 2004). Essentially, the aim of the adjustment was to best estimate the rainfall in the Mkabela Catchment using available data over the period of interest (*i.e.* 1950-1970). In adjusting the records from the Windy Number 2 station to better represent the catchment rainfall, the data from the two selected stations were, consequently, made to be more comparable.

Figure 5.1 Location of the Mkabela Catchment within the Nagle Water Management Unit (WMU). Shown in (b) are the selected rainfall gauging stations (circled) and other rainfall stations and towns in and around the Nagle WMU.

5.2.2 Climate Change Projections Considered

As already noted in the introduction, the climate change projections used in this study were derived from 7 downscaled GCMs. The downscaled climate change projections were obtained from the CSIR and from CSAG based at the University of Cape Town (UCT). Table 5.1 provides a summary of the relevant information regarding the selected downscaled GCMs. The selection of the downscaled GCMs was based on projected changes in mean annual precipitation (MAP) described by each downscaled GCM. The GFDL2.1 and MIROC GCMs downscaled by the CSIR represented wet and dry climate change projections respectively. The GCMs downscaled by CSAG all represented wet climate change projections, with variations in the degrees of change in MAP.

All the downscaled GCMs used in this study were originally derived from coupled GCM (CGCM) projections that contributed to the Intergovernmental Panel on Climate Change (IPCC) Fourth Assessment Report (AR4) (IPCC, 2007).

Table 5.1   Information on selected downscaled GCMs including downscaling institutions and record lengths.

Downscaled GCM	Downscaling Institute	Time Periods Considered
GDFL2.1	CSIR	1971-1990
		2046-2065
MIROC	CSIR	1971-1990
		2046-2065
CSIRO	CSAG-UCT	1971-1990
		2046-2065
ECHO	CSAG-UCT	1971-1990
		2046-2065
IPSL	CSAG-UCT	1971-1990
		2046-2065
ECH5	CSAG-UCT	1971-1990
		2046-2065
MRI	CSAG-UCT	1971-1990

The GFDL2.1 and MIROC GCMs were dynamically downscaled by the CSIR using the high-resolution conformal-cubic atmospheric model (CCAM) developed by the Commonwealth Scientific and Industrial Research Organisation (CSIRO) in Australia. This was performed by forcing the CCAM model using bias-corrected sea-surface temperatures and sea-ice fields of coupled GCMs to produce regional scale climate change projections (Engelbrecht *et al.*, 2009). The CSAG GCMs were empirically downscaled by using observed data to derive relationships between synoptic scale and local climates and applying the resulting relationships to GCM output to generate higher resolution local climate change projections (Hewitson *et al.,* 2005).

As mentioned in Chapter 4, these projections represent a range in global models (including their various sensitivities, parameterizations, *etc.*), downscaling methodologies and institutions and, therefore, reflect the uncertainty that is inherent in climate change projections at present. This was considered critical since using projections from a single combination of GCM-downscaling institution runs the risk of obtaining a biased view of the future.

Changes in mean annual precipitation (MAP), changes in the number of raindays (days with rainfall above 0 mm), number of days between defined rainfall depth thresholds and the variation in daily rainfall amounts were determined in order to characterise changes in rainfall distribution between the present (1971-1990) and the future (2046-2065). These criteria give an indication of whether individual rainfall events are increasing or declining going into the future and thus provide an indication of the probable changes in the behaviour of runoff and NPS pollutants between the present and the future (Lumsden *et al.,* 2009). In summary, the rainfall statistics assessed include:

a) mean annual precipitation (MAP),

b) standard deviation of annual precipitation,

c) coefficient of variation (CV) of annual precipitation,

d) number of days in the time series with zero rainfall,

e) total number of raindays,

f) number of days in the time series with rainfall events between 1 and 5mm,

g) number of days in the time series with rainfall events between 5 and 10 mm,

h) number of days in the time series with rainfall events between 10 and 15mm,

i) number of days in the time series with rainfall events between 15 mm and 20mm,

j) number of days in the time series with rainfall events between 20 mm and 30mm,

k) number of days in the time series with rainfall events between 30 mm and 40mm,

l) number of days in the time series with rainfall events between 40 mm and 50mm,

m) number of days in the time series with rainfall events between 50 mm and 100mm and finally,

n) number of days in the time series with rainfall events above 100mm.

The disaggregation of rainfall into these event ranges was considered important in the isolation and analysis of individual rainfall events that trigger important hydrological responses such as stormflow, runoff and, consequently, NPS pollutant generation and transport. For instance, the 10mm rainfall depth threshold is considered a typical amount required for generating stormflow and, thus, runoff (Lumsden *et al.,* 2009). Similarly, events above the 20mm threshold are associated with heavy rainfall events coupled with resultant high stormflow.

Detailing rainfall patterns of change under conditions of climate change is, therefore, critical in understanding the potential generation and transport characteristics of agricultural NPS pollutants from hydrological response units (HRUs). This also facilitates the potential improvement of the management of these pollutants under future conditions of change. In addition to assessing changes in the frequency of runoff-producing rainfall events, this study also includes the less extreme rainfall events represented by the 1-5mm depth threshold and the more extreme events above the 20-30mm depth threshold. Event ranges above the 20-30mm range were included to ensure completeness of the analyses. This was done in order to fully detail the rainfall time series of each downscaled GCM. The following section outlines the results of these analyses.

5.3   Results and Discussion

The typical rainfall characteristics of the Mkabela Catchment observed for the period 1971-1990 are presented in Table 5.2 for mean annual precipitation (MAP), standard deviation of annual precipitation, CV of annual precipitation, number of days with no rainfall, number of raindays and total number of days in the time series. To facilitate easier interpretation, the rainfall frequencies have been reported as annual means (*i.e.* it was considered more relevant and more meaningful to report these frequencies as *x*-number of days per year rather than *x*-number of days in the entire time-series). This analysis compares the distribution of observed rainfall with the distributions of the two CSIR downscaled present climate GCMs used in the IPCC 4th Assessment Report (AR4) (IPCC, 2007). Table 5.2 indicates significant differences between the statistics of observed and GCM-derived rainfall in almost all statistical variables considered. The GFDL2.1 GCM, for instance, reported an MAP of 1301.6mm for the present period; almost 56% higher than the observed MAP.

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The MIROC GCM also reported a similar trend in terms of MAP under present conditions, with a 57% departure from the observed MAP. When compared to the number of raindays in the observed record, both GCMs reported a significantly higher number of raindays per year with a bias towards low magnitude events over the present period of analysis (compare Table 5.2 and Figures 5.2 and 5.3). This combination of more raindays per year combined with an over-simulation of low magnitude events (and an under-simulation of high magnitude events) explains the significantly higher MAP reported by both these downscaled GCMs.

In terms of changes in rainfall inter-annual variability, the GDFL2.1 GCM did not show significant changes in the variability of annual rainfall between the present and future periods of analysis, whereas the MIROC GCM projects a decrease in inter-annual rainfall variability between the future and the present. Both GCMs project a marginal decrease in the annual number of raindays and an increase in the annual number of rainless days in the future. The difference in these changes between the MIROC and GFDL2.1 GCMs is, however, negligible. Regarding changes in MAP, the GDFL2.1 GCM shows only a slight increase in annual rainfall between the present and the future. This GCM did not show much change in terms of the frequency with which any given depth threshold was met or exceeded between the present and the future (Figure 5.2). This indicates minimal change in runoff-producing events between the future and the present for this GCM. The MIROC GCM, conversely, projects an appreciable decrease in annual rainfall going into the future. With the exception of the 10-15mm depth range, which shows an appreciable decline between the present and the future, this GCM indicated little change in the frequency of low magnitude events (Figure 5.3). The larger events, however, in the 15-30mm range, indicate a decline for this GCM, signalling a reduced number of days per year with runoff-producing events in the future for the MIROC GCM.

Table 5.2 Rainfall conservation statistics and rainday distribution analysis results for observed and GCM-derived rainfall data. Also indicated in this Table are the relative changes in annual rainfall distribution between present and future time periods for the CSIR downscaled GCMs used in the study.

OBSERVED RAINFALL STATISTICS						
	STATISTICS			RAINFALL FREQUENCY (days/annum)		
	MAP (mm)	STDEV	CV	ZERO RAIN	RAINDAYS	TOTAL DAYS
PRESENT (1971-1990)	835.01	154	0.19	247.35	117.90	365.25

GFDL2.1 GCM RAINFALL STATISTICS						
	STATISTICS			RAINFALL FREQUENCY (days/annum)		
	MAP (mm)	STDEV	CV	ZERO RAIN	RAINDAYS	TOTAL DAYS
PRESENT (1971-1990)	1301.6	163.67	0.13	126.45	238.80	365.25
FUTURE (2046-2065)	1361.3	169.85	0.12	129.40	235.85	365.25
%CHANGE	4.59	3.78	-0.78	2.33	-1.24	0.00

MIROC GCM RAINFALL STATISTICS						
	STATISTICS			RAINFALL FREQUENCY (days/annum)		
	MAP (mm)	STDEV	CV	ZERO RAIN	RAINDAYS	TOTAL DAYS
PRESENT (1971-1990)	1310.45	227.69	0.17	129.2	236.05	365.25
FUTURE (2046-2065)	1162.38	124.98	0.11	133.25	232.0	365.25
%CHANGE	-11.30	-45.11	-35.29	3.13	-1.72	0.00
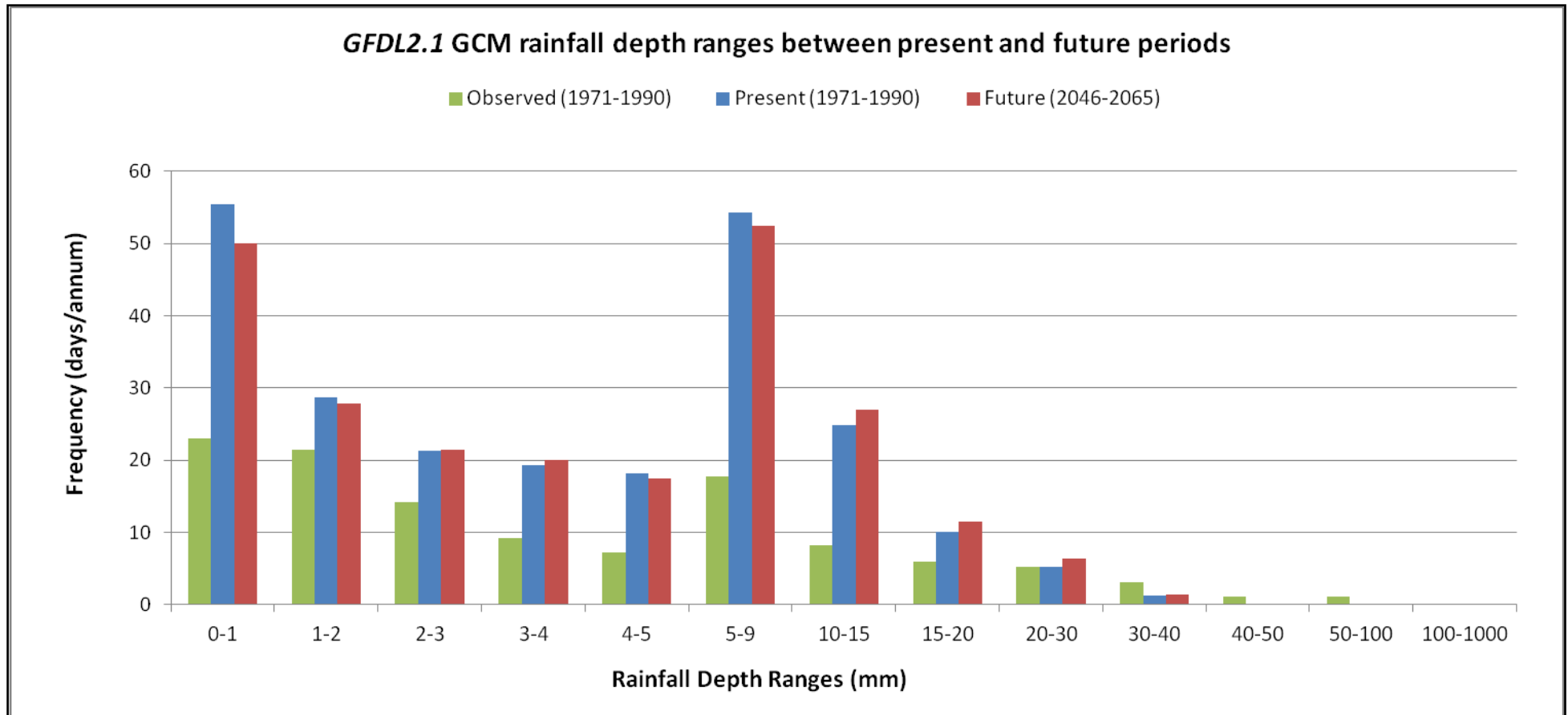
Figure 5.2   Rainfall event frequencies for observed, present and future climates allowing for the assessment of changes/differences. On a depth-by-depth basis, this figure indicates minor increases in projected runoff-producing rainfall events relative to the present period for the GFDL2.1 GCM.

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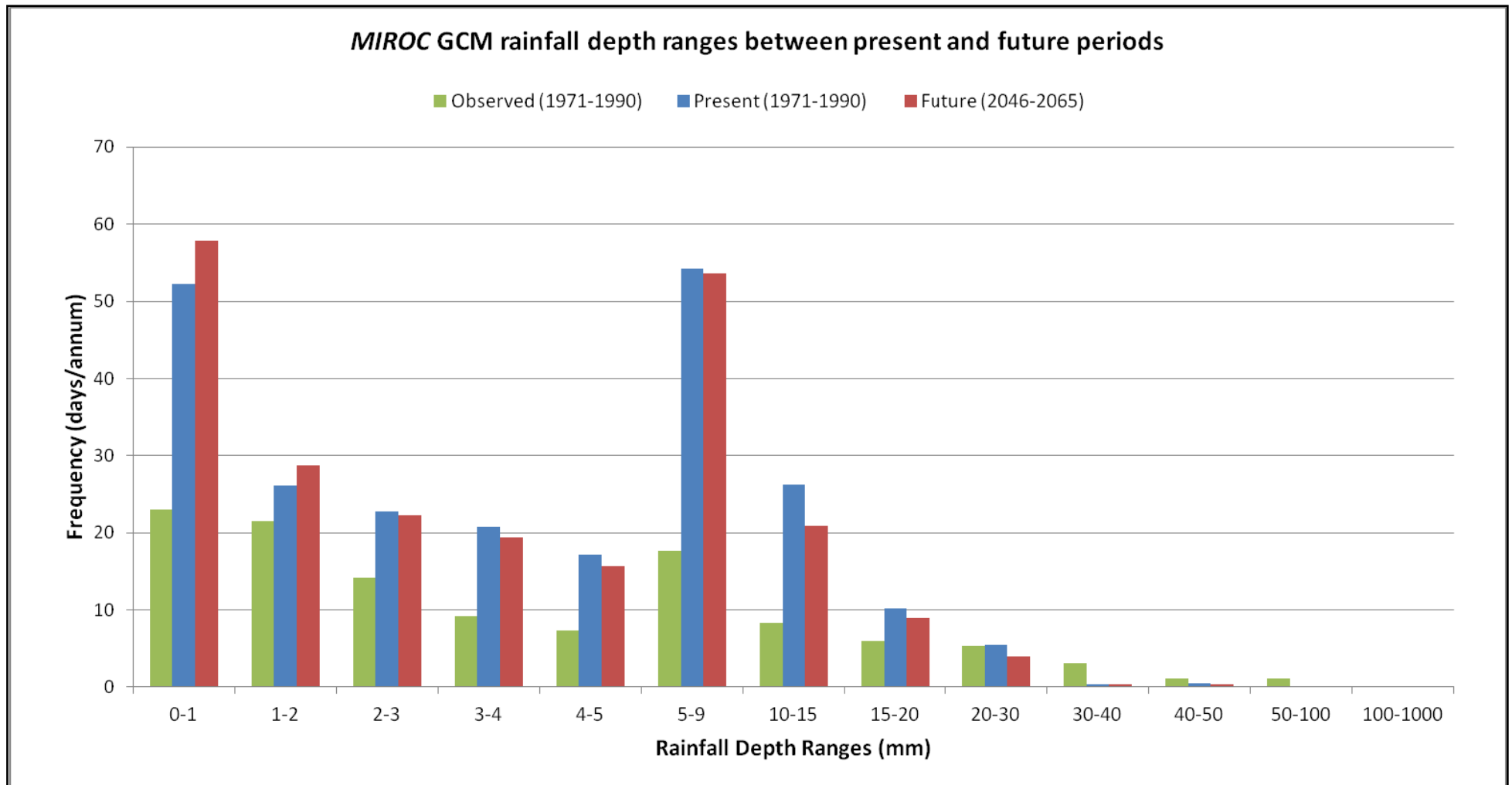
Figure 5.3   Distribution of rainfall event frequencies for observed, present and future climates for the MIROC downscaled GCM, also allowing for the assessment of changes/differences. In contrast to the GFDL2.1 GCM, the depth-by-depth analysis of highlights decreases in projected runoff-producing events under future and altered climatic conditions.

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Similar to the GCMs downscaled by the CSIR, the CSAG downscaled GCMs were assessed in terms of changes in rainfall statistics between the present (1971-1990) and future (2046-2065) periods. The results of these analyses are indicated Figures 5.4 to 5.9 (with the exception of Figure 5.5). Table 5.3 (a, b) presents conservation statistics of mean annual precipitation, CV of annual rainfall and standard deviations of annual rainfall for the observed record and for all the CSAG downscaled GCMs considered. Figures 5.4 to 5.9 are graphical representations showing the relationships between observed and rainfall threshold frequencies for the CSAG downscaled GCMs.

The GCMs downscaled by CSAG appeared to be more representative of the Mkabela Catchment with regard to rainfall distribution (Tables 5.3a and 5.3b). Improved correlations between observed and GCM-derived rainfall were found for all the statistical variables considered. Additionally, very similar trends were observed in terms of the number of annual rainless days and annual raindays when the observed and GCM rainfall time series were compared. This was attributed to the empirical downscaling technique used by CSAG to downscale these particular GCMs, which downscales GCM projections to a scale more suited to catchment modelling. In doing so, this technique offers a better representation of local scale rainfall distribution (see Chapter 4, Section 4.4.2). On a depth-by-depth basis, however, the frequency of runoff-producing events in 10-15mm range was found to be consistently over-simulated by the CSAG GCMs for the present period. For instance, the CSIRO, IPSL and MRI GCMs respectively reported 184, 273 and 206 days at which events in the 10-15mm range occurred, compared to the 170 days found in the observed record (Table 5.4). Similar trends were observed for the ECHO and ECH5 GCMs. This was repeated for all other depth ranges with the exception of the 1-5mm range, where the observed frequency of events exceeded that of the CSAG downscaled GCMs. It is important to note that the skill of a downscaled GCM to represent present climates and accurately capture the distribution and frequency of rainfall events for a particular region is limited by the choice of predictor variables used to reproduce local climates (Hughes, 2012).

Table 5.3a Rainfall conservation and threshold statistics for GCM-derived rainfall data and historical rainfall data. Also indicated in this table are the relative changes in annual rainfall distribution between present and future time periods for the CSAG downscaled GCMs used in the study.

	STATISTICS			RAINDAY THRESHOLDS (days/annum)		
OBSERVED RAINFALL STATISTICS						
	MAP	STDEV	CV	ZERO RAIN	RAINDAYS	TOTAL DAYS
PRESENT (1971-1990)	835.01	154.00	0.19	247.35	117.9	365.25
CSIRO GCM RAINFALL STATISTICS						
	MAP	STDEV	CV	ZERO RAIN	RAINDAYS	TOTAL DAYS
PRESENT (1971-1990)	803	125.58	0.16	264.05	101.20	365.25
FUTURE (2046-2065)	870.93	112.67	0.13	254.00	111.25	365.25
%CHANGE	8.46	-10.28	-18.75	-3.81	9.93	0.00
IPSL GCM RAINFALL STATISTICS						
	MAP	STDEV	CV	ZERO RAIN	RAINDAYS	TOTAL DAYS
PRESENT (1971-1990)	957.92	113.33	0.12	242.05	123.20	365.25
FUTURE (2046-2065)	1012.21	182.44	0.18	246.05	119.20	365.25
%CHANGE	5.67	60.98	50.00	1.65	-3.25	0.00
MRI GCM RAINFALL STATISTICS						
	MAP	STDEV	CV	ZERO RAIN	RAINDAYS	TOTAL DAYS
PRESENT (1971-1990)	906.06	191.73	0.21	265.15	100.10	365.25
FUTURE (2046-2065)	984.06	221.78	0.23	258.45	106.80	365.25
%CHANGE	8.61	15.67	9.52	-2.53	6.69	0.00

Table 5.3b   Continued from Table 5.5a, this table indicates rainfall conservation and threshold statistics for the ECH5 and ECHO downscaled GCMs. Also indicated in this table are the relative changes in rainfall distribution between present and future time periods for the ECH5 and ECHO downscaled GCMs used in the study.

ECH5 GCM RAINFALL STATISTICS						
	STATISTICS			RAINDAY THRESHOLDS (days/annum)		
	MAP	STDEV	CV	0 RAIN	RAINDAYS	TOTAL DAYS
PRESENT (1971-1990)	842.68	216.18	0.22	268.80	96.45	365.25
FUTURE (2046-2065)	842.1	170.28	0.17	262.00	103.25	365.25
%CHANGE	-0.07	-21.23	-22.73	-2.53	7.05	0.00

| ECHO GCM RAINFALL STATISTICS						
	STATISTICS			RAINDAY THRESHOLDS (days/annum)		
	MAP	STDEV	CV	0 RAIN	RAINDAYS	TOTAL DAYS
PRESENT (1971-1990)	856.65	148.63	0.16	262.70	102.55	365.25
FUTURE (2046-2065)	891.61	129.23	0.13	254.25	111.00	365.25
%CHANGE	4.08	-13.05	-18.75	-3.81	9.93	0.00
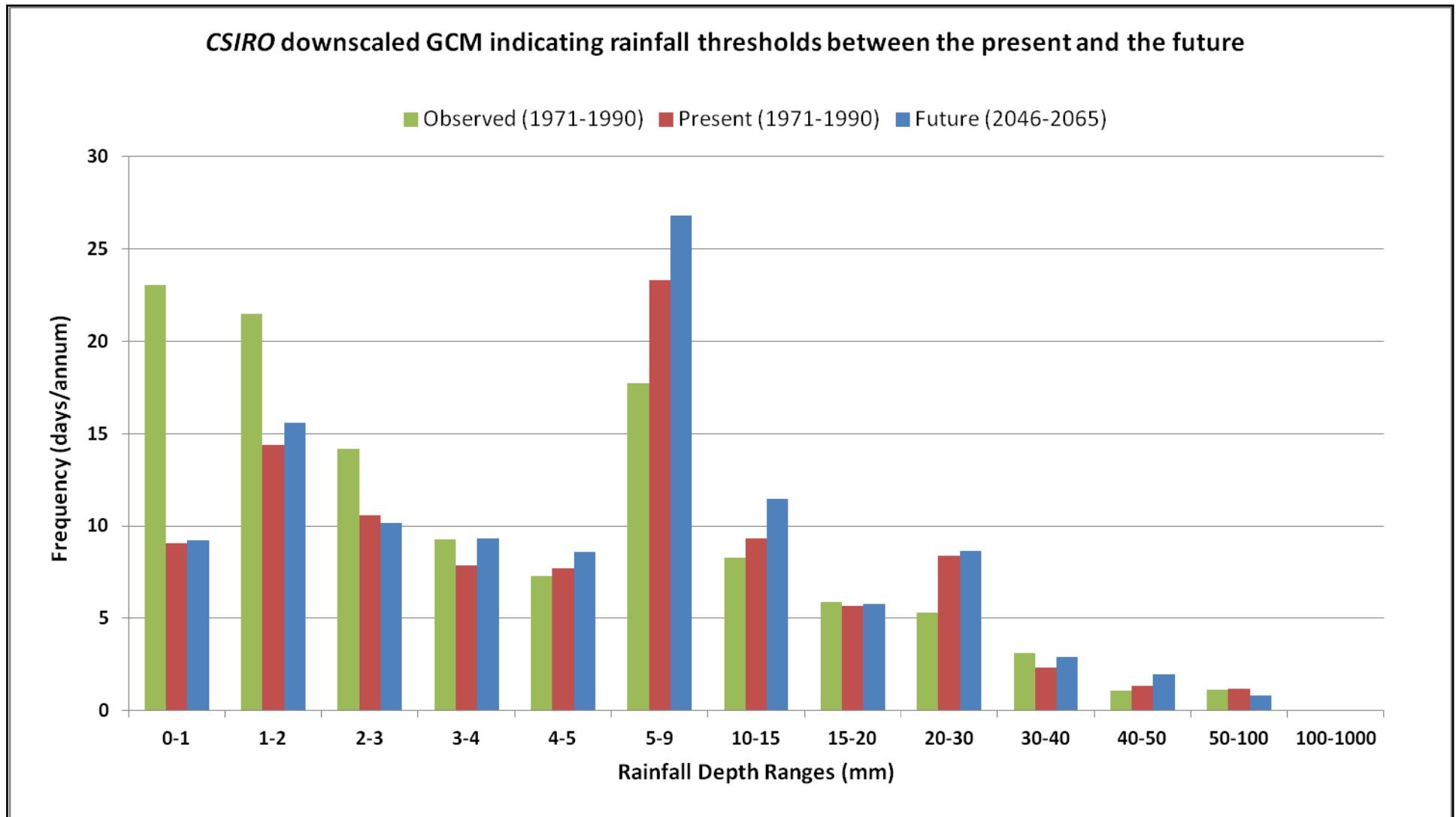
Figure 5.4 Rainfall event frequencies for present and future climates for the CSIRO downscaled GCM. Observed rainfall event frequencies are included in this Figure to allow for changes/differences to be assessed.

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In terms of changes in the frequency distribution of rainfall events between the present and the future, nearly all CSAG downscaled GCMs (4 out 5 GCMs) projected increases in the annual number of runoff-producing events or raindays. The exception to this trend was the IPSL GCM which indicated marginal declines in the 5-10, 10-15 and 15-20mm event ranges. Although most of the CSAG downscaled GCMs indicated increasing trends in rainfall, the degrees of change vary across these GCMs. The CSIRO, IPSL and ECH5 downscaled GCMs indicated the most pronounced changes, particularly in the frequencies of runoff-producing rainfall events in 5-10mm and 10-15mm range. The CSIRO GCM reported projected increases of 18.35% and 22.83% respectively in the frequency of these events, while the ECH5 GCM reported increases of 18.08% in the frequency of events in the 10-15mm range (Table 5.4). The IPSL GCM reported projected decreases of 4.93% and 5.49% in the frequency of events in the same ranges (Table 5.4). Although the MRI GCM also reported a decline in the frequency of events in the 10-15mm range, the overall trend for this GCM was an increase in the frequency of all other rainfall event ranges. These projected changes in the frequency distribution of rainfall have significant implications for the generation and transport of NPS pollutants and, in particular, sediment.

There was little consistency in the frequency of larger events above 20mm across all the downscaled GCMs considered (Figure 5.5). Admittedly, the 20-25mm event range indicated some consistency (all downscaled GCMs indicate positive changes with variations in the degrees or magnitude of these changes); however, there remains a large amount of disagreement between the downscaled GCMs as to the changes in the frequency of events above 20mm envelope. In terms of the intensity of individual events, most GCMs (with the exception of the CSIR GCMs) indicated an increase in large events above 20mm and 30mm envelopes (Figure 5.5 and Table 5.4). For instance, some GCMs like the MRI and ECHO indicated increases up to 16% and 70% respectively in the 25-30mm range. This conforms to the general consensus regarding the effects of climate change on rainfall that more intense events with an increased frequency may be anticipated under climate change. This is coupled with the increase in rainfall variability also anticipated under climate change, an expectation confirmed by the results of these analyses.
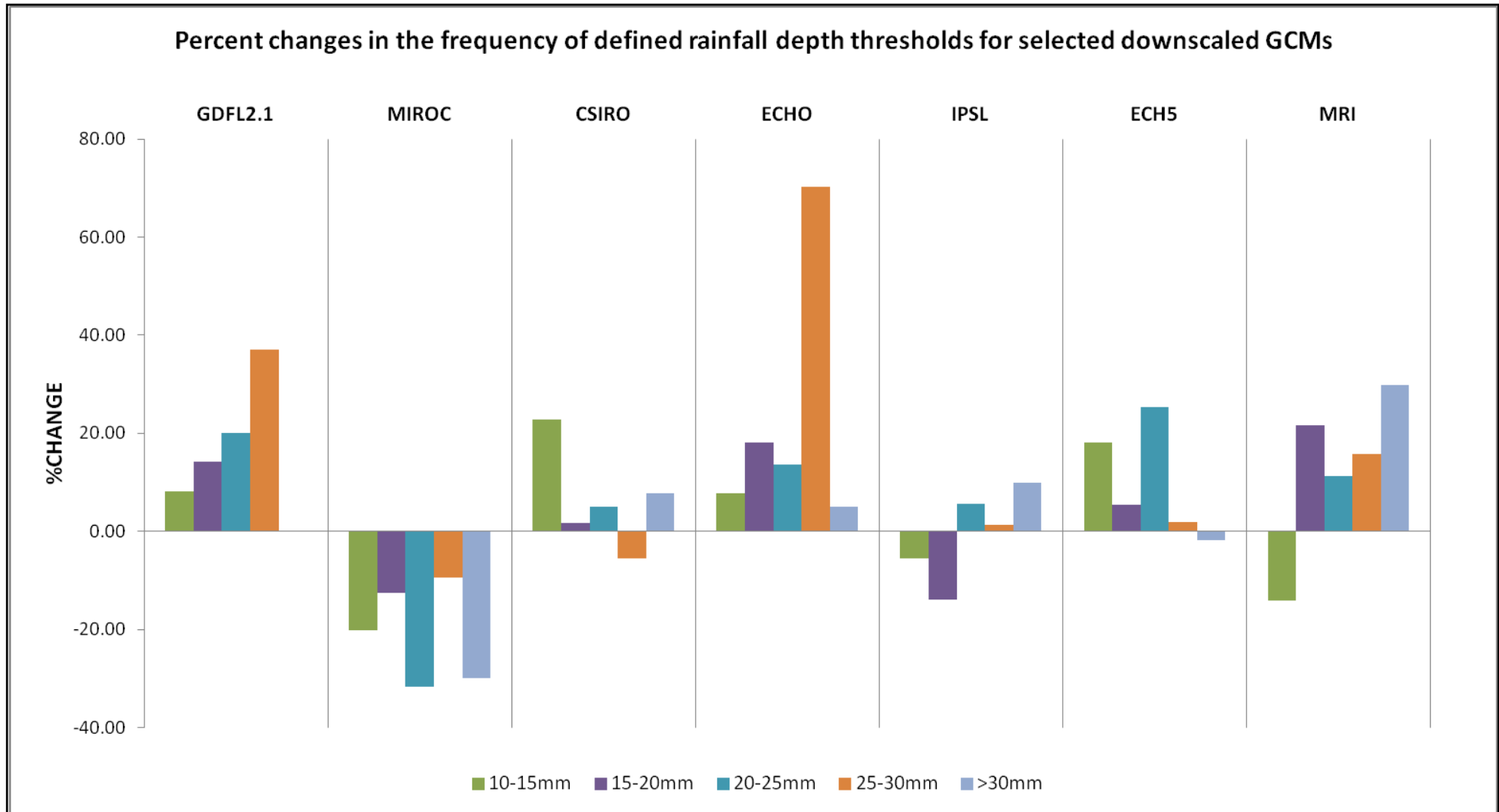
Figure 5.5 Percentage changes in the frequency distribution of rainfall events for selected downscaled future GCM projections as percentages of present.

Table 5.4   Comparative analyses between observed and GCM rainfall data including summary of future changes in rainfall event frequencies.

|						RAINFALL INTERVAL FREQUENCY (DAYS)				
		MAP	1-5mm	5-10mm	10-15mm	15-20mm	20-25mm	25-30mm	>30mm	Institute
Observed		835.01	974	344	170	111	61	45	105	
GDFL2.1	PRESENT	1301.6	1709	1070	491	197	75	27	29	CSIR
	FUTURE	1361.3	1723	1039	531	225	90	37	29	
	%CHANGE	4.59	0.82	-2.90	8.15	14.21	20.00	37.04	0.00	
MIROC	PRESENT	1310.45	1699	1073	517	200	85	21	20	
	FUTURE	1162.38	1689	1052	413	175	58	19	14	
	%CHANGE	-11.30	-0.59	-1.96	-20.12	-12.50	-31.76	-9.52	-30.00	
CSIRO	PRESENT	803.00	800	436	184	112	100	72	103	CSAG
	FUTURE	870.93	862	516	226	114	105	68	111	
	%CHANGE	8.46	7.75	18.35	22.83	1.79	5.00	-5.56	7.77	
ECHO	PRESENT	856.65	865	415	181	116	95	47	118	
	FUTURE	891.61	895	446	195	137	108	80	124	
	%CHANGE	4.08	3.47	7.47	7.73	18.10	13.68	70.21	5.08	
IPSL	PRESENT	990.45	970	507	273	157	89	72	132	
	FUTURE	999.42	1197	482	258	135	94	73	145	
	%CHANGE	0.91	23.40	-4.93	-5.49	-14.01	5.62	1.39	9.85	
ECH5	PRESENT	842.68	759	426	177	129	75	51	114	
	FUTURE	842.10	823	433	209	136	94	52	112	
	%CHANGE	-0.07	8.43	1.64	18.08	5.43	25.33	1.96	-1.75	
MRI	PRESENT	817.04	801	434	206	111	89	51	94	
	FUTURE	848.08	869	454	177	135	99	59	122	
	%CHANGE	3.80	8.49	4.61	-14.08	21.62	11.24	15.69	29.79	
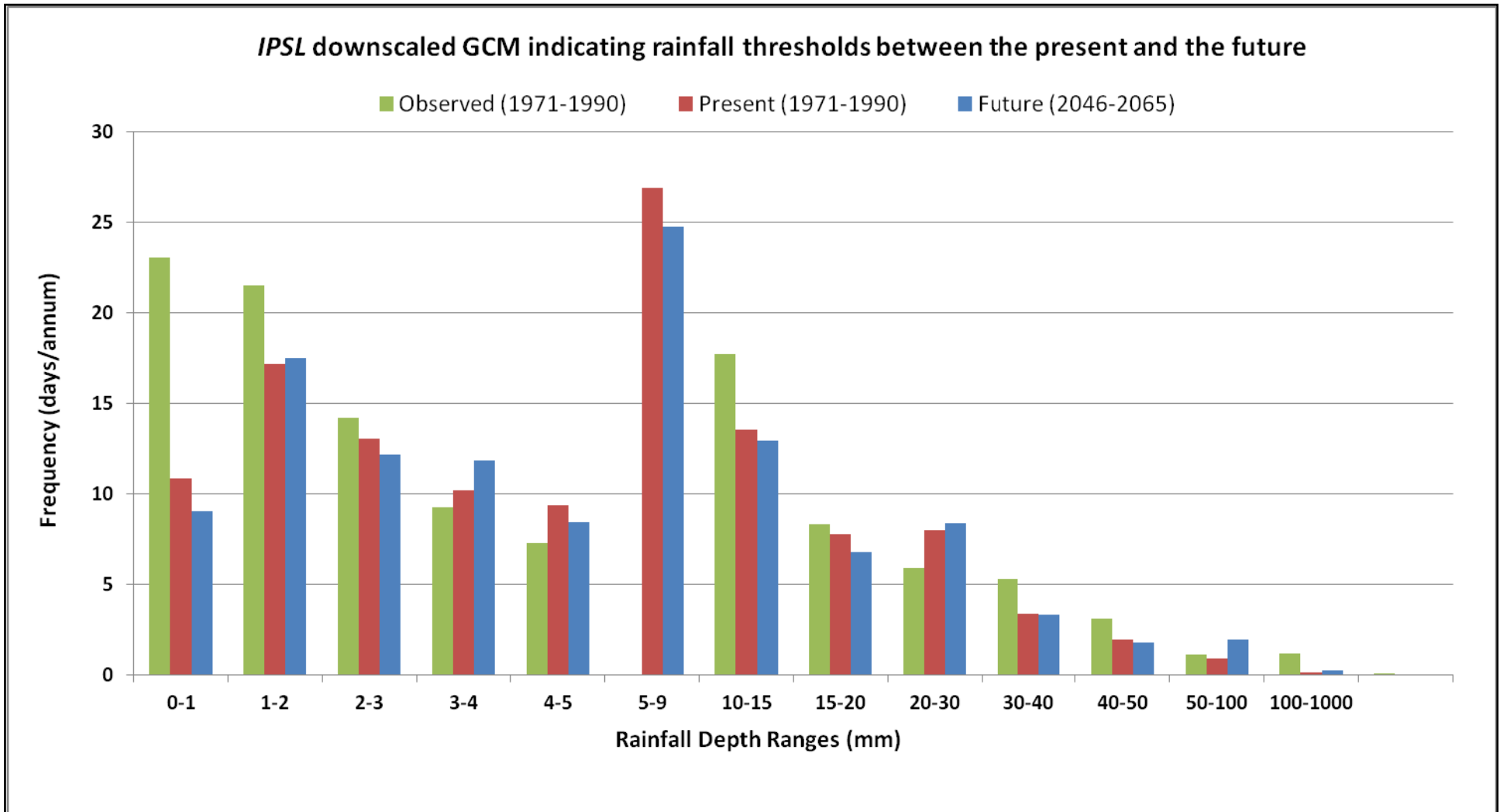
Figure 5.6 Rainfall e vent f requencies for p resent and futur e c limates for the IPSL downscaled GCM. Observed rainfall event frequencies are included in this Figure to allow for changes/differences to be assessed.
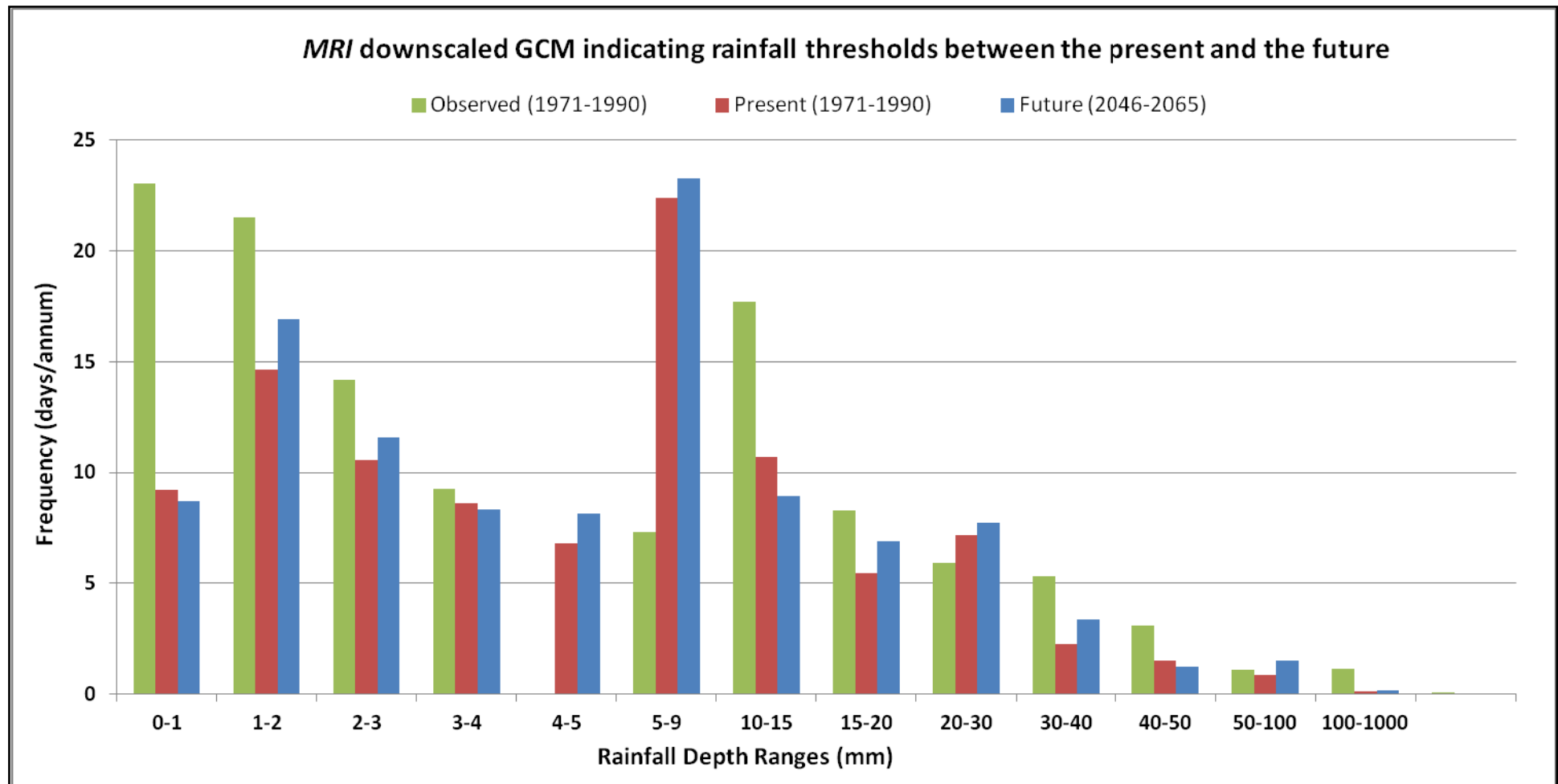
Figure 5.7 Rainfall e vent frequencies for pr esent and futur e c limates for the MRI downscaled GCM. Observed r ainfall e vent frequencies are included in this Figure to allow for changes/differences to be assessed.
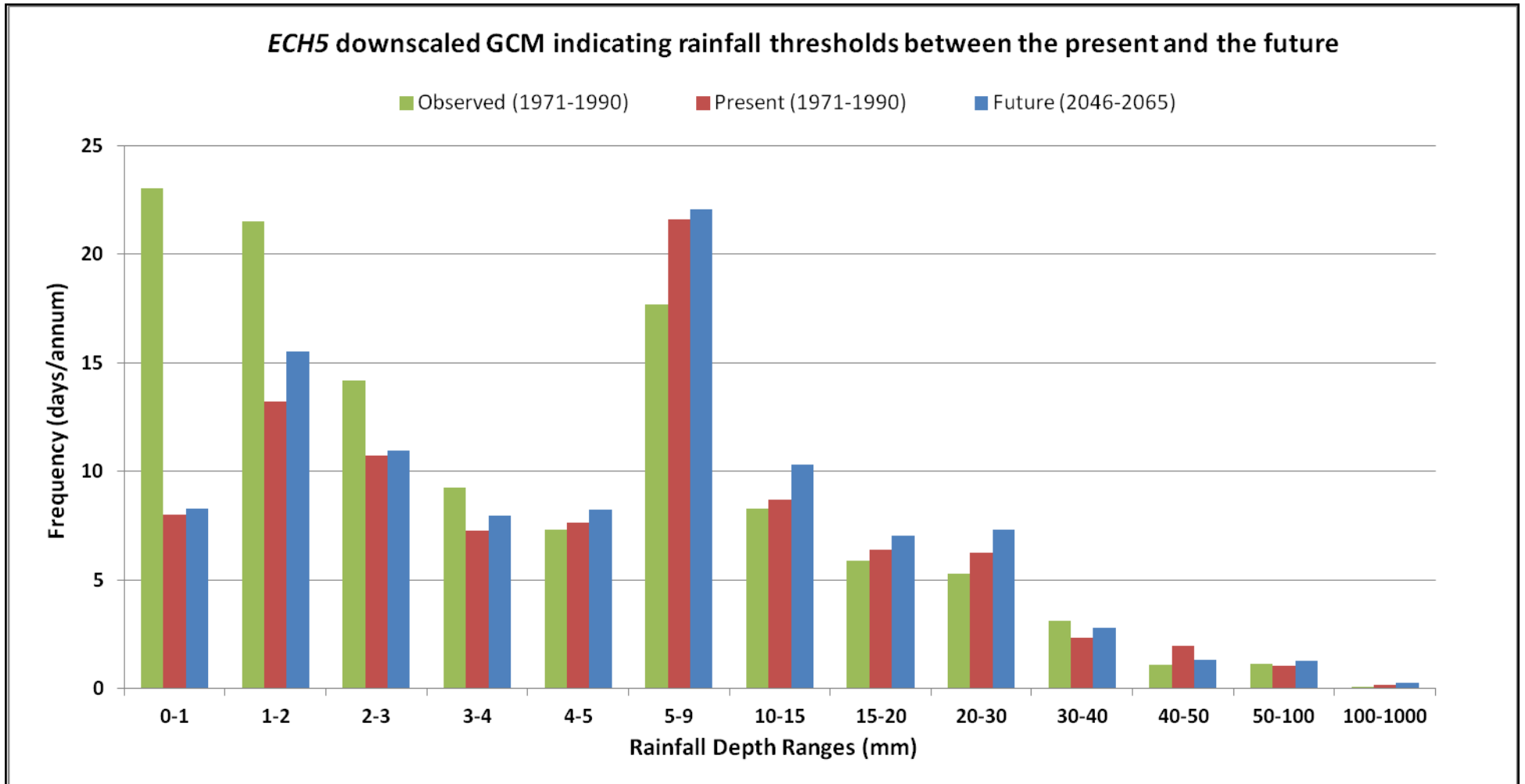
Figure 5.8 Rainfall event frequencies for present and future climates for the ECH5 downscaled GCM. Observed rainfall event frequencies are included in this Figure to allow for changes/differences to be assessed.
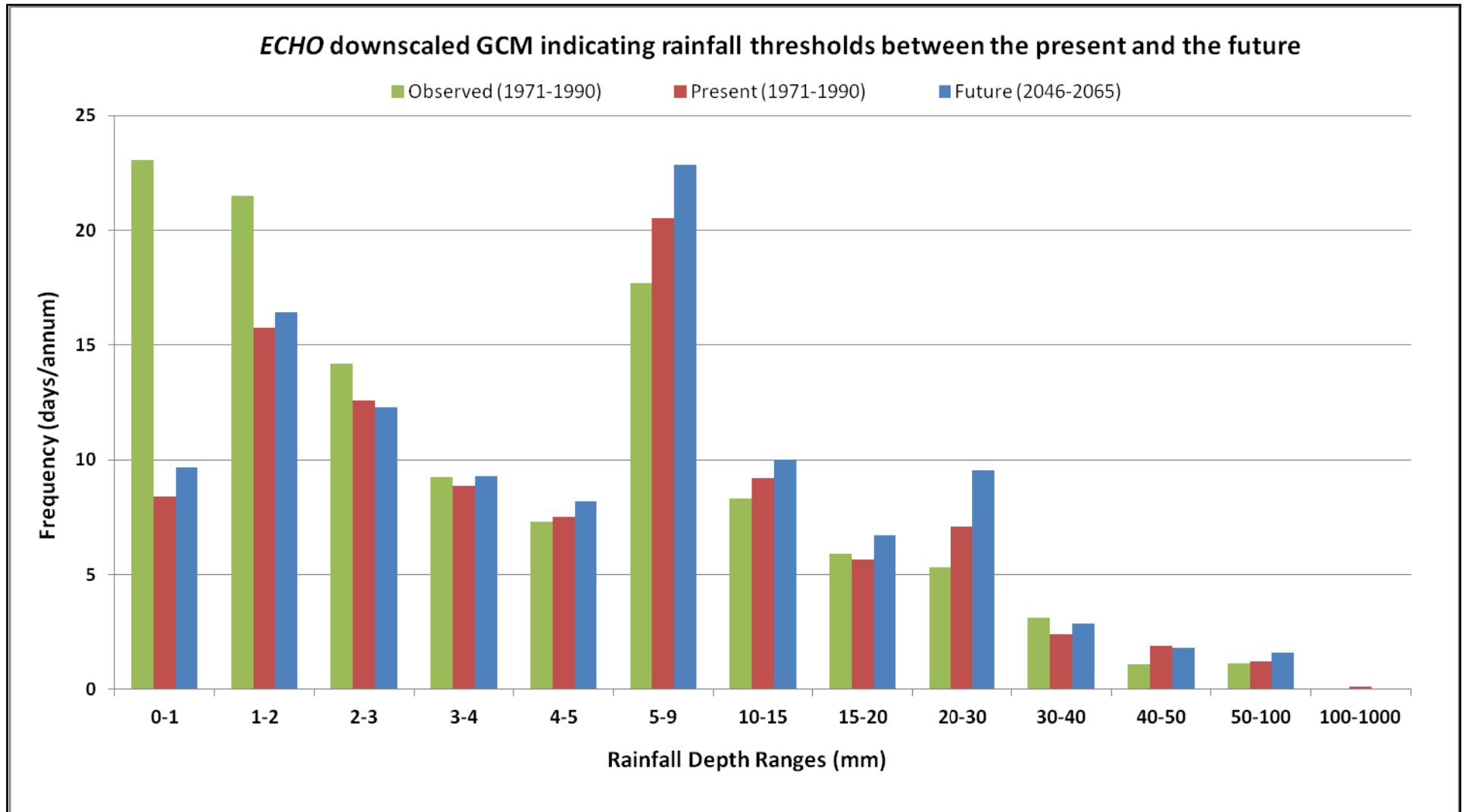
Figure 5.9 Rainfall event frequencies for present and future climates for the ECHO downscaled GCM. Observed rainfall event frequencies are included in this Figure to allow for changes/differences to be assessed.

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5.4   Conclusions

Regardless of the projected increases in MAP reported by most of the downscaled GCMs, these analyses indicate considerable variations in the frequency of present and projected annual rainfall events between the downscaled GCMs assessed (Figure 5.5 and Table 5.4). This was particularly true in the so-called runoff-generation rainfall event range of 10-15mm. Some consistency was, admittedly, observed below and above certain rainfall range envelopes. Most downscaled GCMs indicated increases (positive percentage changes) in events below the 5mm envelope and those above the 20- and 30mm envelopes. The degrees of change in these ranges, however, were highly inconsistent, with some downscaled GCMs like the IPSL GCM projecting 23.40% increases in the 1-5mm threshold and some, like the GFDL2.1 downscaled GCM, projecting only a 0.82% increase. Similarly, the ECH5 downscaled GCM projected an increase of 25.33% in the number of events in the 20-25mm range, whereas the CSIRO downscaled GCM projected an increase of only 5.00% in the same event range.

To isolate and describe potential changes fully, these analyses looked at daily rainfall characteristics. The reason for this was that it is only at this temporal resolution that the complete range of potential changes in rainfall can be fully represented. This enables the confirmation or dismissal of certain notions regarding the anticipated impacts of climate change on hydroclimatic variability. For instance, the limited agreement between the downscaled GCMs, regarding projected increases in intense events in the future, does not provide a solid basis for making radical changes to current water resources management paradigms. That is not to suggest that adaptive measures to potential change do not need to be undertaken, rather it is to highlight the need to view these projected changes in a more realistic light in order to effect management changes in an equally realistic sense. These analyses have highlighted a critical aspect regarding the use of downscaled GCM projections: the importance of understanding their uncertainty. The limited agreement between the downscaled GCMs highlights the need to focus more on uncertainty and on seeking robust patterns of change, rather than on absolute estimates projected by the downscaled GCMs. Although there is high uncertainty surrounding the use of GCM-derived data in climate change modelling, it should not preclude the development and implementation of pragmatic, relevant and realistic adaptive management measures.

In conclusion, the analyses presented in this paper have indicated the importance of being more critical regarding the application of GCM projections (downscaled or otherwise) in developing adaptive water quality and water resources management strategies. Not only will this ensure that relevant strategies and policies are formulated, but it will also lend credence to climate change predictive modelling. This study has shown that downscaled GCMs, like any other model, are uncertain. It would therefore be highly imprudent to place absolute trust on quantitative predictions generated by these models as these predictions cannot be verified. Rather, as the results of this study have shown, focus should be directed more on robust relative changes presented by climate change in the development of adaptive strategies. This will also allow adaptation to the projected increased climatic variability and consequently increased uncertainty presented by climate change.

5.5   Acknowledgements

5.6   References

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CHAPTER SIX

Towards a Framework for the Adaptive Management of Water Quality under

Climate Change

6. TOWARDS A FRAMEWORK FOR THE ADAPTIVE MANAGEMENT OF WATER QUALITY UNDER CLIMATE CHANGE

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ABSTRACT

Modelling advances have enabled the application of downscaled Global Circulation Models (GCMs) and hydrological models, to describe probable future behaviours of biophysical systems and simultaneously improve the understanding of present natural system behaviours. The knowledge gained from the output generated by these models is often applied to improve water resources management. Using the results from climate and water quality modelling exercises conducted within the Mkabela Catchment near Wartburg in KwaZulu-Natal, South Africa, in conjunction with an extensive review of the literature, the aim of this paper is to suggest adaptation strategies for water quality management within this and similar agricultural catchments. This paper also presents a framework that could be applied in the adaptive management of water quality under climate change. The assessment of the links between biophysical processes, climate change and adaptation is essential in the pursuit of reducing vulnerabilities and building adaptive capacity. Projections from various downscaled GCMs indicated increases in rainfall and runoff and associated changes in WQ variable generation and migration from upstream sources. However, there was little agreement between the projections as to the magnitude and direction of these changes. It was concluded that the uncertainty presented by downscaled GCM projections needs to be recognised in order to ensure the development of relevant and effective adaptation strategies in water quality management and policy development.

Keywords: Climate Change, Water Quality, Hydrological Modelling, Global Circulation Models, Adaptation, Policy Development.

6.1 Introduction

Climate change is anticipated to induce pressures on environmental and socio-economic aspects such as ecological health and integrity, food security, water security, economic stability and socio-economic development (IPCC, 2001; IPCC, 2007; Heltberg *et al.,* 2009). This implies that environmental and socio-economic systems will become increasingly vulnerable to any natural or anthropogenic disturbances introduced by the additional "layer" of impacts presented by climate change. It is widely acknowledged that the impacts of climate change will affect all water users (IPCC, 2001; IPCC, 2007; Schulze, 2005; Sadoff and Muller, 2007; Bates *et al.,* 2008), with the spectrum of affected users being determined by their individual ability to effectively respond to such changes (Paavola, 2008) (see Chapter 2). In the context of adaptation and vulnerability, the developing world is considered to have limited adaptation capacity and to be highly vulnerable to the impacts of climate change (Desanker and Magadza, 2001; Paavola and Adger, 2005). This is owing to the high dependence on climate-sensitive economic sectors, geographic exposure and low-income status characteristic of the developing world (Heltberg *et al.,* 2009). Consequently, the most adverse climate change related impacts are anticipated to occur in the developing regions of the world, of which South Africa is a part (Bates *et al.,* 2008). This serves to highlight the importance of understanding vulnerability and adaptation concepts for application in the most sensitive (*i.e.* highly exposed and least adaptive) regions of the world, including South Africa. As alluded to in Chapter 2, Section 2.2.4, the anticipated and potentially compounding impacts of climate change on water quality and socio-economic systems, accentuate the necessity of developing robust and adaptive management strategies that will minimize the vulnerability of environmental, social and economic systems. Therefore, in the pursuit of fully representing, understanding and mitigating the impacts of climate change on the biophysical processes which influence water quality, it is important to include adaptation strategies which have the potential to be translated into policy and, ultimately, into adaptation action.

In many instances, there is a significant disconnect between adaptive water quality management and policy development. This disconnect can be attributed to a number of reasons, including: significant time constraints for detailed catchment scale investigations which inform policy, information is usually disconnected in time, space and function and knowledge cannot be effectively generated from environmental studies owing to the disjointed nature of the information collected (Harrison, 2007; Nangia *et al.*, 2008). The result of this is usually the development of inadequate policies, redundant water resource management instruments, inappropriate or inadequate catchment biophysical process knowledge, missing or inadequate monitoring programs and unclear institutional responsibilities (Huang and Xia, 2001; Gourbesville, 2008). This creates an environment where engagement in adaptation action or adaptive management is limited and the vulnerability of socio-economic and biophysical systems to the impacts of climate change is enhanced. Such conditions underscore or facilitate the undermining of adaptive capacity. Adaptive capacity essentially refers to "the potential or ability of a system, region or community to adapt to the effects or impacts of (climate) change" (IPCC, 2001; Gallopìn, 2006; Smit and Wandel, 2006). If the proper frameworks designed to enhance adaptive capacity are not in place, it is highly unlikely that any adaptation action can be undertaken.

As mentioned in Chapter 2, Section 2.1.4, effective policy development and water quality management both need to be informed by evidence obtained from well executed environmental studies and research. It is therefore critical that the biophysical or catchment processes and linkages that describe how agricultural non-point source (NPS) pollution and land use changes influence water quality be reconciled with adaptive water resources management both in management and in policy development and governance structures. The assessment of the links between biophysical processes, climate change and adaptation is of significant importance in the pursuit of reducing vulnerabilities to climate change and building adaptive capacity. Effective WQ management requires a sound, implementable policy framework that is informed by well executed environmental studies and research (Brainwood *et al.,* 2004; Nangia *et al.*, 2008), as well as monitoring and evaluation. Thus, the primary aim of this paper was to develop or suggest relevant adaptation strategies that can facilitate adaptive water quality (WQ) management and policy development, based on appropriate scientific investigation.

6.2   An Adaptive Water Quality Management Framework

It has been repeatedly noted in this study that as part of the current global change mosaic, climate change could aggravate current water quality problems. Indeed, climate change is anticipated to introduce added complexities that water quality managers will have to contend with. Although decision makers make decisions under uncertainty every day, even in the absence of climate change (World Bank, 2010), the extent of changes that are likely under climate change means that a paradigm shift is required in which the compounding set of uncertainties presented by climate change are recognised and included in the decision-making process (Kundzewicz *et al.,* 2007) and that these decisions are reflected upon and revised as new information becomes available. This essentially constitutes adaptive management (Kundzewicz *et al.,* 2007; Bates *et al.,* 2008). Based on an analysis and synthesis of the available literature conducted in Chapters 2 and 3, this study proposes an adaptive water quality management framework that, if successfully implemented, could prove beneficial in local water quality management (Figure 6.2). This framework, combined with the adaptive management framework proposed by Bennet *et al.,* (2005) (Figure 6.1), is intended to be used as an effective tool to assist in dealing with the potential impacts of climate and global change on water quality management in an adaptive way. This framework is, of course, not limited to climate change. It also considers natural variability and socio-economic changes as potential "hazards" in the fluctuation of catchment water quality. Adaptive management is a cyclic learning, application and review process in which the focus is on action and learning and not in preparing to learn (Figure 6.1) (Lee, 1999; Bennet *et al.,* 2005).

According to Bennet *et al.,* (2005), adaptive management can be defined as ''a systematic process for continually improving management policies and practices by learning from the outcomes of operational programs". In Figure 6.1, the components are all linked through a continuous process of learning and participative action. To summarise (with reference to Figure 6.1): *Information collation* refers to the pooling of information collected from research and from stakeholder consultation and is usually the first step in the development of an adaptive management framework. This step would essentially be informed by catchment process observation and monitoring conducted in operational and experimental catchments.
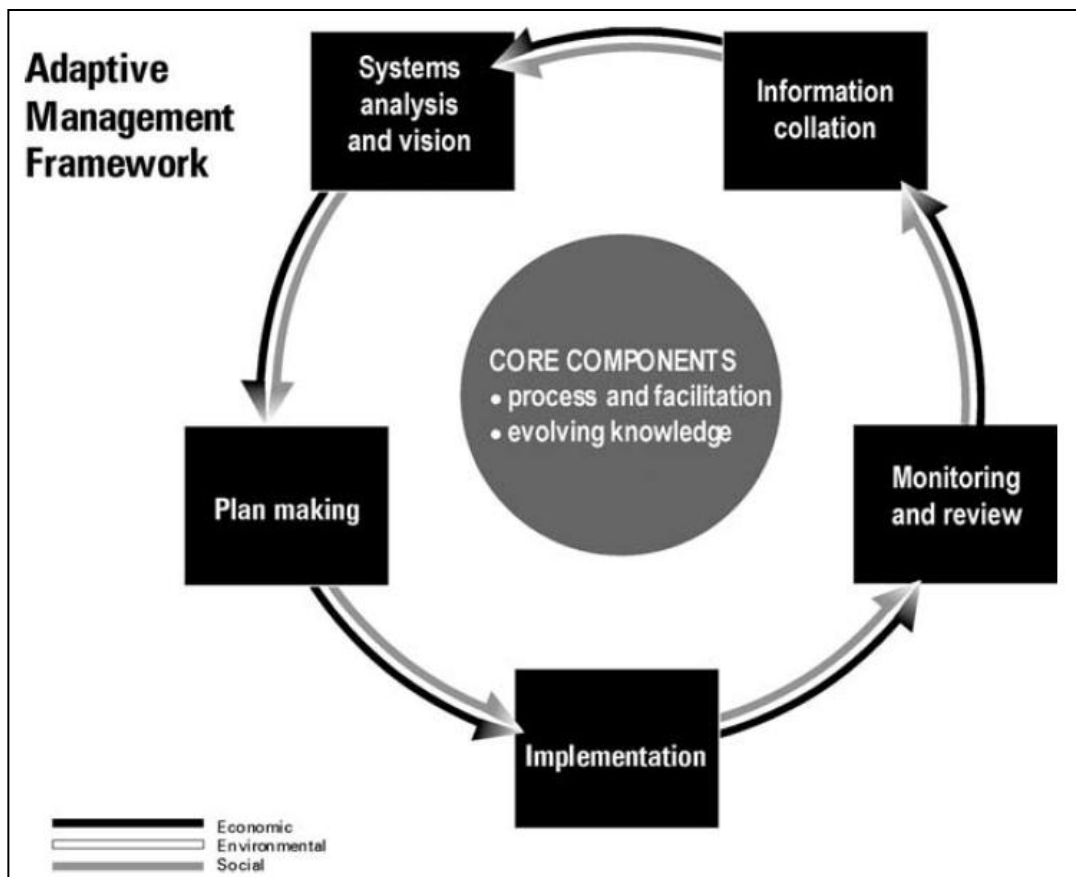
Figure 6.1   Schematic diagram of the Coastal CRC Adaptive Management Framework (Bennet *et al.,* 2005).

The *core components* of process and facilitation and evolving knowledge are essential in the planning and management cycle and comprise the establishment of healthy relationships amongst catchment stakeholders such that the entire adaptive management cycle proceeds efficiently. This step, as shown in Figure 6.2, would be facilitated through the unbiased and transparent inclusion of stakeholders in decision-making and in the introduction of incentives to promote engagement in adaptation action by the relevant stakeholders. *Systems analysis and vision* focuses on identifying and understanding the most important catchment systems in order to clearly define the vision and aspirations for the catchment. This step would need to be extended to account for the long-term visions of catchment stakeholders. *Plan making* involves the setting of clearly defined resource management goals such that impacts on ecological and socio-economic systems are recognised and strategies are developed. This would, essentially, constitute the development of adaptation strategies as outlined in this study.

Implementation involves the actual execution of the goals created in plan making and systems analysis and vision creation. In essence, this step describes the actual practice of adaptive water quality management. Unfortunately, it also represents one of the biggest challenges faced in South African water resources management. However, the promotion of stakeholder participation in catchment water resources management through the introduction of incentives and the transparent inclusion of stakeholders in decision-making may ensure that implementation proceeds efficiently and with limited complications. The process of *monitoring and review* follows implementation and involves the assessment of the effectiveness of the goals set during the initial stages of framework development and of the effectiveness of the implementation process (Bennet *et al.,* 2005). It also embodies the continuous monitoring of various aspects of the framework, including biophysical processes, monitoring and gauging networks, engagement in adaptation action and the literacy of stakeholders with respect to the impacts of climate change and water quality management. Finally, it includes the re-evaluation of initial adaptation strategies and policies to ensure that the natural dynamism of environmental and socio-economic systems is accounted for and any changes are incorporated into these strategies and policies. It is apparent from Figures 6.1 and 6.2 that adaptive (water quality) management is a process that facilitates intervention in the face of uncertainty. For instance, catchment monitoring and hydrological modelling serve as approaches that water resource managers can use to abstract information about the natural environment and synthesise knowledge and make decisions based on that information.

Water quality is influenced by various potential hazards and risks such as climate change, population and economic growth and natural variability. The framework presented in Figure 6.2 recognizes these hazards and risks (summarised in "a", Figure 6.2) and suggests that a better understanding of the impacts these hazards and risks have on catchment processes, which influence water quality, should be developed through the continuous process of information collation and systems analysis and vision (summarised in "b", Figure 6.2). Information collation and systems analysis and vision need to be followed by comprehensive and clearly defined plans or strategies (summarised in "c", Figure 6.2) designed to mitigate the impacts presented by the various hazards and risks on natural and socio-economic systems. This, as has been mentioned already, would emerge through the development of adaptation strategies (also summarised in "c").

The successful application of these strategies would rely on the participatory and explicit involvement of stakeholders (*e.g.* farmers, extension officers and other water users within the catchment) in catchment water quality management. This implies that any knowledge gained from modelling exercises, similar to the one presented in this study, should be communicated to the various stakeholders in a comprehensive manner. This is to ensure that the literacy of stakeholders regarding water quality management is improved. Not only is this a way of enhancing adaptive capacity (*i.e.* by improving access to information and knowledge, thus, enhancing awareness) but it also facilitates or improves the potential for the engagement in adaptation action. This is summarised in the core components presented in "d" Figure 6.2. Implementation, which describes the actual practice of adaptive water quality management, would be guided by well-informed policies developed through the use of knowledge gained from both modelling results and stakeholder consultations. As already mentioned, implementation needs to be followed by the monitoring and review of the effectiveness of the adaptation strategies designed during the initial stages of the framework's development. In Figure 6.2, the processes of monitoring and review (highlighted by the feedback loops), involves the continuous monitoring and updating of various aspects of the framework, including knowledge regarding changes in biophysical processes, deployment and updating of monitoring and gauging networks, re-assessing changes in hazards and risks, monitoring engagement in adaptation action by stakeholders and the re-evaluation of initial adaptation strategies and policies to ensure that the natural dynamism of environmental and socio-economic systems is accounted for and any changes are incorporated into the development of revised strategies and policies.
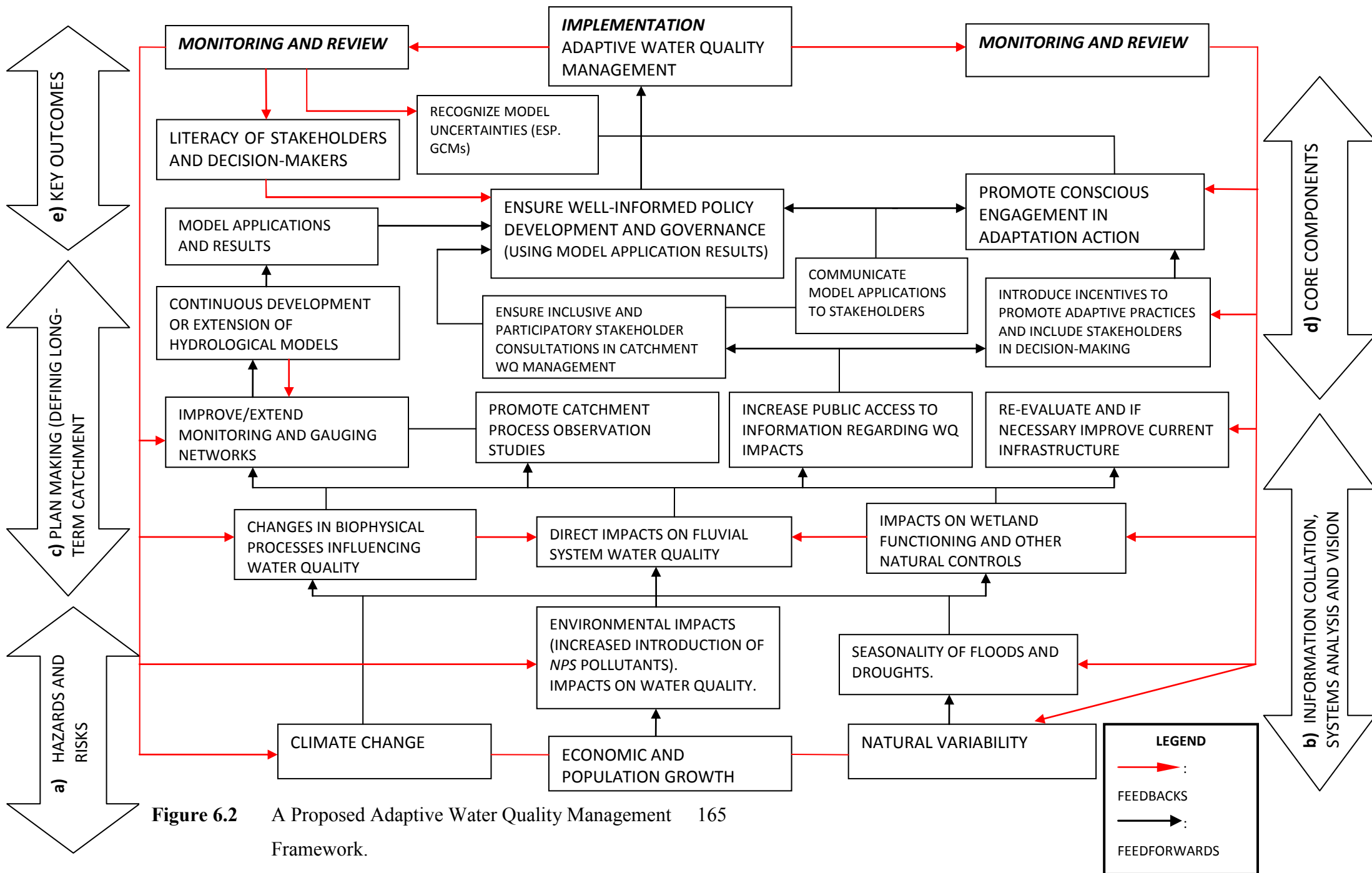
Figure 6.2 A Proposed Adaptive Water Quality Management   165
Framework.

It has already been noted that catchment monitoring and hydrological modelling serve as useful tools that water resource managers use to understand the behaviour of the natural environment and make decisions based on the knowledge synthesised from these studies. However, as will be shown in this Chapter, water quality models are often fraught with input data limitations (also refer to Chapters 4 and 5). This does not imply that these models are not appropriate to be used as decision support tools by water resource managers; rather it implies that water quality models should be used as tools that facilitate explicit learning from experiments in order to inform and improve future decisions. This is also highlighted by the feedbacks indicated in Figure 6.2 which signify the importance of continually updating the knowledge related to biophysical and socio-economic changes.

Adaptive WQ management requires the development of robust strategies that recognize the reality of a world of shifting baselines, intermittent disturbances and the uncertainty of future projection of change (Adger and Vincent, 2005; World Bank, 2010; Firman *et al.,* 2011). This demands a re-think of traditional WQ management practices which assume a predictable future based on past experiences. The World Bank (2010) recognizes four management strategies that are essential in facilitating adaptive (resource) management under climate change. These strategies have been adapted by the authors to be more specific to WQ management:

a) Priority should be given to no-regrets options: policy and investment options that maximise benefits related to water quality management even in the absence of climate change *e.g.* improving water and wastewater infrastructure to minimize water quality degradation in receiving waters (see Novotny, 2003).

b) Increase resilience of water resource systems by buying "safety margins" in low cost long-term investments *e.g.* increasing water quality awareness education and forming social resource protection schemes (see Petermann, 2008).

c) Reversible and flexible options need to be favoured such that in instances of bad decisions being made, the cost of reversing the impacts of decisions is kept as minimal as possible *e.g.* restrictive urban planning due to uncertain flooding trends can be reversed easily and is less expensive than retreat and protection options (see Heltberg *et al.,* 2008).

d) Long term planning should be based on forward-thinking scenario analysis and on the assessment of strategies that consider a wide range of possible futures.

A recurring theme in this discussion has been that adaptive water quality management requires a risk- or hazard-based decision-making model (Figures 6.1 and 6.2), which favours long-term planning and robustness taking into cognisance the dynamic nature of socio-economic and environmental systems (Figure 6.2). Additionally, the uncertainties presented by the use of downscaled GCM projections, as shown in Chapter 5, also suggest that robust patters of change and natural variability need to be the primary foci in water quality management rather than absolute unverifiable predictions of change. Increasing global change pressures on water resources coupled with the potentially compounding effects of climate change imply that risks related to water quality management cannot be ignored or omitted in the decision-making process. The aforementioned compounding sets of uncertainties presented by climate change necessitates the development of robust and adaptive management strategies that will minimize the risk and, thus, vulnerability of environmental, social, economic and demographic systems as outlined in this section. As mentioned in Chapter 2, Section 2.1.2, these strategies have to be based on sound scientific principles. Therefore, as an extension of this discussion, the following section presents a case study where a water quality modelling exercise was undertaken in the Mkabela Catchment, a subcatchment of the Nagle Water Management Unit (WMU) of the Mgeni Catchment in South Africa. The results obtained from this exercises are then used to assess their usefulness in the framework presented and the adaptation strategies suggested in this Section.

6.3   Methodology

6.3.1   Study Area

As detailed in Chapter 4, the water quality modelling work in this study was conducted in the Mkabela Catchment located approximately 1km east of the town of Wartburg, near Pietermaritzburg, South Africa (Figure 6.3). The Mkabela Catchment is a subcatchment of the Nagle Water Management Unit (WMU) which forms part of the Mgeni Tertiary Catchment in KwaZulu-Natal. Commercial irrigated agriculture is the most dominant land use activity in the Mkabela Catchment.

Various structures, which act as hydraulic controls to the movement of water and pollutants are found in the catchment, including an assortment of farm dams, wetlands and riparian buffer strips. Synthetic fertilization occurs in sugar cane, vegetable and dairy (pastures) farming systems using nitrogen (N) and phosphorus (P) based fertilizers.

The Mkabela Catchment falls within the summer rainfall region of South Africa and experiences a warm subtropical climate with distinct dry and rainy seasons interlaced with high inter-seasonal variability. The altitude in the catchment ranges from 965 m.a.s.l from the eastern escarpment to 755 m.a.s.l at the catchment outlet. The mean annual precipitation (MAP) of the catchment averages 835 mm per annum. The baseline vegetation is classified by Acocks (1988) as the Southern Tall Grassveld and the catchment relief ranges from open hills, low relief to open hills, high relief.
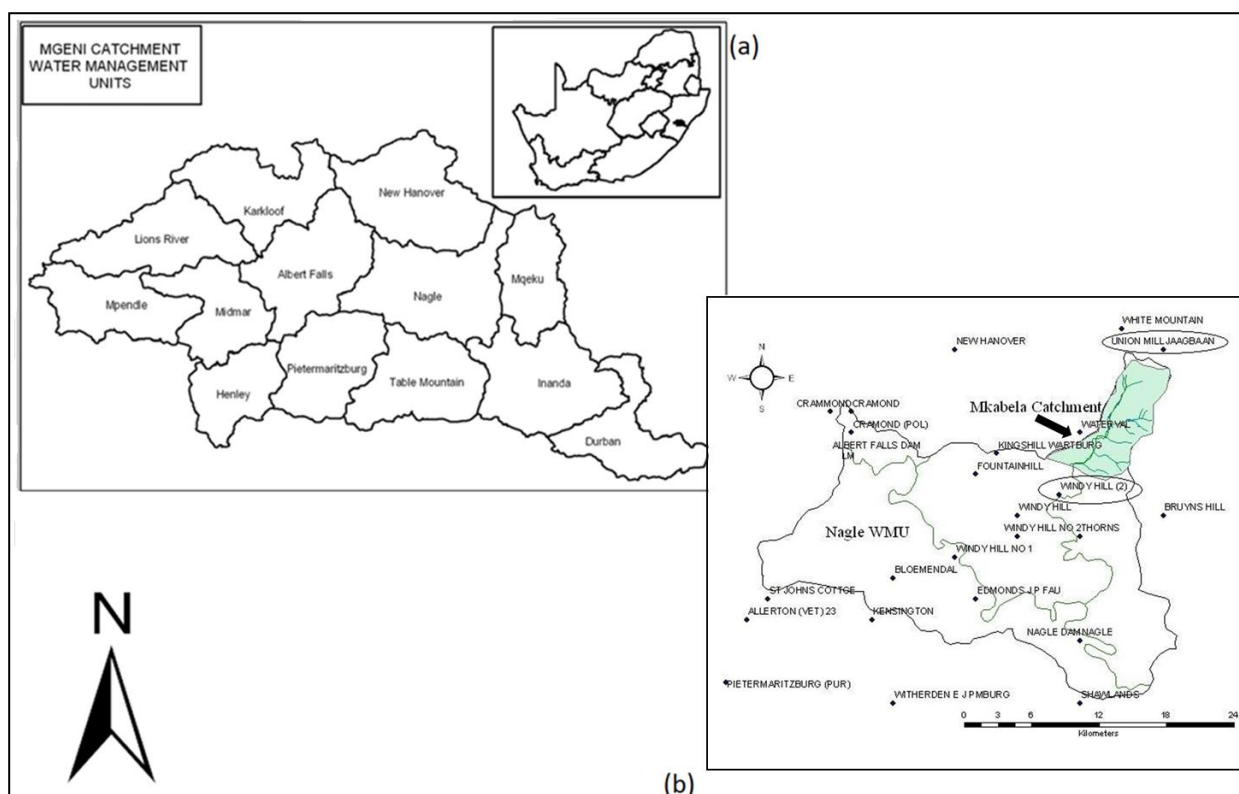
Figure 6.3 Location of the Nagle WMU within the Mgeni Quaternary Catchment in (a) and the Mkabela Research Catchment within the Nagle WMU in (b).

6.3.2   Input Data Acquisition and Processing

Since the aim of this study was to develop relevant adaptation strategies based on appropriate scientific investigation, modelling exercises were used to detail potential changes to selected WQ variables under climate change. Two types of climatic data were used as input in the *ACRU*-NPS model: *i.e.* observed climate data derived from the catchment monitoring network and climatic data derived from various downscaled GCMs. Daily observed climate data were acquired from two rainfall gauging stations located in and around the Mkabela Catchment. These were the Windy Hill Number 2 and Noodsberg-Jaagbaan rainfall stations. The records from these stations had rainfall data available over different periods and were combined to form a single composite record for the period 1950 to 2011. The reader is referred to Chapter 4, Section 4.4 for the full description related to the treatment of the observed datasets from these stations and for the creation of the composite rainfall record.

Climate change data used in this study were derived from 7 (seven) downscaled global circulation models (GCMs) employed in the Intergovernmental Panel on Climate Change Fourth (AR4) Assessment Report (IPCC, 2007). The downscaled climate change projections, derived from the downscaled GCMs, were obtained from the Council for Scientific and Industrial Research (CSIR) and from the Climate Systems Analysis Group (CSAG) based at the University of Cape Town (UCT). The downscaled climate change projections used this study were based on the Special Report on Emission Scenarios (SRES) A2 storyline and emission scenario (Nakićenović *et al.,* 2000), which assumes that global efforts to reduce greenhouse gas emissions are relatively ineffective. The reader is also referred to Chapter 4, Section 4.4 for the full description and treatment of these data.

6.3.3   Simulations Performed

Source-pathway-response modelling of the Mkabela Catchment with the intention of understanding the impacts of agricultural NPS pollutants on the water quality of hydraulic controls across the catchment was conducted in this study. The simulation of runoff processes (from rainfall measured within the catchment) was carried out for 3 individual Hydrological Response Units (HRUs) located in the headwaters of the Mkabela Catchment (Figure 6.4). The general characteristics of each of these HRUs are detailed in Table 6.2.

The HRUs are located upstream of a perennial wetland, marked as "wetland1" in Figure 6.4. The combined runoff and streamflow from each of these HRUs form the inflow into this wetland, as indicated in Figure 6.4.

The *ACRU*-NPS model was selected as the primary model for use in the study simulations. The description of this model and the rationale behind its selection are detailed in Chapter 4, Section 4.3. It is important to differentiate between simulations performed based on observed climate data and simulations performed based on downscaled GCM climate data in the context of this study. Both modes of simulation were performed using the *ACRU*-NPS model for the individual HRUs. However, in one instance observed/historical climate data derived from *in-situ* catchment observations was used and in the other, GCM climate data derived from the downscaled GCM projections was used. For instance, the 1950 to 2011 simulations (encompassing the 1971-1990 period) in the *ACRU*-NPS model were based on observed climate data whereas the 1961-2100 simulations (encompassing the 1971 to 1990 and 2046 to 2065 periods), also in the *ACRU*-NPS model, were based on downscaled GCM-derived climate data.

Table 6.2   General characteristics of the 3 Hydrological Response Units located in the headwaters of the Mkabela Catchment.

HRU Name	Area (km^2)	Elevation (m.a.s.l)	Slope (%)
Sugar Cane	6.31	965	3.5
Commercial Afforestation	0.61	965	5.5
Vegetable Patch	1.06	965	1.5
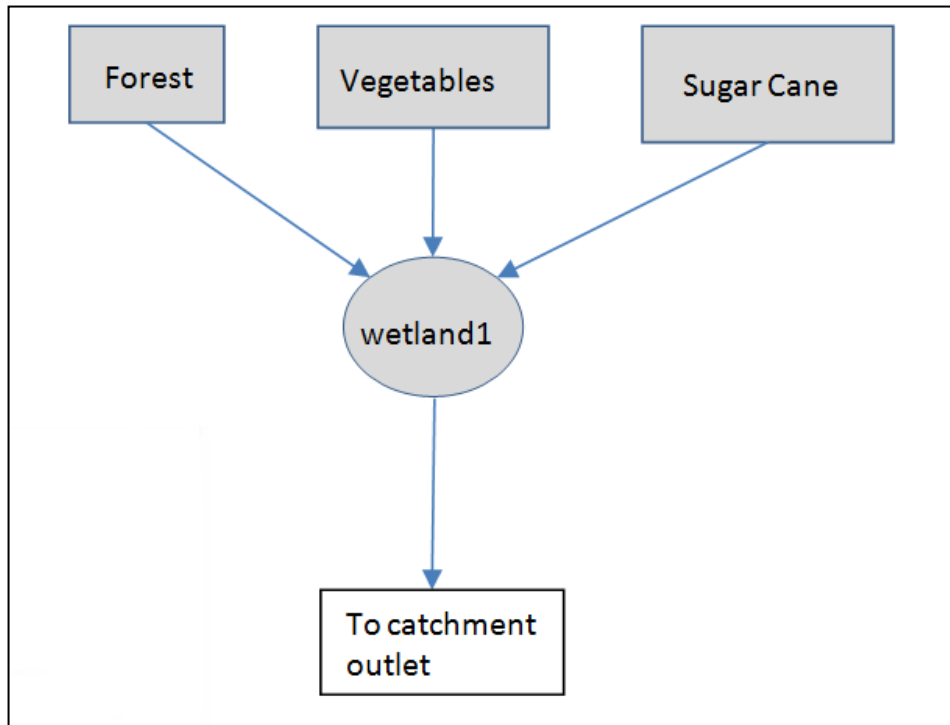
Figure 6.4 Location of the 3 HRUs relative to the wetland. Also indicated in this Figure is the flow direction from each HRU in the Mkabela catchment headwaters into the wetland and, finally, the catchment outlet.

6.4 Results and Lessons Learnt

This section presents a summary of the results obtained from the simulation exercises (Chapter 4) and rainfall frequency analyses (Chapter 5) conducted in this study and outlines the lessons learnt from those exercises and how they relate to the development of adaptive water quality management strategies as outlined in Section 6.2. For relevance purposes, these results have not been entirely repeated and only a synopsis of the main findings is offered.

6.4.1 Verification of the *ACRU*-NPS Model

A number of verification studies were conducted to ensure that the *ACRU*-NPS model adequately represented the observed behaviour of the Mkabela Catchment with regard to the WQ variables of concern *i.e.* runoff, sediment, nitrogen and phosphorus. Model simulations were verified against observed WQ variable data from the Mkabela Catchment and results from these exercises indicated that the model was representing the hydrological system satisfactorily. The results of these verification studies are detailed in Chapter 4, Section 4.7.

## 6.4.2 Impact of the Wetland on the Transfer of NPS Pollutants

Based on the simulations performed using observed input data, the influence of the wetland on runoff and on the transfer of nutrients and sediments was assessed by observing the changes between variable amounts entering the wetland (Wetland1-"variable" IN) and amounts exiting the wetland (Wetland1-"variable" OUT). These changes are indicated in Figure 6.5 for runoff and in Table 6.3 for all WQ variables considered. Table 6.3 presents mean annual estimates of the variables entering and exiting the wetland and the percent changes between variable amounts entering the wetland and amounts exiting the wetland for the period between 1971 and 1990. The graphical representations showing the behaviour of nitrogen, phosphorus and sediment before and after the wetland are presented in Chapter 4, Section 4.6.2.

Table 6.3 Simulated mean annual estimates of water quality variables entering and exiting the wetland based on observed input for the present period.

Variable	Wetland1-IN	Wetland1-OUT	%Change
Runoff (mm)	185.15	54.22	-70.72
Sediment (t)	297.75	8.69	-97.08
Nitrogen Loads (kg)	69579.00	19258.27	-72.32
Phosphorus Loads (kg)	22101.31	6602.58	-70.13

Mean annual runoff decreases by 70.72% subsequent to being routed through the wetland (Table 6.3). This simulation also highlights the high effectiveness of the wetland to mitigate floods, judging by the reduction in exit flow in the September 1987 floods by over 97% (Figure 6.5). Sediment, being sensitive to runoff, also displays a similar attenuation trend to that of runoff as indicated in Table 6.3. A linear relationship exists between runoff, streamflow and sediment generation. Following a rainfall event, the amount of sediment generated from upstream sources generally increases with an increase in runoff. The sharp decline in sediment between wetland entry and exit can be attributed to the settling effect of sediment when routed through the wetland. The factors affecting sediment transfers across water bodies were outlined in Chapter 3, Section 3.2.8.

Subsequent to we tland routing, a sim ilar reduction tre nd observed for both runoff a nd sediment was also observed for nutrients. The mean annual estimates of both N and P appear to follow the runoff trend with regard to being retained in the wetland (Table 6.3). The reason for this is that nutrients have been shown (*e.g.* Donohue *et al.,* 2005; Lorentz *et al.,* 2011) to migrate e asily with runoff and thi s was an e xpected trend considering the fact that crop fertilization is a dministered using pr imarily N - and P -based fertilizers in the Mkabe la Catchment. Chapter 3, S ection 3.2 de tailed the factors a ffecting the behaviour of nutrie nts across hydraulic controls and it wa s shown that these nutrie nts have a hi gh de pendency on runoff-generating discharge mechanisms such as rainfall events and irrigation. The decline in nutrients subsequent to be ing rout ed throu gh the wetland c an b e a ttributed to the hydropedological and bi ochemical characteristics of w etlands, which e nable water retention for prolonged periods of time, thus promoting anaerobic conditions which facilitate the loss of both N and P through volatilisation, mass a dsorption and immobilisation. Having detailed the im pacts of the we tland on the tra nsfer of WQ va riables under pr esent conditions, the following se ction of fers a summ ary o f the projected impacts of climate c hange on WQ variables.
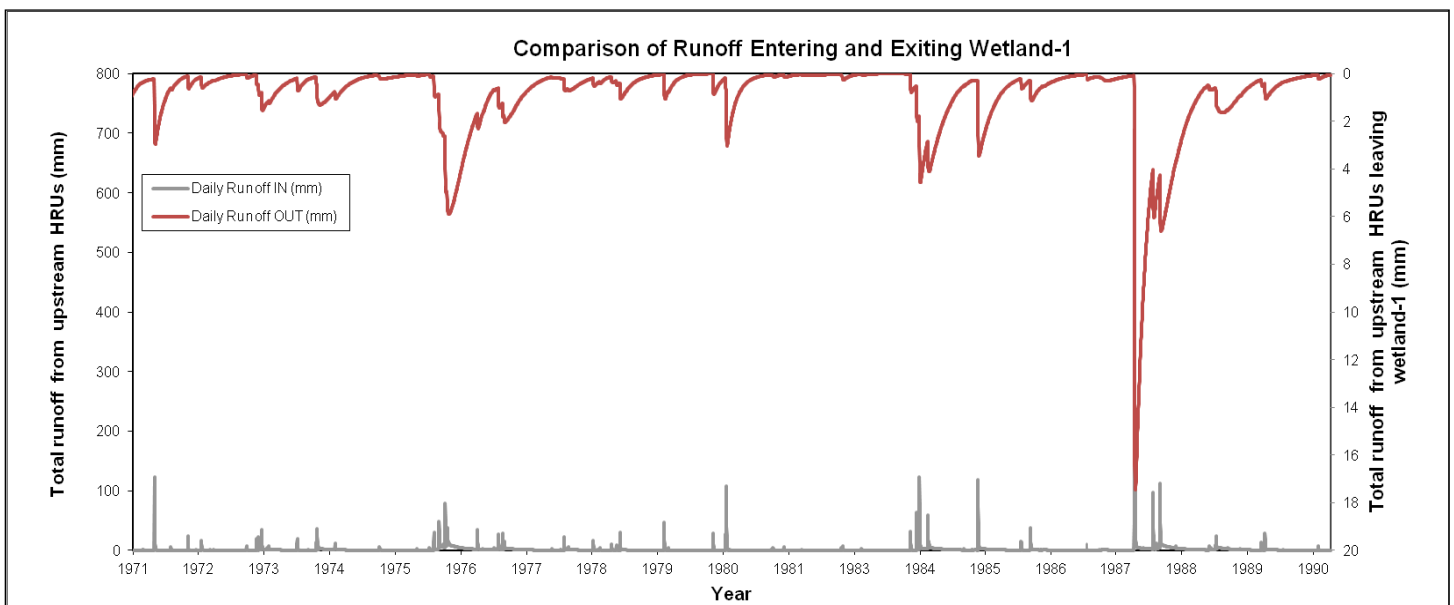

Figure 6.5   Simulated daily runoff entering and exiting the wetland for the period 1971 to 1990 based on observed input data.

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6.4.3 Projected Impacts of Climate Change

The changes of WQ variables between the present (1971-1990) and the future (2046-2065) were presented as ratios of change and percentage changes. Ratio values above 1 indicate an increasing trend in the simulated variable, whereas values below 1 indicate a decreasing trend in the simulated variables (Table 6.4). The ratios represent qualitative rather than quantitative changes in the simulated WQ variables. Quantitative estimates of these variables were considered to be less appropriate owing to the uncertainty presented by future GCM projections with regard to rainfall changes (see Chapter 5) and the apparent large variations in the runoff outputs generated by the *ACRU*-NPS model using GCM-derived input. Therefore, qualitative analyses were deemed more appropriate as they give a holistic representation of the potential future changes in simulated variables and highlight relative changes better than quantitative assessments which are, admittedly, only as accurate and relevant as the modelling assumptions applied.

Percentage changes, calculated by subtracting the future value of a variable from the present value of the same variable and dividing by the present value of the variable, were also included in these analyses. To summarise: a "positive" percentage change suggests an increasing trend in the variable while a "negative" percentage change suggests a declining trend in the variable. The potential impacts of climate change on mean annual runoff, nutrient loads and sediment yield are indicated as ratios of change in Table 6.4 for all downscaled GCMs considered and in Figures 6.6 and 6.7 as percentage changes for the CSIR and CSAG downscaled GCMs, respectively. Figures 6.6 and 6.7 show the potential impacts of both climate change and the potential impacts of the wetland under climate change (*i.e.* under future conditions) on the generation and transfer of the WQ variables considered. In these Figures, the impacts of climate change ("Impact CC") are represented by the future versus present changes in wetland inflows. The combined impacts of climate change and the wetland ("Impact CC and Wetland) are represented as future wetland outflows versus present wetland inflows. Since the analyses of these results have been outlined in detail in Chapter 4, Section 4.6.4, only a summary of the main findings will be offered here.

Table 6.4 and F igures 6.6-6.7 show that only 4 out the 7 downs caled GCMs c onsidered project increases in runoff, nutrients and sediment going into the wetland (ratios above 1 and positive pe rcentage changes). These w ere the GDFL2.1, MR I, IPSL a nd C SIRO GCMs. However, 3 of thes e G CMs *viz.* the MIROC, ECH5 a nd ECHO GCMs, project decreases (albeit small decreases) in runoff, nutrients and sediment going into the wetland.
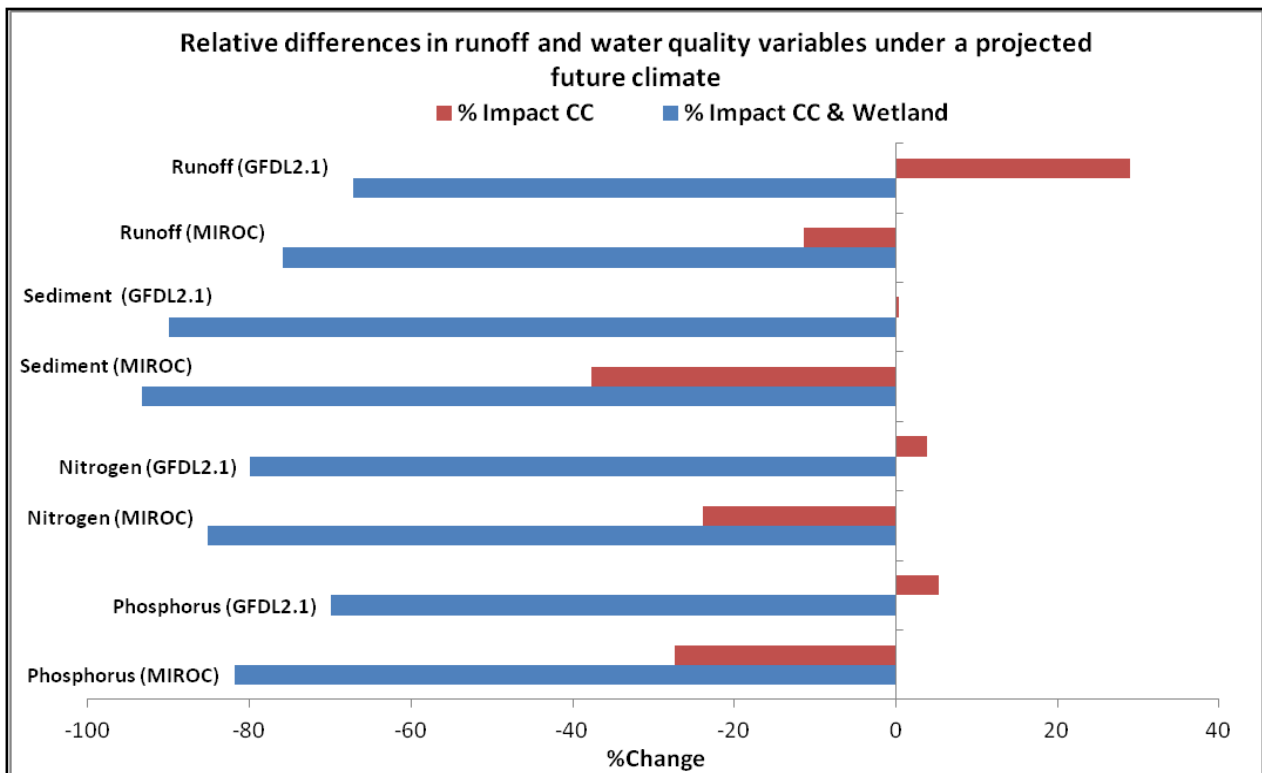
Figure 6.6   Impact of climate change (as a percentage difference) on mean annual wetland inflows and outflows in terms of runof f, sediment yield, nit rogen load a nd phosphorus load for the CSIR downscaled GCMs.

For the GCMs downscaled by the CSIR, the GFDL2.1 GCM projects increased runo ff going into the we tland and posi tive but minimal change with regard to nutrients and se diment incident to the wetland. The M IROC GCM, conversely, pr ojects decreased runoff and decreased nutrients and sediment going into the wetland. In all instances, however, the role of the wetland is much greater than the impact of climate change and results in overall decreases in nutrients and sediments (Figure 6.6). Although the simulations project increases in runoff for most of the GCMs under climate c hange a nd a lso point to the potential incr ease in the generation of sediment and nutrients, the downstream transfer of these va riables is mitigated to a high degree by the wetland.
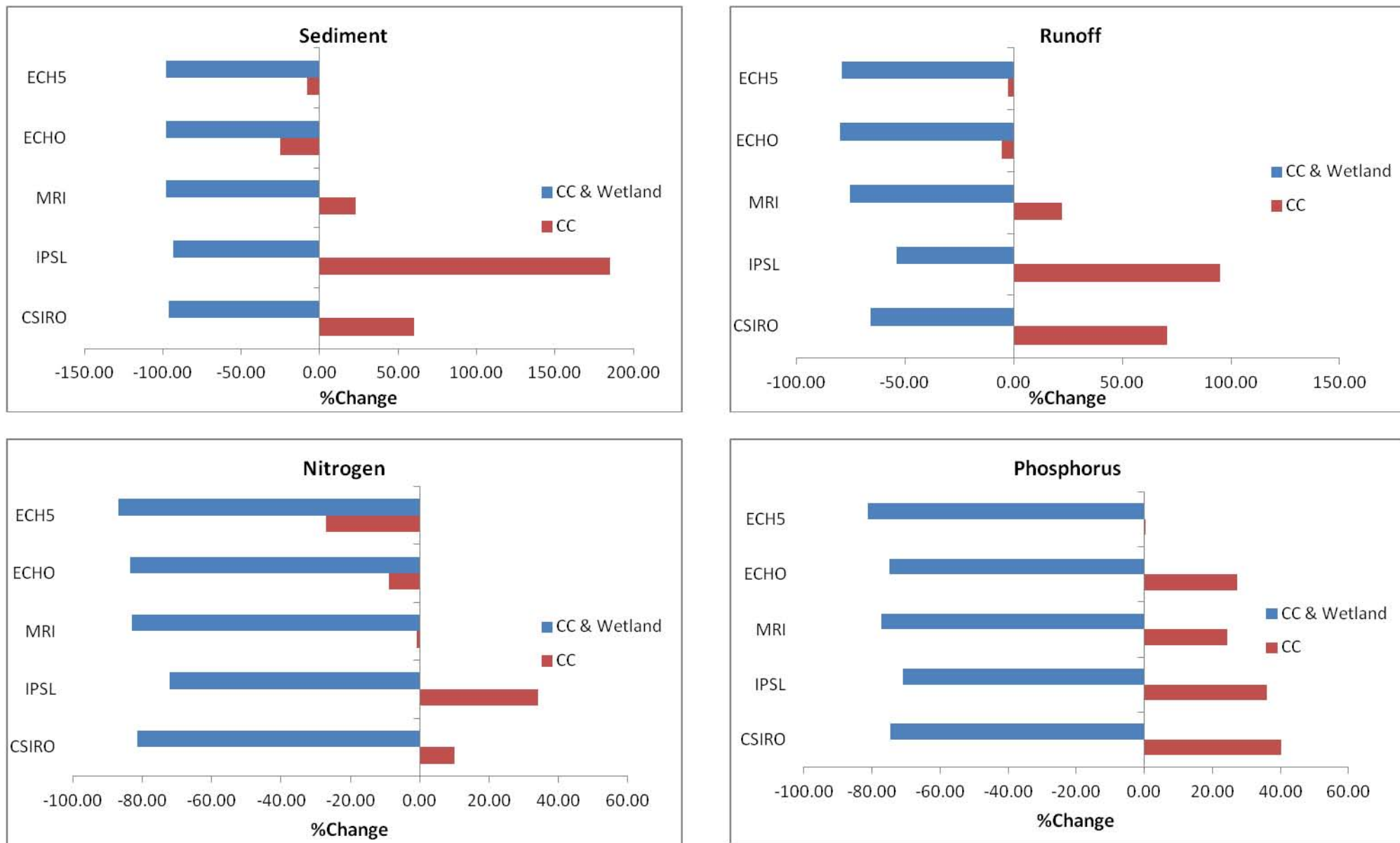
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The majority of the CSAG downscaled GCMs indicated positive changes with regard to projected runoff, nutrients and sediment (Figure 6.7) under future conditions. The exceptions to these trends were the ECHO and ECH5 GCMs which indicated negligible decreases in runoff, nutrients and sediment between the future and the present. The various GCMs downscaled by CSAG indicated large variations in projected runoff, nutrients and sediment. For instance, the IPSL GCM suggested increases in runoff of up to 95%, while the MRI GCM suggested increases of only 22%. In the same sense the CSIRO GCM suggested increases of up to 71%. This, as it is evident, represents a large amount of disagreement between these GCMs. Regardless of these variations, the majority of the CSAG downscaled GCMs indicated the same direction of change, which was a generally increasing trend in the generation of runoff, nitrogen, phosphorus and sediment under climate change. As mentioned in Chapters 4 and 5, GCMs are highly uncertain and they are not always expected to explicitly reproduce the exact time series variations of point scale rainfall and, consequently, that of local scale runoff. It was, therefore, considered highly critical that the focus of these analyses be on the variability and relative changes presented by the downscaled GCM projections rather than on the absolute estimates that they project.

It has been noted that there are significant variations between the CSAG downscaled GCMs regarding increases in runoff, nutrients and sediment. A closer inspection of mean annual precipitation was undertaken in an attempt to isolate and describe these trends (also see Chapter 5). MAP changes indicated neutral to slight increases, yet runoff changes range from neutral to large increases (Table 6.4). Downscaled GCMs projecting large runoff increases, thus, indicate a change in the distribution of rainfall (*e.g.* at seasonal or daily levels) which results in a lot more runoff from the same total rainfall. Some GCMs (*e.g.* ECHO, ECH5 and MRI) show reductions in sediment and nitrogen. These are GCMs that also project minimal change in annual runoff (save for the MRI GCM) – again this suggests changes in the distribution of the rainfall, this time in the opposite manner (less concentrated/intense rainfall). To gain a better understanding of these variations in runoff and WQ variables, it was considered important that the nature of the changes in daily rainfall (as the main "driver" of these trends) under climate change be fully detailed. The reader is referred to Chapter 5 for the complete analysis of rainfall frequency changes between present and future climates.

Table 6.4   Ratios of future to present mean annual precipitation, runoff, nutrients and sediment for all downscaled GCMs.

	RATIOS OF CHANGE*				
	MAP	**RUNOFF**	**SEDIMENT**	**NITROGEN**	**PHOSPHORUS**
DOWNSCALED GCM					
GDFL2.1	**1.05**	**1.29**	**1.00**	**1.04**	**1.05**
MIROC	**0.89**	**0.89**	**0.62**	**0.76**	**0.73**
CSIRO	**1.08**	**1.71**	**1.60**	**1.10**	**1.40**
ECHO	**1.04**	**0.95**	**0.75**	**0.91**	**1.27**
IPSL	**1.01**	**1.95**	**2.85**	**1.34**	**1.36**
ECH5	**1.00**	**0.97**	**0.92**	**0.73**	**1.00**
MRI	**1.04**	**1.22**	**1.23**	**0.99**	**1.24**
*As ratio of future to present					

Figure 6.7 Impact of climate change on mean annual wetland inflows and outflows in terms of WQ variables for the CSAG downscaled GCMs.

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6.4.4   Summary of Results

To summarise, the various analyses conducted in this study to detail changes in rainfall, runoff, nutrients and sediment between the present and the future, highlighted a few critical points:

a) Global Circulation Models, like any other mathematical model, are inherently uncertain.

b) It is more appropriate to focus on relative changes and robust patterns of change described by the downscaled GCM projections rather than on absolute quantitative estimates which cannot be verified. This is particularly crucial in water resources planning under climate change.

c) The high degrees of variability presented by the downscaled GCM projections highlight the need to develop robust and flexible adaptation strategies that take into consideration risk and, thus, have realistic safety margins.

Additionally, the uncertainties presented by the various GCM projections need to be taken into consideration particularly in the development of adaptation strategies in the highly assorted profile of South African agricultural catchments. For instance, South African catchments range from relatively simple catchments, such as those in the interior of the country, to highly complex catchments, such as those in the Western Cape and KwaZulu-Natal Midlands. Therefore, any strategies developed need to be transferrable across these catchments in order to ensure that they are robust, flexible and relevant. The following section details the development of adaptive water quality management strategies as informed by the framework suggested in Section 6.2 and by the results obtained from the water quality and climate change modelling exercises offered in Section 6.3. Also included in the following Section is an assessment of the vulnerability and potential for adaptation characteristic of the Mkabela Catchment as informed by the *ACRU*-NPS simulations.

6.5   Adaptive Water Quality Management

An adaptation strategy may be thought of as a plan of action intended to minimise the anticipated impacts of change on catchment water resources. The ultimate goal of adaptation strategies is, therefore, to build adaptive capacity and reduce vulnerability (Chapter 2, Section 2.1.2). The development of these strategies is therefore important particularly in developing countries. This section presents selected adaptation strategies considered relevant in the management of nutrients and sediment and, thus, catchment water quality as observed in the Mkabela case study and drawn from a synthesis of other relevant studies (see Chapters 2 and 3). Before these strategies are outlined, however, it was considered important that the vulnerability and potential for adaptation characteristic of the Mkabela Catchment be assessed.

6.5.1   Vulnerability and Potential for Adaptation as Informed by the *ACRU*-NPS Model Simulations

Vulnerability was defined in Chapter 2 as the "degree to which a system is likely to experience harm due to exposure to a hazard" (Füssel, 2006; Ionescu *et al.,* 2009). Vulnerability is, therefore, a relative property denoting the vulnerability *of* something *to* something (Ionescu *et al.,* 2009). In the context of this study, the vulnerability of the Mkabela Catchment was assessed from a perspective of the potential deterioration of catchment water quality to the increased introduction of nutrients and sediment into the Mkabela fluvial and hydraulic systems (rivers, dams, wetlands *etc.*), between the present and the future. That is, if an assumption is made that climate change will trigger increased runoff (as suggested by the *ACRU*-NPS simulation outputs) for the Mkabela Catchment, and there is an increase in the introduction of pollutants into the system for any reason (*e.g.* increased use of synthetic fertilizers to increase yields and meet economic demands for agricultural products), then the vulnerability of the fluvial systems and the people/farming communities who depend on them in the catchment, may also be expected to increase. It is important to note that this study considered changes in the distribution of agricultural NPS pollutants up to one specific wetland (termed "wetland1") downstream of the pollutant contributing sites or HRUs (see Figure 6.4).

The relative changes in inputs into the wetland between the present and the future were used as indices that describe the vulnerability of the catchment fluvial systems or at least the headwaters of the catchment where the study was primarily focused. As noted above, all simulations based on downscaled GCM projections suggested increases in runoff and in the subsequent generation and transfer of nutrients and sediment in the future (ratios above 1, Table 6.4). This consequently implies that there will be an increase in the loads of nutrients and sediment going into the wetland. This in turn suggests that the wetland will become increasingly vulnerable to the increased introduction of NPS pollutants, which may potentially lead to the deterioration of the water quality of the wetland. While it is true that the increased runoff volumes projected by downscaled GCMs for this catchment will potentially result in the increased washout of pollutants from agricultural lands, it is important to note that the ability and competency of wetlands to attenuate flow and limit the downstream transfer of nutrients or pollutants differs between individual wetlands. The wetland assessed in this study, as already mentioned, displayed high competency in retaining NPS pollutants and limiting their downstream transfer.

The role and importance of wetlands and other buffers was clearly indicated in the results presented. Several authors have noted that numerous factors that determine how well a particular wetland prevents the downstream translocation of nutrients and sediment. Some of these factors include:

a) the size of wetland relative to the upstream contributing sources of pollutants,

b) the shape of the wetland (as a determinant of the time of concentration for runoff and thus the residence time for pollutants),

c) the permanence and seasonality of the moisture regime of a wetland (IPCC, 2007; Bates *et al.,* 2008),

d) the physicochemical properties of the wetland (*e.g.* C:N ratios, bacterial density or concentration, suspended sediment concentration) (Novotny, 2003),

e) the ecological conditioning of the wetland (pristine vs disturbed, flora and fauna density) (Braskerud, 2002) and,

f) anthropogenic influences or pressures on the wetland (*e.g.* the use of wetlands as poplar/*Populus tremula* plantations) (Braskerud, 2002).

Although the Mkabela wetland does not explicitly conform to all the factors presented above, simulation results suggested that this wetland demonstrates high competency to limit the downstream translocation of nutrients and sediment, regardless of changes in runoff and nutrient fluxes between the present and the future (Figures 6.6 and 6.7). This suggests that this particular wetland has the potential of not becoming any more vulnerable to future conditions of climate change than it is to present conditions. In the context of adaptation, this highlights an important finding: the behaviour demonstrated by the wetland suggests that its preservation by the local farming community in the Mkabela Catchment would not only be an adaptation strategy in itself but it would also potentially build the adaptive capacity of this catchment and increase the resilience of this catchment to water quality deterioration instigated by the impacts of climate change. This would also prevent or limit the water quality deterioration of downstream fluvial and hydraulic systems.

It is important to note that the high competency of the wetland to limit the downstream movement of nutrients and sediment both under present and future conditions does not suggest that the appropriate and judicious management of these pollutants should not be observed. Rather, it serves to highlight the need to recognize the importance of the wetland in attenuating nutrients and sediment and the importance of having the appropriate management strategies in place to protect the water quality of downstream fluvial systems. The following section therefore provides a few of these adaptive management strategies as informed by the results of this study, as well as the literature.

6.5.2 Adaptive Management of Nutrients and Sediment Transport

As mentioned before, South African agricultural catchments are a kaleidoscope of relatively simple (*e.g.* the Maize Triangle in the Free State Province) to highly complex (*e.g.* mixed cropping systems in the KwaZulu-Natal Midlands) systems. It is important, therefore, that any adaptation strategies developed or suggested with the intention of minimising the anticipated impacts of climate change on water quality be transferable across these distinct catchments. Providentially, the Mkabela Catchment offers an appropriately large blend of cropping systems including vegetables, dairy, commercial afforestation, sugar cane and pastures. This provides an opportunity for the development or suggestion of adaptation strategies takes into consideration all the various cropping systems and, arguably, allows the

transferability of these strategies to other catchments, notwithstanding the limitations of the modelling exercise as detailed in Section 6.5.3. The following strategies based, in part, on the work conducted in the Mkabela Catchment and largely on a synthesis of other studies (Chapters 2 and 3), were considered generic enough to permit their application on other "ungauged" catchments; *i.e.* catchments in which similar studies have not been conducted as yet.

a) Integrate catchment water quality management, applying principles from integrated water resources management (IWRM) (GWP, 2000; Schulze, 2003). Recognizing the connectivity that exists between catchment water users and uses will construct resilience and facilitate engagement in adaptation action.

b) Improve irrigation efficiency (Molden, 2007). Prevent the unnecessary increase in runoff generation which causes increased washout of nutrients and sediment.

c) Adjust fire management in forestry and sugar cane plantations. Fire is known to create hydrophobicity in soils which can enhance the susceptibility of soils to erosion, leading to increased sediment generation. Therefore only burn during low rainfall seasons.

d) Prevent waterlogging, erosion and leaching. The loss of nutrients is considered to occur with a high degree when there is an overabundance of water (as shown in Chapter 3). This is related to prudent irrigation.

e) Improve access to information. Implementing seasonal forecasting can be beneficial in improving the timing of cropping and fertilizer applications such that soil and nutrient losses are minimized. Additionally, communicating modelling results to stakeholders can also assist in promoting literacy regarding water quality management.

f) Construct discharge rate conservation structures (McCartney, 2009). This applies mainly to catchments where the release of high concentrations of nutrients and sediment is prevalent.

g) Increase public and decision-maker awareness. Cooperation between local water resource managers, farmers, local policy makers and the general public is critical in reducing anthropogenic impacts on local water quality.

h) Adopt planned rather than autonomous adaptation (Adger, 2003). In some instances, adaptation strategies are already being observed, albeit inadvertently (*e.g.* crop rotation and mixed cropping systems). Under future conditions of

change, however, this can facilitate mal-adaptation in the sense that applying fixed management practices under altered conditions can undermine the systems integrity and potentially create new vulnerabilities and exposures.

i) "Mainstream climate change adaptation options/strategies in national development plans. Strategies and options for climate change adaptation need to be considered when preparing national development action plans" (Petermann, 2008).

j) Improve gauging and monitoring (Lorentz *et al.,* 2011). Having a dense monitoring network within a catchment not only improves daily water quality management and decision-making but it also facilitates the isolation and effective control of problem areas.

It was noted before that adaptation strategies need to be based on well-executed research and experimental work based on sound scientific principles. This study presented a case study in which the impacts of climate change on water quality constituents were assessed primarily through modelling. Admittedly, the case study offered limited scope to allow for the inclusion of catchment-wide nutrient and sediment delivery mechanisms that influence catchment water quality. This was owing to a variety of limitations, which included time constraints, particularly in the verification of the model, the scale at which the study was conducted and climate change input data problems (see Chapter 5 for the analyses of climate change input data). Strategies to address these limitations in future research will be outlined in Chapter 7. The reviews presented in Chapters 2 and 3, however, served as useful guides in the development of the adaptive management framework presented in this Chapter (see Figures 6.1 and 6.2).

6.5.3   Assessment of the Adaptive Water Quality Management Framework

The framework presented in Figure 6.2 was intentionally designed to be generic in nature. The reason for this approach was to allow for the development or suggestion of an adaptive water quality management framework that can be applied in any agricultural catchment in South Africa. This was owing to the highly diverse nature of local catchments, ranging from relatively "simple" (*e.g.* rural) to highly complex (*e.g.* peri-urban to urban) catchments. This approach, it was found, has its own merits and shortcomings. The advantages of this approach were considered to be:

a) The transferability of the framework, suggesting that it is not limited to the Mkabela Catchment but can be applied in other similar agricultural catchments as well.

b) The inclusion of all aspects relating to catchment water quality management and policy development within the framework (*i.e.* hazards and risks, plan-making, core components and information collation aspects, as outlined in Figure 6.2), based on a detailed review of the literature (Chapters 2 and 3).

c) Highlighting the explicit importance of communicating model applications (or any other similar research results) to catchment stakeholders and policy-makers.

d) The updating of current knowledge relating to climate change and water quality (*i.e.* monitoring and review) to be on par with the natural dynamism of environmental and socio-economic systems.

e) The importance of recognizing the uncertainties presented by the various GCMs used in this study is highlighted in the framework.

This approach had some shortcomings which were duly noted:

a) The framework is only applicable up to the local catchment scale (*e.g.* Mkabela Catchment and Nagle WMU). Regional factors (*e.g.* the incidence of urban areas) which would have influenced the development of the adaptive water quality management framework could not be addressed.

b) The results from the case study provided limited scope for the development of adaptive catchment water quality management strategies, but rather provide a starting point for this. This was owing to the relatively small scale at which the study was conducted and time constraints (see Chapter 4 and Section 6.3 of this Chapter).

As mentioned before, the framework presented in Figure 6.2 can be applied in agricultural catchments similar to the Mkabela Catchment. However, this framework would need to be adapted for these catchments to ensure that it maintains its primary purpose, which is to promote adaptive water quality management. To do this, the methodology presented in this study would need to be revisited and refined (see Chapter 7). For instance, this study was limited to the local catchment scale; a fact which may have potentially precluded the identification of geographically extensive biophysical mechanisms that govern the transport of nutrients and sediment.

Therefore, the extension of this and similar studies to larger catchment scales may ensure that a better understanding of these mechanisms is developed and this may, ultimately, assist in adaptive decision-making and policy development. Furthermore, the human element, or the impact of human activities on catchment water quality, could not be directly addressed in this study. That is, consultations with catchment stakeholders to understand their role in catchment water quality management could not be carried out owing to time constraints. This is an important facet of adaptive water quality management since the successful application or implementation of the framework relies on the acquiescence of catchment stakeholders to actively engage in adaptation action. Therefore, before this framework is applied in other catchments, the opinions and visions of catchment stakeholders would need to be taken into account and incorporated into the framework. This would ensure that the framework is as comprehensive as possible and includes water quality related issues most pertinent to the catchment in question.

This study also highlighted the importance of understanding uncertainty in predictive modelling. Models, such as the downscaled GCMs used in this study (Chapter 5), are uncertain. In addition, models are mathematical abstractions of reality and they are inherently limited by the boundary conditions and assumptions which they assigned. Therefore, the output from these models needs to be treated with a certain degree of measured scepticism. That is not to imply that the output from these models should not be used to further the understanding of natural system behaviour or to isolate and contain anthropogenic impacts on the environment, but rather it is to highlight the importance of recognizing the uncertainty of the output generated by these models. Decisions, particularly those pertaining to an uncertain future under climate change, need to be taken regardless of the uncertain nature of the output from these models. The framework presented in this study recognises this uncertainty and highlights the need for monitoring and review in order to ensure that these decisions remain robust and relevant under a changing biophysical and socio-economic climate. This would be applicable to all catchments where this framework may be applied. Having outlined the development of an adaptive water quality management framework and various adaptation strategies using both a review of the literature (Chapters 2 and 3) and the modelling exercises conducted using the Mkabela Catchment as a case study, the following section provides a synthesis of the results of this Chapter and the implications it presents for similar studies.

6.6   Discussion and Conclusions

This paper has attempted to outline the use of the water quality model *ACRU*-NPS to suggest appropriate and adaptive water quality management strategies. Admittedly, the modelling results of this study were relatively limited for use in the development or suggestion of these adaptation strategies. The impacts of climate change on water quality could only be assessed in terms of the response of a single wetland to projected changes in biophysical process and the consequential changes in processes governing the behaviour of nutrients and sediment across the Mkabela Catchment. This precluded the identification and assessment of geographically extensive mechanisms that control nutrient and sediment transfer dynamics. However, the local catchment-scale focus assumed in this study allowed the identification and isolation of unique catchment pulses that govern the behaviour of non-point source pollutant migration, therefore allowing the identification of the processes that may have the greatest impact on catchment water quality under climate change. This also enabled the design of management strategies and the adaptive water quality management framework and its refinement, which were considered to be both relevant and specific to the Mkabela and similar agricultural catchments (Section 6.5).

The reviews conducted in Chapters 2 and 3 to outline the procedures involved in developing adaptation strategies, served as important guides in the development of the adaptive water quality management framework and adaptation strategies suggested in this paper. This study showed that adaptive water quality management requires risk- and hazard-based decision-making models (Figures 6.1 and 6.2) which favour long-term planning and robustness taking into cognisance the dynamic nature of socio-economic and environmental systems. Additionally, the uncertainties presented by the use of data derived from downscaled GCM projections, as shown in Section 6.4.5, also suggest that natural variability and robust patterns of change need to be the primary foci and not absolute unverifiable projections of change.

Increasing global change pressures on water resources coupled with the compounding effects of climate change imply that risks related to water quality management cannot be ignored or omitted in the decision-making process. The compounding set of uncertainties presented by climate change necessitates the development of adaptive management strategies that will minimize the vulnerability of environmental and socio-economic systems to climate change.

The strategies and frameworks outlined in this study not only have the potential to enhance the adaptive capacity of catchment water quality management but they can also serve as useful guides in the development of new adaptation strategies in other ungauged South African catchments. Limited as the results of study may have been, they still provided insight into the complexities and uncertainties involved in both water quality and climate change modelling. They showed the absolute importance of exercising caution in the application of GCM-derived data in the investigation of point-scale hydrological responses/processes. Additionally, they showed the importance of extending such investigations to larger catchment scales in order to fully represent source-pathway-response relationships that govern nutrients and sediment migration. Furthermore, the review into the probable changes in the behaviour of climate-sensitive processes under climate change served as a useful reference that allowed the explanation of the results obtained in this study.

In conclusion, this study has attempted to demonstrate the absolute importance of strategic and adaptive intervention, even under uncertainty. The framework and adaptation strategies that have been suggested take cognisance of the uncertainties surrounding the climate change discussion and note the importance of continuous monitoring and review, to ensure that any changes in environmental and socio-economic systems are factored into adaptive water quality management and policy development. Although this study was limited by scale, the adaptation strategies suggested were considered to be holistic and applicable up to local catchment scales. It was also noted that such studies need to be extended to regional catchment scales to ensure the inclusion of geographically extensive catchment biophysical processes.

6.7   Acknowledgements

6.8   References

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CHAPTER SEVEN

Synthesis and Recommendations for Future Research

7. SYNTHESIS AND RECOMMENDATIONS FOR FUTURE RESEARCH

It is now a well-accepted fact that climate change is going to aggravate water quality (WQ) problems by instigating rapid and potentially negative changes in the natural hydrological environment. The projected impacts of climate change on water quality and quantity are expected to introduce added complexities in an already complex water resources management environment. This is going to be especially true in South Africa considering the high risk and high variability hydroclimatic environment that characterizes this country. Although the impacts of a changing climate on local water resources have been widely studied with a marked emphasis on water quantity, minimal effort has been directed towards assessing water quality issues under climate change. It is therefore important that the projected impacts of climate change on the water quality of local fluvial systems be assessed and detailed fully in order to ensure preparedness, secure resilience and reduce the vulnerability of these systems to the impacts of climate change. It is critical to also note that very little has been achieved with respect to linking the basic catchment processes that drive water quality variability with climate change projections, and ultimately, incorporation of that particular research into policy development and governance. In an attempt to close this knowledge gap, this study sought to:

e) Review processes of sediment yield, nitrogen and phosphorus transport in local (agricultural) catchments and highlight the factors that influence the generation and transport of these water quality variables within local catchments.

f) Develop the ability to model the projected impacts of climate change on sediment yield, nitrogen and phosphorus in the Mkabela Catchment using the *ACRU*-NPS water quality model by incorporating projected changes in driver variables and, where necessary, modifying the variables based on expert opinion.

g) Assess the vulnerability and potential for adaptation with regard to water quality under conditions of climate change for the entire Mkabela Catchment and develop an adaptive water quality management framework based in this analysis.

h) Use the results from the above exercises to develop (or suggest) appropriate adaptation strategies relevant to the Mkabela Catchment and make recommendations for policy development and governance at local and regional levels.

The first objective was considered to be achieved in this study. Chapters 3 provided a full description of the processes and factors that govern the transport of nutrient   ts (N and P) and sediment across agricultural catchments under "normal" or historical conditions. Additionally, since the majority of these processes are climate-sensitive, the potential influence of an altered climate on their behaviour was also detailed in Chapter 3. This was considered critical since this study had as one of its primary foci, the modelling of the potential impacts of climate change on these processes. This review served as a useful guide in the subsequent water quality and climate change modelling exercises and strategy development conducted in this study.

The second objective was also considered to be achieved, albeit partially owing to the limitations and uncertainties presented by the use of projected climate data as input in the model. The historical behaviour of water quality variables (runoff, nutrients and sediment), however, were considered to be successfully simulated, primarily due to the availability of high quality, observed input data and access to expert opinion with regard to input variables. In addition to the noted shortcomings of using climate change projections, there were other uncertainties in the model inputs, which were duly noted. Certain input variables or parameters were kept constant, primarily because it is not currently possible to calculate future estimates of these input parameters. An example of this is the *X130* variable which influences the generation of peak discharge and sediment yield. Notwithstanding the above shortcomings, it was believed that the input variables used in this study were realistic enough to permit their application in climate change simulations.

A major limitation related to the use of downscaled GCMs was revealed in this study. These GCMs are downscaled to regional scales using either dynamical or statistical approaches (Chapters 4 and 5). Assumptions have to be made in order to ensure that the output from these downscaled GCMs resembles observed climatic regimes as closely as possible. It was, however, noted in this study that downscaled GCMs are not always expected to explicitly or faithfully reproduce the exact time series variations of point scale rainfall; although they are usually accurate with respect to projected variations in temperature. This was considered to be a major limitation of the GCMs considering the point scale resolution at which this study was conducted.

This scaling or resolution limitation of the downscaled GCMs was revealed when simulations of water quality variables were assessed for present (1971-1990) and future (2046-2065) climatic conditions. There were inconsistent degrees of variation between WQ variables simulated based on observed input data and simulations based on GCM-derived input data (Chapter 4, Results). Admittedly, some consistency was observed between downscaled GCMs derived from one of the downscaling institutions with respect to simulated water quality variables (*i.e.* the majority of CSAG GCMs). However, when the downscaled GCMs were considered together, there was little agreement as to the degrees of change in magnitudes simulated for water quality variables for present and future climates. The only consistency observed in this regard was that 6 out of the 7 downscaled GCMs projected increases in MAP, runoff and all other water quality variables considered (positive percentage changes). It was for this variation in magnitude that prompted this study to focus only on *relative* changes between the future and the present in the assessment of potential changes in WQ variables as influenced by climate change. This approach also proved more relevant and useful in describing potential changes and in the development of relevant adaptation strategies.

Owing to the limitations presented by the use of downscaled GCMs outlined above, this study went further and performed detailed rainfall analyses at daily resolutions for all the downscaled GCMs used in the study in order to identify changes in rainfall distribution between the present and the future (Chapter 5). These analyses assessed relative changes in raindays, number of days with no rainfall and changes in pre-defined rainfall intervals as described by each one of the downscaled GCMs. A host of conservation statistics were also considered including MAP changes, standard deviations and coefficient of variations (CV) of annual rainfall. Nearly all downscaled GCMs projected increases in the number of raindays and days each pre-defined interval (or rainfall event range) will be met or exceed between the present and the future. The exceptions to these trends were the MIROC and ECH5 downscaled GCMs. Similarly, an analysis of MAP changes also indicated increases across most downscaled GCMs; the same was true for standard deviation and CV of annual rainfall. Consequently, it was expected that there would be differences in rainfall event frequencies at the daily level because there were already differences evident at an annual level.

The point of the daily analyses was to try to understand the annual differences in rainfall frequencies *e.g.* if a certain downscaled GCM had a very high MAP this could be the result of it simulating more large (*i.e.* daily level) events.

The third objective of this study, which was the assessment of the vulnerability and potential for adaptation in the Mkabela Catchment with respect to water quality changes under climate change, was considered to be achieved. The vulnerability assessment was carried out by assessing the vulnerability of the wetland (termed "wetland1") to the impacts of climate change. This was deemed appropriate since the functioning of a wetland in terms of the wetland's ecological health can be used as a reliable reference to indicate the effectiveness of water quality management within a catchment. This is because the functioning of wetlands is limited by a host of factors, of which anthropogenic influences (*i.e.* people) are a part of. (It is not unrealistic to assume that the integrity of catchment water quality is directly related to the anthropogenic influences and impacts on the fluvial systems of that catchment.) The wetland assessed in this study indicated almost no signs of vulnerability to the impacts of climate change. Regardless of the increases in runoff, nutrients and sediment incident to the wetland as projected by the various downscaled GCMs, the wetland consistently indicated high competency in limiting the downstream transfer of all these water quality variables.

Unfortunately, a detailed assessment of the potential for adaptation in this catchment could not be carried out due to time constraints. Such an assessment would necessarily require stakeholder consultations, workshops that bring together different water users at local and regional levels and detailed monitoring and assessment of the tools applied to manage water quality in this catchment (*e.g.* erosion prevention measures and irrigation regimes), activities considered to be outside the scope of this study. However, adaptation strategies were nonetheless suggested based on lessons learned from the various results obtained in this study. This constituted the fourth aim of this study and included the development of an adaptive water quality management framework. These strategies were primarily suggested for the adaptive management of nutrients and sediment within agricultural catchments and the adaptive water quality management framework proposed in this study was considered to be generic enough to allow its application across various agricultural catchments in South Africa.

In conclusion, this study has shown that adaptation to climate change in water quality management and policy development is going to require approaches that fully recognise the uncertainties presented by climate change. Admittedly, the application of downscaled GCMs to assess potential changes in biophysical processes is a useful approach that allows the conscientious management of water resources in order to ensure the sustainable use of this finite resource. This is particularly true in South Africa, considering the semi-arid nature of this country. However, and most critically, these downscaled GCMs are inherently uncertain and their application in any water quality management endeavours needs to reflect this. In addition to this, this study has shown that the natural climatic variability of local catchments should not be overlooked in the development of adaptive water quality management strategies. For instance, it has almost become the norm to attribute recent extreme climatic events to climate change, when it is possible that some of these extreme events are actually entirely natural and are not influenced by climatic change at all. It is therefore crucial that equal attention be given to climate change, natural variability and robust patterns of change in order to ensure that adaptation strategies remain robust, relevant and effective.

7.1 Recommendations for Future Research

Based on the work conducted in this study and the potential for improvements to the methodology that were identified, it was recommended that the following be addressed in future research:

a) Similar to the rainfall frequency analyses conducted in this study (Chapter 5), changes in temperature as projected by the downscaled GCMs also need to be characterized and represented in future modelling methodologies. These analyses also need to be extended to other catchments.

b) The impacts of climate change on selected water quality variables needs to be investigated at larger catchment scales (preferably at the tertiary catchment scale and under different climatic regimes).

c) Tailored adaptation strategies that are exclusive and unique to the Mkabela (and the Mgeni) catchment need to be developed with the explicit inclusion and consultation of the relevant stakeholders within the catchment.

d) Develop a method in consultation with expert opinion to calculate the *XI30** factor which influences peak discharge in *ACRU*-NPS for future conditions.

e) The applicability of the adaptive water quality management framework suggested in this study needs to be tested over a wide range of South African catchments and under different climatic regimes.

f) Additional dynamically downscaled GCMs (*i.e.* CSIR downscaled GCMs) need to be introduced to ensure a more inclusive and comprehensive view of downscaled climate change projections for South Africa.

*The 2-year return period for the 30-minute rainfall intensity, calculated in mm.hr^{-1}.

GLOSSARY

Adaptation

Initiatives and measures to reduce the vulnerability of natural and human systems against actual or expected climate change effects.

Adaptive Capacity

The whole of capabilities, resources and institutions of a country or region to implement effective adaptation measures.

Vulnerability

The degree to which a system is susceptible to, and unable to cope with, adverse effects of climate change, including climate variability and extremes.

Exposure

The fact or condition of being exposed as in the condition of being unprotected from severe weather.

Resilience

The ability of a social or ecological system to absorb disturbances while retaining the same basic structure and ways of functioning, the capacity for self-organisation, and the capacity to adapt to stress and change.

Sensitivity

Sensitivity is the degree to which a system is affected, either adversely or beneficially, by climate variability or climate change. The effect may be direct (e.g., a change in crop yield in response to a change in the mean, range, or variability of temperature) or indirect (e.g., damages caused by an increase in the frequency of coastal flooding due to sea-level rise).

1   Rainfall   file organisation
IRAINF sugarc_Base.csv
3 Rainfall information
FORMAT 4
PPTCOR 0
MAP 820.
12   Monthly   rainfall adjustment   factors, CORPPT(i)
CORPPT(01) 0.76
CORPPT(02) 0.86
CORPPT(03) 0.93
CORPPT(04) 0.80
CORPPT(05) 0.97
CORPPT(06) 0.82
CORPPT(07) 0.72
CORPPT(08) 0.74
CORPPT(09) 0.92
CORPPT(10) 0.83
CORPPT(11) 0.90
CORPPT(12) 0.83
3 Availability of observed streamflow data
IOBSTQ 0
IOBSPK 0
IOBOVR 0
1   Streamflow   file organisation
ISTRMF blank
1 Dynamic file option
DNAMIC 0
1   Dynamic   file organisation
IDYNFL blank
2 General Heading of simulation
GENERAL   Sugarcane, Avalon soil form
HEADING 1:
6 Locational information 0.58km2
CLAREA 0.58
ELEV 965.
ALAT 29.42
ALONG 30.65

IHEMI 2
IQUAD 1
2 Period of record for simulation
IYSTRT 2006
IYREND 2012
2   Simulation   printout options
WRIDY 0
WRIMO 0

2   Statistical   output options (I)
SUMMRY 99
ICOMPR 0
2   Statistical   output options (II)
ICOMPV 0
LOGVAL 0
12   Monthly   means of daily max temperature, TMAX(i)
TMAX(01) 2.0
TMAX(02) 2.0
TMAX(03) 2.0
TMAX(04) 2.0
TMAX(05) 2.0
TMAX(06) 2.0
TMAX(07) 2.0
TMAX(08) 2.0
TMAX(09) 2.0
TMAX(10) 2.0
TMAX(11) 2.0
TMAX(12) 2.0
12   Monthly   means of daily min temperature, TMIN(i)
TMIN(01) 0.0
TMIN(02) 0.0
TMIN(03) 0.0
TMIN(04) 0.0
TMIN(05) 0.0
TMIN(06) 0.0
TMIN(07) 0.0
TMIN(08) 0.0
TMIN(09) 0.0

TMIN(10) 0.0
TMIN(11) 0.0
TMIN(12) 0.0
1 #   Reference potential evaporation   control variables
EQPET 106
7   Evaporation   input availability control flags
IEIF 0
ILRF 0
IWDF 0
IRHF 0
ISNF 0
IRDF 0
IPNF 0
12 Means of monthly totals of pan evaporation, E(i)
E(01) 0.0
E(02) 0.0
E(03) 0.0
E(04) 0.0
E(05) 0.0
E(06) 0.0
E(07) 0.0
E(08) 0.0
E(09) 0.0
E(10) 0.0
E(11) 0.0
E(12) 0.0
2 Temperature adjustment for altitude
TELEV 908.5
LRREG 2
2 Mean lapse rates for min   and   max temperatures
TMAXLR 0.0
TMINLR 0.0
1 Mean daily windspeed (m/s)
WNDSPD 1.6
1   Windspeed   region number
LINWIN 0

12 Monthly means of daily windrun (km/day), WIND(i)
WIND(01) 11.0
WIND(02) 11.0
WIND(03) 11.0
WIND(04) 11.0
WIND(05) 11.0
WIND(06) 11.0
WIND(07) 11.0
WIND(08) 11.0
WIND(09) 11.0
WIND(10) 11.0
WIND(11) 11.0
WIND(12) 11.0
12 Monthly means of daily average relative humidity, RH(i)
RH(01) 55.0
RH(02) 55.0
RH(03) 55.0
RH(04) 55.0
RH(05) 55.0
RH(06) 55.0
RH(07) 55.0
RH(08) 55.0
RH(09) 55.0
RH(10) 55.0
RH(11) 55.0
RH(12) 55.0
12 Monthly means of daily hours of sunshine, ASSH(i)
ASSH(01) 2.0
ASSH(02) 2.0
ASSH(03) 2.0
ASSH(04) 2.0
ASSH(05) 2.0
ASSH(06) 2.0
ASSH(07) 2.0
ASSH(08) 2.0
ASSH(09) 2.0
ASSH(10) 2.0
ASSH(11) 2.0
ASSH(12) 2.0
3 Penman equation control variables
ALBEDO .07
ICONS 0
ISWAVE 0

12 "A" coefficient in Penman equation, ACONS(i)
ACONS(01) .27
ACONS(02) .27
ACONS(03) .28
ACONS(04) .24
ACONS(05) .24
ACONS(06) .25
ACONS(07) .24
ACONS(08) .21
ACONS(09) .23
ACONS(10) .23
ACONS(11) .22
ACONS(12) .24
12 "B" coefficient in Penman equation, BCONS(i)
BCONS(01) .52
BCONS(02) .49
BCONS(03) .52
BCONS(04) .52
BCONS(05) .51
BCONS(06) .50
BCONS(07) .51
BCONS(08) .55
BCONS(09) .57
BCONS(10) .56
BCONS(11) .58
BCONS(12) .54
12 Monthly means of daily incoming radiation, RADMET(i)
RADMET(01) 12.0
RADMET(02) 12.0
RADMET(03) 12.0
RADMET(04) 12.0
RADMET(05) 12.0
RADMET(06) 12.0
RADMET(07) 12.0
RADMET(08) 12.0
RADMET(09) 12.0
RADMET(10) 12.0
RADMET(11) 12.0
RADMET(12) 12.0
1 Penman equation option for either S-tank (0) or A-pan (1) equivalent evaporation
SAPANC 0

12 Smoothed mean monthly A-pan/S-pan ratios, SARAT(i)
SARAT(01) 1.26
SARAT(02) 1.25
SARAT(03) 1.26
SARAT(04) 1.27
SARAT(05) 1.30
SARAT(06) 1.34
SARAT(07) 1.36
SARAT(08) 1.37
SARAT(09) 1.35
SARAT(10) 1.32
SARAT(11) 1.28
SARAT(12) 1.27
1 Pan adjustment option
PANCOR 0
12 Monthly pan adjustment factors, CORPAN(i)
CORPAN(01) 1.26
CORPAN(02) 1.25
CORPAN(03) 1.26
CORPAN(04) 1.27
CORPAN(05) 1.30
CORPAN(06) 1.34
CORPAN(07) 1.36
CORPAN(08) 1.37
CORPAN(09) 1.35
CORPAN(10) 1.32
CORPAN(11) 1.28
CORPAN(12) 1.27
1 # Level of soils information
PEDINF 1
1 Soils texture information
ITEXT 5
1 Soil physics based infiltration/soil water redistribution option
REDIST 0
1 Rainfall intensity distribution type
IRDIST 1
1 Soil thickness information
PEDDEP 1
10 Soils information (adequate)

DEPAHO .30
DEPBHO .45
WP1 .110
WP2 .110
FC1 .290
FC2 .290
PO1 .43
PO2 .43
ABRESP 0.60
BFRESP 0.62
1   Shrink-swell   soils
option
ICRACK 0
2 Initial values of soil
water retention constants
SMAINI 0.170
SMBINI 0.170
1 Option for statistical
analysis of soil water
regime
SWLOPT 0
6   Soil   water   content
thresholds for A horizon,
SWLA_M(i)
SWLA_M(01) .11
SWLA_M(02) .11
SWLA_M(03) .12
SWLA_M(04) .16
SWLA_M(05) .21
SWLA_M(06) .34
6   Soil   water   content
thresholds for B horizon,
SWLBM(i)
SWLBM(01) .11
SWLBM(02) .12
SWLBM(03) .12
SWLBM(04) .17
SWLBM(05) .22
SWLBM(06) .33
1 #   Level of land cover
information
LCOVER 1
1   Land   cover   number
information
CROPNO 3020700
1   Determination   of
canopy interception loss
INTLOS 1
1   Leaf   area   index
information

LAIND 2
12   Monthly   means   of
crop coefficients, CAY(i)
CAY(01) .78
CAY(02) .74
CAY(03) .72
CAY(04) .74
CAY(05) .81
CAY(06) .85
CAY(07) .90
CAY(08) .92
CAY(09) .93
CAY(10) .91
CAY(11) .88
CAY(12) .82
12 Monthly means of leaf
area index, E1M(i) - for
grown sugarcane
ELAIM(01) 6.0
ELAIM(02) 5.5
ELAIM(03) 5.0
ELAIM(04) 4.0
ELAIM(05) 3.0
ELAIM(06) 2.5
ELAIM(07) 2.5
ELAIM(08) 3.0
ELAIM(09) 4.0
ELAIM(10) 5.0
ELAIM(11) 5.5
ELAIM(12) 6.0
12 Canopy interception
loss (mm) per rainday,
VEGINT(i)
VEGINT(01) 1.8
VEGINT(02) 1.8
VEGINT(03) 1.8
VEGINT(04) 1.8
VEGINT(05) 1.8
VEGINT(06) 1.8
VEGINT(07) 1.8
VEGINT(08) 1.8
VEGINT(09) 1.8
VEGINT(10) 1.8
VEGINT(11) 1.8
VEGINT(12) 1.8
12 Fraction of active root
system in topsoil horizon,
ROOTA(i)
ROOTA(01) .65
ROOTA(02) .65

ROOTA(03) .65
ROOTA(04) .65
ROOTA(05) .65
ROOTA(06) .65
ROOTA(07) .65
ROOTA(08) .65
ROOTA(09) .65
ROOTA(10) .65
ROOTA(11) .65
ROOTA(12) .65
1 Effective total rooting
depth
EFRDEP 0.0
2   Total   evaporation
control variables
EVTR 2
FPAW 0
1 Fraction of PAW at
which plant stress sets in
CONST 0.2
1   Critical   leaf   water
potential
CRLEPO -1500.0
1 Option for enhanced
wet canopy evaporation
FOREST 0
1 Option for simulation
under   enhanced
atmospheric CO_2 levels
CO2TRA 0
1   Mean   temperature
threshold (øC) for active
growth to take place
TMPCUT 10.0
1   Unsaturated   soil
moisture redistribution
IUNSAT 0
1 Option for lysimeter
routine
LYSIM 0
7 Streamflow simulation
control variables
QFRESP 0.60
COFRU 0.001
SMDDEP 0.18
IRUN 1
ADJIMP .000
DISIMP .000
STOIMP 1.00

12 Coefficient of initial abstraction, COIAM(i)
COIAM(01) .35
COIAM(02) .35
COIAM(03) .35
COIAM(04) .35
COIAM(05) .30
COIAM(06) .30
COIAM(07) .30
COIAM(08) .30
COIAM(09) .35
COIAM(10) .35
COIAM(11) .35
COIAM(12) .35
1 #   Peak discharge : option
PEAK 1
2 Peak discharge : control variables (I)
LAG 2
SLOPE 3.5
2 Peak discharge : control variables (II)
HYLEN 72114.
CNII 75.
1 Peak discharge : control variables (III)
XI30 58.4
1 Peak discharge : control variables (IV)
TCON .00
1 #   Sediment yield : option
MUSLE 1
6 Sediment yield : variables (I)
SOIFC1 .5
SOIFC2 .5
ELFACT 0.65
PFACT 0.1
ICOVRD 0
SEDIST .45
2 Sediment yield : variables (II)
ALPHA 8.934
BETA 0.56
12 Means of monthly cover factors, COVER(i)
COVER(01) .07
COVER(02) .07

COVER(03) .07
COVER(04) .07
COVER(05) .07
COVER(06) .07
COVER(07) .07
COVER(08) .07
COVER(09) .07
COVER(10) .07
COVER(11) .07
COVER(12) .07
3 #   Hydrograph routing input
XMUSK 0.
XAK 0.
FTINC 0.0
5 Hydrograph routing input : channel dimensions (I)
ISHAPE 1
FDEPTH 0.
ROUGHN 0.
CSLOPE .0
CHLEN 0.0
1 Hydrograph routing input : channel dimensions (II)
BWIDTH .0
1 Hydrograph routing input : channel dimensions (III)
ZSIDE .0
1 Hydrograph routing input : channel dimensions (IV)
TWIDTH .0
2 Wetland input options
IVLEI 0
CAPM3S 1.2
1 #   Shallow groundwater : analysis option
IGWATR 0
6 Shallow groundwater : variables for vertical flow
IZTEXT 5
POIZ .466
FCIZ .276
WPIZ .127
DEPIMP 7
DEPROT 900

8 Shallow groundwater : variables for lateral flux
VALUEK 250.0000
ALTIS 1035.0
ALTIR 1026.0
ALTH 1044.0
DISTR 800.0
DISTA 1600.0
SIZEHA 58
OBSWTD 4.659
2 #   Irrigation : option
IRRIGN 0
WRIRR 0
12 Irrigation : month for application, IRRMON(i)
IRRMON(01) 1
IRRMON(02) 1
IRRMON(03) 1
IRRMON(04) 1
IRRMON(05) 1
IRRMON(06) 1
IRRMON(07) 1
IRRMON(08) 1
IRRMON(09) 1
IRRMON(10) 1
IRRMON(11) 1
IRRMON(12) 1
12 Irrigation : areas, HAIRR(i)
HAIRR(01) 0.
HAIRR(02) 0.
HAIRR(03) 0.
HAIRR(04) 0.
HAIRR(05) 0.
HAIRR(06) 0.
HAIRR(07) 0.
HAIRR(08) 0.
HAIRR(09) 0.
HAIRR(10) 0.
HAIRR(11) 0.
HAIRR(12) 0.
12 Irrigation : catchment rainfall adjustment, PPTIRR(i)
PPTIRR(01) 1.00
PPTIRR(02) 1.00
PPTIRR(03) 1.00
PPTIRR(04) 1.00
PPTIRR(05) 1.00
PPTIRR(06) 1.00

PPTIRR(07) 1.00
PPTIRR(08) 1.00
PPTIRR(09) 1.00
PPTIRR(10) 1.00
PPTIRR(11) 1.00
PPTIRR(12) 1.00
12 Irrigation : coefficient of initial abstractions, COIAIR(i)
COIAIR(01) .30
COIAIR(02) .30
COIAIR(03) .30
COIAIR(04) .30
COIAIR(05) .30
COIAIR(06) .30
COIAIR(07) .30
COIAIR(08) .30
COIAIR(09) .30
COIAIR(10) .30
COIAIR(11) .28
COIAIR(12) .25
1 Irrigation : soils information (I)
ITEXTI 8
1 Irrigation : soil information (II)
IRRPED 0
3 Irrigation : soil information (III)
WPIR .200
FCIR .300
POIR .450
12 Irrigation : crop coefficients, CAYIRR(i)
CAYIRR(01) .80
CAYIRR(02) .80
CAYIRR(03) .80
CAYIRR(04) .70
CAYIRR(05) .60
CAYIRR(06) .50
CAYIRR(07) .50
CAYIRR(08) .50
CAYIRR(09) .60
CAYIRR(10) .70
CAYIRR(11) .80
CAYIRR(12) .80
12 Irrigation : interception loss, DINTIR(i)
DINTIR(01) 1.40

DINTIR(02) 1.40
DINTIR(03) 1.40
DINTIR(04) 1.40
DINTIR(05) 1.20
DINTIR(06) 1.00
DINTIR(07) 1.00
DINTIR(08) 1.20
DINTIR(09) 1.30
DINTIR(10) 1.40
DINTIR(11) 1.40
DINTIR(12) 1.40
2 Irrigation : rooting characteristics
RDMAX 1.00
RDUP .80
4 Irrigation : total evaporation control variables
CCOV .65
CCMAX 0.70
PGRDM 90.0
CRLW -1200.0
12 Irrigation : mode of scheduling, ISCHED(i)
ISCHED(01) 1
ISCHED(02) 1
ISCHED(03) 1
ISCHED(04) 2
ISCHED(05) 2
ISCHED(06) 2
ISCHED(07) 2
ISCHED(08) 2
ISCHED(09) 2
ISCHED(10) 1
ISCHED(11) 1
ISCHED(12) 1
12 Irrigation : scheduling control variables (I), STPRO(i)
STPRO(01) .50
STPRO(02) .50
STPRO(03) .50
STPRO(04) .50
STPRO(05) .50
STPRO(06) .50
STPRO(07) .50
STPRO(08) .50
STPRO(09) .50
STPRO(10) .50
STPRO(11) .50

STPRO(12) .50
2 Irrigation : scheduling control variables (II)
IRAMT 21
IRCYC 7
1 Irrigation : scheduling control variables (III)
RLIM 12.0
2 Irrigation : application control variables
ILOS 1
IRUNIT 0
12 Irrigation : scheduling control variables (IV), RASTO(i)
RASTO(01) 16.0
RASTO(02) 16.0
RASTO(03) 16.0
RASTO(04) 16.0
RASTO(05) 16.0
RASTO(06) 16.0
RASTO(07) 16.0
RASTO(08) 16.0
RASTO(09) 16.0
RASTO(10) 16.0
RASTO(11) 16.0
RASTO(12) 16.0
3 Irrigation : supply losses
CONLOS .05
FAMLOS .05
EVWIN .15
1 Irrigation : catchment supplying water
IRSPLY 0
3 Irrigation : water supply information
IRRAPL 1
INCELL 1
UPSTIR 1
1 Option for domestic abstractions
IDOMR 0
12 Domestic abstractions per day * 1000, DOMABS(i)
DOMABS(01) 1.0
DOMABS(02) 2.0
DOMABS(03) 3.0
DOMABS(04) 3.0

DOMABS(05) 3.0
DOMABS(06) 3.0
DOMABS(07) 3.0
DOMABS(08) 3.0
DOMABS(09) 3.0
DOMABS(10) 3.0
DOMABS(11) 3.0
DOMABS(12) 12.7
1 #   Reservoir yield analysis : option
RESYLD 0
8 Reservoir yield analysis : control variables (I)
DAMCAP 0.
SURFAR 0.
ARCAP 1
QNORM .0
SEEP .0
PCCDAM 100.
PERDAM 50.0
DEDSTO 0.0
1 Reservoir yield analysis : control variables (II)
WIDTH 1.00
2 Reservoir yield analysis : control variables (III)
RESCON 7.20
RESEXP .77
4 Hydrograph routing : options
SWIDTH 1.00
CDISCH .50
RTINC 30.0
IRESUP 10
12   Reservoir   yield analysis : additions and abstractions   (I),
PANDAM(i)
PANDAM(01) .67
PANDAM(02) .60
PANDAM(03) .80
PANDAM(04) .80
PANDAM(05) .86
PANDAM(06) .86
PANDAM(07) .81
PANDAM(08) .81
PANDAM(09) .74
PANDAM(10) .73
PANDAM(11) .83
PANDAM(12) .70

12   Reservoir   yield analysis : additions and abstractions   (II),
PUMPIN(i)
PUMPIN(01) .00
PUMPIN(02) .00
PUMPIN(03) .00
PUMPIN(04) .00
PUMPIN(05) .00
PUMPIN(06) .00
PUMPIN(07) .00
PUMPIN(08) .00
PUMPIN(09) .00
PUMPIN(10) .00
PUMPIN(11) .00
PUMPIN(12) .00
12   Reservoir   yield analysis : additions and abstractions   (III),
XDRAFT(i)
XDRAFT(01) .00
XDRAFT(02) .00
XDRAFT(03) .00
XDRAFT(04) .00
XDRAFT(05) .00
XDRAFT(06) .00
XDRAFT(07) .00
XDRAFT(08) .00
XDRAFT(09) .00
XDRAFT(10) .00
XDRAFT(11) .00
XDRAFT(12) .00
1 Off-channel storage : option
IOFCHW 0
5 Off-channel storage : pump & pumping control variables
IPCAP 50
IPNUM 4
IPHRS 24
IPCPMN 25
IFLDLM 2000
2 #   Crop yield : option
CROP 0
WRTYLD 0
1 Crop yield : method of determining   planting dates
PLDATE 1

2 Crop yield : planting dates
ISTDAY 1
ISTMO 11
1 Crop yield : length (days) of growing season
LENGTH 95
1 Crop yield : ACRU maize yield model option (I)
HKSINF 0
8 Crop yield : ACRU maize yield model option (II)
YLDPOT 3.0
ELAMD1 .5
ELAMD2 .5
ELAMD3 .5
IPRD1 1
IPRD2 2
IPRD3 3
IPRD4 4
3 Crop yield : ACRU sugar cane yield options
IRRDRY 0
IREG 1
NRAT 2
1 Crop yield : ACRU wheat yield option (I)
RASINF 0
7 Crop yield : ACRU wheat yield option (II)
WTPOT 3.5
WLAMD1 .5
WLAMD2 .5
WLAMD3 .5
IWPRD1 10
IWPRD2 20
IWPRD3 31
1 Crop yield : economic analysis option
IEANAL 1
2 Crop yield : economic analysis input variables
SPRICE 1000.
BRKEVN 40.
1 #   Frequency analysis : extreme values
IEVD 0

2 Frequency analysis : extreme events variable selection
IRANK 1
IPRTRK 0
12 Frequency analysis : months to be included in stats, MOSTAT(i)
MOSTAT(01) 1
MOSTAT(02) 1
MOSTAT(03) 1
MOSTAT(04) 1
MOSTAT(05) 1
MOSTAT(06) 1
MOSTAT(07) 1
MOSTAT(08) 1
MOSTAT(09) 1
MOSTAT(10) 1
MOSTAT(11) 1
MOSTAT(12) 1
2 Frequency analysis : probability distribution selection
SERIES 1
EVD 1
1 Land Segment ID
LSEGID 1_1
12 Fraction of active root system in second soil horizon ROOTB(i)
ROOTB(01) 0.35
ROOTB(02) 0.35
ROOTB(03) 0.35
ROOTB(04) 0.35
ROOTB(05) 0.35
ROOTB(06) 0.35
ROOTB(07) 0.35
ROOTB(08) 0.35
ROOTB(09) 0.35
ROOTB(10) 0.35
ROOTB(11) 0.35
ROOTB(12) 0.35
12 Monthly percentages of surface cover (mulch etc) PCSUCO(i)
PCSUCO(01) 100.
PCSUCO(02) 100.
PCSUCO(03) 100.
PCSUCO(04) 100.
PCSUCO(05) 100.

PCSUCO(06) 100.
PCSUCO(07) 100.
PCSUCO(08) 100.
PCSUCO(09) 100.
PCSUCO(10) 100.
PCSUCO(11) 100.
PCSUCO(12) 100.
2 Reservoir ID and initial storage volume
DAMID Dam_1
DAMST 0.0
2 Channel reach options
CHANL 1
CHANID River_1_1
1 Channel Node ID
NODEID ChannelNode_1_1
1 Irrigated Area ID
IRRAID IrrigArea_1
1 Irrigated crop number information
IRCROP 1000001
1 Irrigation soil water management depth
IRMDEP 0.8
1 Irrigation Water Supply Owner
IRROWN null
3 Irrigation Water Supply Path
IRPATH(01) Dam_1
IRPATH(02) WaterTrans_1
IRPATH(03) IrrigArea_1
1 Irrigated Area Transfer Priority
IRRTP 1
2 Channel reach inflow file info
CRINFT 2
CRINFN blank
2 Channel reach natural time series flow file info
NTSFT 2
NTSFN blank
2 Dam reach inflow file info
DRINFT 2
DRINFN blank

3 Eucalyptus Grandis growing season
IEGSTY 1909
IEGSTM 10
IEGNO 96
2 Adjunct impervious area
ADJID AdjImpArea_1
ADJIA 0.0
2 Disjunct impervious area
DISID DisImpArea_1
DISIA 0.0
1 Surface flow option
SFLOW 1
1 Nutrient option switch variable
NUTRI 1
1 Acru_Veld option switch variable
AVELD 0
1 Andrew Butler's option switch variable
ANDREW 0
1 Riparian Zone option
IRIPARIAN 0
1 % alien infestation in the riparian zone
PcRipInfest 100.0
1 Salinity option switch variable
SALINITY 0
2 Channel reach salt input file information
CRINFSAT 2
CRINFSAN blank
2 Reservoir salt input file information
DRINFSAT 2
DRINFSAN blank
1 Andrew Butler's option switch variable
ANDREW 0
1 Riparian Zone options
IRIPARIAN 0
1 Long-term mean temp
LTMTMP 15.0
4 Rain and irrigation nutrient concentrations
RNCONC 8.0

RPCONC 0.3
INCONC 0.
IPCONC 0.
3   Plant residue initial values
PLRBMAS 9595.
PLRENS 37.0
PLREPS 10.0
2   Soil P sorption characteristics
PSRPCD 2
SSACLY 20.0
12 Fraction of active root system in soil surface layer ROOTSS(i)
ROOTSS(01) 0.0
ROOTSS(02) 0.0
ROOTSS(03) 0.0
ROOTSS(04) 0.0
ROOTSS(05) 0.0
ROOTSS(06) 0.0
ROOTSS(07) 0.0
ROOTSS(08) 0.0
ROOTSS(09) 0.0
ROOTSS(10) 0.0
ROOTSS(11) 0.0
ROOTSS(12) 0.0
6   Soil surface layer characteristics
smsini0.002035
DEPSS 0.01
WPSS 0.123
FCSS 0.272
POSS 0.438
SARESP 1.0
SMSINI 0.003
7   Soil surface layer characteristics
OMSS 1.2
BDSS 1.65
BSATSS 62.0
CACOSS 0.5
PHSS 4.5
CLSS 11.0

SLTSS 22.7
11   Soil surface layer initial residue and nutrient flux record values
STNSS 1100.3
ACNSS 529.4
STPSS 717.8
ACPSS 179.5
OHPSS 1042.3
AMMNSS 3.3
NITNSS 16.5
LABPSS 35.2
PLBMASS 9595.0
PLRSNS 37.0
PLRSPS 10.0
7   Soil horizon 1 characteristics
OM1 1.2
BD1 1.65
BSAT1 62.0
CACO1 0.5
PH1 4.5
CL1 11.0
SLT1 22.7
11   Soil horizon 1 initial residue and nutrient flux record values
STN1 1100.3
ACN1 529.4
STP1 717.8
ACP1 179.5
OHP1 1042.3
AMMN1 3.3
NITN1 16.5
LABP1 35.2
PLBMAS1 9595.0
PLRSN1 37.0
PLRSP1 10.
7   Soil horizon 2 characteristics
OM2 0.67
BD2 1.65
BSAT2 83.0
CACO2 0.5

PH2 5.83
CL2 18.67
SLT2 24.29
11   Soil horizon 2 initial residue and nutrient flux record values
STN2 653.08
ACN2 234.6
STP2 180.37
ACP2 45.09
OHP2 1040.67
AMMN2 3.3
NITN2 16.43
LABP2 15.50
PLBMAS2 9595.0
PLRSN2 37.0
PLRSP2 10.0
3 Acru_NP 0_Vegetation variables (EVTR=1&2)
V0AREA 1.0
V0DIG   1.0
V0POTLAI 6.0
3 Acru_NP 0_Vegetation variables (EVTR=2)
V0COMP 0
V0DENS 1.0
V0GLAI 6.0
2 Acru_NP 0_Vegetation growth stress variables
V0INST 1
V0IWST 1
3   Acru_Veld 0_Vegetation   root fractions V0ROOT(i)
V0ROOT(1_1.1_CSoil.1 _CSoilSurfaceLayer) 0.01
V0ROOT(1_1.1_CSoil.1 _CHorizon) 0.75
V0ROOT(1_1.1_CSoil.2 _CHorizon) 0.24
1 At end of file
STOP   1