Informing the Responses of Water Service Delivery Institutions to Climate and Development Changes: A Case Study in the Amatole Region, Eastern Cape

Report to the
Water Research Commission

by

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EXECUTIVE SUMMARY

This report has been generated by the Water Research Commission (WRC) funded project *Developing Climate Change Adaptation Measures and Decision-Support System for Selected South African Water Boards* (Project No. K5/2018).

Introduction

Reports by the Intergovernmental Panel on Climate Change have placed emphasis on freshwater resources, in particular their vulnerability, and the development of management and adaptation measures, in recognition that water resources are fundamental to basic human needs in addition to facilitating present and future planned development projects. Few projects have recognised that climate change adds an additional dimension of concern to the range of issues (such as development, mismanagement and pollution) that are already causing the deterioration of South African water resources. The climate in South Africa is naturally highly variable, and this, along with compromised governance, results in South Africa being very vulnerable. The WRC-funded project aimed to quantify changes associated with near future (2046-2065) climate change (using the Special Report on Emissions Scenarios (SRES) A2 emission scenario) and socio-economic development, with inclusion of the uncertainty linked to these changes, in order to develop a decision support system that incorporates these uncertainties. The aims for the project were:

1. To identify potential impacts and threats to sustainable water services delivery posed by climate change, as well as the uncertainties associated with these, with regards to changes in water quantity, water quality and socio-economic developments. This will be done through application of existing or newly developed estimation tools that can be used to convert downscaled Global Climate Models (GCM) output data to likely changes (including uncertainties) in the variables that impact directly on the operations of water boards (water quantity and quality). Part of the estimation process will include timescales of the expected changes.
2. Develop a methodology for assessing risks and vulnerabilities (including uncertainties in predictions) to climate change for Water Boards and their capacity to fulfil their mandate on water services delivery.
3. Develop a strategy and monitoring network for water audits in order to monitor indicators of change.
4. Derive Thresholds of Potential Concerns (TPCs) for water quality and quantity issues for Water Boards related to raw and potable water, discharges, pricing effects, etc. based on the outputs of the climate models.
5. Develop a decision-support framework for an adaptive management strategy to assess and modify water services delivery and development plans of the Water Boards in terms of infrastructure repair and developments, water conservation and demand management, water pricing changes and other associated issues.

Aim 1 is addressed in Chapters 4-6 and Appendix B that present the results of modelling using the Pitman and the Water Evaluation and Planning Model (WEAP, developed by the Stockholm Environment Institute SEI) applications with inputs of the downscaled GCMs and the socio-economic development uncertainties. Aim 2 was not met by the project due to the changed focus in the second year towards the development of the in-house water quality model (WQSAM) on which the decision support system is being built. The motivation for this change was the limitations of WEAP encountered during the water quality modelling stage 1. The monitoring network for Aim 3 is given in Chapter 8 (current network) and Chapter 10 (recommendations). The TPCs required to achieve Aim 4 were derived by the project team in consultation with the reference group members (particularly input from Amatola Water and DWA) and these are given in Chapter 2. Achieving Aim 5, the Decision Support System, which is in a draft stage at present, will be based on the in-house water quality model (WQSAM) and it will use the developed TPCs (Chapter 2).

The project commenced with interaction with both the Amatole and Caledon system teams, but following the first workshop, the project team was not able to renew discussions with the Bloem Water Board. Thus, the report focuses primarily on the Amatole system, for which modelling on hydrology, water availability and use, and water quality was conducted. The climate change uncertainty estimation that was performed for the Caledon system is also presented here.

The focus of the project has been on near future (2046-2065) climate change predictions using nine climate change models, for which the downscaled climate data were made available by the Climate Systems Analysis Group (CSAG) based at the University of Cape Town. The reason for the focus on the near future period is primarily because the climate change predictions for the far future (2081-2100) period are expected to include even greater uncertainty; thus, it would be more difficult for water services delivery institutions to plan for the far future period. It is also believed that planning for the near future period will build resilience and knowledge of the system that will prepare the water services delivery institutions for the far future.

Summary and main findings

The focus of the project has been on the water supply area of two moderate size water boards, in particular, the Amatole system (for the Amatola Water Board area) and the Modder and Caledon River systems (for the Bloem Water Board area). As the project focussed on uncertainty estimation, the climate model data consisted of downscaled daily rainfall plus maximum and minimum temperatures from nine GCMs using the SRES A2 emission scenario. The nine GCMs chosen for use were selected by default as these are the downscaled climate data available from the CSAG group. The analyses were conducted for the present day situation (year 2005) and for the near future (2046-65) using the Pitman model and the WEAP model. Hydrological modelling was conducted for both the systems – Amatole and Caledon. However, the focus of the WEAP modelling, which incorporated both the downscaled GCMs and projections for socio-economic development, was on the Amatole system only, as the data required for system level modelling was readily available. In comparison, limited information is available in the readily available literature for the Caledon system.

The project rationale, background information to climate change in the context of water resources in South Africa, and an introduction to decision-making risk and uncertainties is presented in Chapter 1. This is presented in the context of developing responses (or adaptation strategies) to future climate and development changes, which involve three key issues: the institutional framework in which responses can be developed; the instruments for developing the responses and; the information that is available to inform the responses.

The background information for the Amatole (Buffalo River) and Caledon River systems is given in Chapter 2. Issues related to water quantity and water quality are discussed for the Amatole system, which has been the major focus of the project. These form the basis of the TPCs, which have been used to develop the draft decision support system for the Amatole system.

An innovative technique that was developed in the project was that for a ‘skill’ measurement of a GCM (see Chapter 4). Based on the concept that certain GCMs are more ‘skilful’ than others, it was hoped that the output of this development would be reduction of the uncertainty in near future climate predictions. The ‘skill’ analysis indicated that four GCMs (CCCMA, GFDL, MPI and MRI) were more ‘skilful' than the others. However, the results found very small changes with respect to the uncertainty in future runoff predictions made by the Pitman model. There was only minor reduction in the width of the uncertainty bands noted.

The WEAP model was used to facilitate system level modelling. Chapter 3 discusses this model along with a selection of other models that have been used or considered for use in South Africa. WEAP is an off-the-shelf system level model, whose application to the Amatole system is presented in Chapter 5. The model was calibrated using the present day water discharge data (1980-2005) obtained from the Department of Water Affairs (DWA) stream gauges. The WEAP water use and availability results are presented as three major sections. The model was first run using three socio-economic development predictions (i.e. Lower, Intermediate and Upper Development scenarios) for the near future (years 2046-2065) under the hydrological variability for present climate (years 1921-2005). The population water requirements in the near future were the major contributor to the uncertainty in the total water requirements for the Buffalo area. These set of model runs allowed assessment of the Amatole system's ability to meet future water demands under present day hydrological variability. This was followed by model runs using the near future climate predictions (years 2046-2065) for rainfall and evapotranspiration using nine downscaled GCMs with water requirements fixed at present day needs. This allowed analysis of the Amatole system's ability to meet the present day water demands under the nine climate change scenarios, so as to assess the impacts of climate change in isolation. Finally, the near future water requirements were combined with near future climate change scenarios, and the combined uncertainty was assessed and compared with the first two sets of model runs. The results indicate that although the present infrastructure is sufficient to meet present day demands, it cannot meet the water user demands under the Intermediate and Upper Development scenarios particularly in the Lower Amatole area. Therefore, additional scenarios with increased water treatment works (WTW) production capacity, upgraded waste water treatment works (WWTW) capacity, and water transfers from the Wriggleswade Dam were run for the nine climate change models in combination with the Intermediate and Upper Development scenarios. The results indicate that with these upgrades, there should be sufficient water to meet the Intermediate Development Scenario demands in the near future, but water deficits will still occur if the Upper Development Scenario becomes reality. Environmental flows have however, not been included in these scenarios, as only preliminary estimations have been conducted to date, and these are expected to be updated in the very near future. Thus, the results presented for water deficit should be considered to be conservative estimates.

The use of WEAP for modelling the water quality of the Amatole system was next investigated (Chapter 6). The limitations encountered during this process led to the reference group approving the development of the in-house Water Quality Systems Assessment Model (WQSAM) which forms the basis of the draft decision support system that is being drafted (Chapter 7).

The main recommendation that has come out of the investigation of the Amatole system in this project has been the assessment of the present monitoring network (presented in Chapter 8) in terms of available data for modelling and for monitoring future changes in the system. The recommendations generated out of this process (Chapter 10) are repeated here. A major recommendation that needs highlighting is the need for coordinated planning and management (i.e. an integrated monitoring network) in order to deal with the uncertainty resulting from near future development and climate scenarios.

The following specific recommendations for water quantity monitoring are made for the Amatole system based on the analysis conducted in this project:

- Reinstating the stream flow gauging station on the iZele River (R2H007) in order to monitor inflow into the Buffalo River. These data would be useful for modelling inflows and change in flows when removal of alien vegetation is undertaken.

- Consider installing a stream flow gauging station above the Nahoon Dam in order to monitor flow (natural flow and flow under water transfers from Wriggleswade Dam). Although transfers from the Wriggleswade Dam are monitored in the tunnels, a stream flow gauge would assist with calculation of the actual flows in the river reach under transfer conditions, which would be useful for conducting a Reserve in future and for modelling the Nahoon River more accurately.
- Monitor the estuary water levels for the Nahoon River. This would require accounting for both flow and tidal effects, which admittedly is not an easy exercise.
- Monitoring and modelling of evaporation from dams for reducing the present day and future climate uncertainty when modelling reservoir storage.
- Monitor and collate water use data over time in terms of water requirements of various users, losses in the distribution and bulk water system. Notably, the population water requirements are the major contributor to the uncertainty in the total water requirements in the future (Figure 5.10), and thus, reducing the uncertainty in the socio-economic development demands will go a long way in managing the system sustainably.
- A second important consideration in regards to the socio-economic data is that the Reconciliation Strategy (DWAF, 2008) data that were used in the present project are for the Upper, Middle and Lower Amatole system, and are not broken down by areas and social classes. Obtaining breakdown in water use data and the trajectory in the future will assist in finding appropriate management solutions for the water requirements under future development.
- Lastly, as has been noted above in the report, environmental flow requirements (that are only available as preliminary calculations that are in the process of re-evaluation) have not been included in the model runs. Thus, the results presented here for water deficits are conservative, and updates to the environmental flows will require follow-up and management.

The following recommendations for water quality monitoring are made for the Amatole system:

- Within all reservoirs: besides the water quality variables routinely measured by DWA, inclusion of Chlorophyll a, microbial water quality, yearly assessments of dam capacity, turbidity, vertical profiles of DO, temperature, salinity, nutrients and the toxin profile of sediments would be useful for modelling and management.
- Monitor effluent return flows for water quality in order to meet environmental and user water quality objectives.
- Monitor estuarine water quality for meeting future environmental water quality objectives.
- In all river reaches: besides water quality variables routinely measured by DWA, inclusion of turbidity in all river monitoring gauges, and microbial water quality within tributaries leading to reservoirs is recommended.
- In WWTWs, besides the water quality variables routinely measured by DWA, inclusion of NO_3, problematic toxins and microbial water quality is suggested.

The final two chapters of this report revisit and elaborate on the instruments and data that are essential for appropriate responses to climate and development changes expected in the near future in terms of the project results. Various adaptation measures, some that fall under good governance, are suggested including:

- Integrated land and water management.
- Building resilience.
- Prioritisation of measures and follow through on the reconciliation strategy, Integrated Development Plans, Water Services Development Plans and the Eastern Cape Provincial Spatial Development Plan.
- Maintenance (essential part of good governance).

- Monitoring (essential to reduce the uncertainty in the predictions).
- Water literacy and training.
- Use of the Risk and Vulnerability Atlas to identify expected changes and prioritise adaptation interventions.
- Dialogue with agencies at local, regional, national and international level (essential to learn from and to share experiences and knowledge).

Finally, Appendices A, B and C present a summary of the work that has been conducted by an MSc student (Bret Whiteley), a PhD student (Thabiso Mohobane) and an Honours student (Kelly Stroebel), who have been partially funded by this project. A list of project outputs is given in Appendix D.

Note about Amatole spellings

Note that there are various spellings of “Amatole”, including Amatole, Amathole and Amatola, in the names of various organisations (such as Amatole Bulk Water Supply System, Amatola Water Board, Amathole District), and in the literature and report titles. These have been followed, thus the various spellings in this report are not a mistake.

ACKNOWLEDGEMENTS

The downscaled climate data for the nine GCMs were gratefully received from the Climate Systems Analysis Group (CSAG) based at the University of Cape Town. Without these data, the water quantity and quality analyses for the near future would not have been possible. The project team acknowledges the assistance of the employees of the Amatola Water Board, specifically Dr Nikite Muller and Mr Craig Thompson, who assisted with providing data, ideas and their involvement in the annual workshops and reference group meetings. Mr Louis van Oudtshoorn of Bloem Water Board was present and contributed during the first annual workshop in 2010. Additionally, Mrs Isa Thompson from the DWA and Mr Wayne Ketteringham of UWP Consulting provided valuable input and documents throughout the project. The data for reservoir storage was kindly provided by Mr Cobus Ferreira of the DWA East London. Additional water quantity and quality data were obtained from the DWA.

Finally, the project team would like to thank all the reference group members, who donated their time and knowledge in assisting the project to meet its aims, in their flexibility to support new ideas and change of direction of the project, and in introducing the team to different approaches to examining issues:

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ACRONYMS

ACRU	Agricultural Catchments Research Unit
ADM	Amathole District Municipality
AWB	Amatola Water Board
BCM	Buffalo City Municipality
BLASRoute	Basin Land Area to Stream Routing
BUCSHELL	Basin Unique Cell Shell program
CCCMA	Canadian Centre for Climate Modelling and Analysis
CNRM	France Centre National de Recherches Meteorologiques
CSAG	Climate Systems Analysis Group
CSIRO	GCM generated by Australian CSIRO Atmospheric Research
DEA	Department of Environmental Affairs
DSS	Decision Support System
DWA	Department of Water Affairs
DWAF	Department of Water Affairs and Forestry
DYRESM	Dynamic Reservoir Simulation Model
EAAMOD	Everglades Agricultural Area Model
EC	Electrical Conductivity
EWR	Environmental Water Requirements
FDC	Flow Duration Curves
GCM	Global Climate/Circulation Models
GFDL	GCM generated by USA NOAA Geophysical Fluid Dynamics Lab
GIS	Geographical Information System
GISS	GCM generated by USA Goddard Institute for Space Studies
GLEAMS	Groundwater Loading Effects of Agricultural Management Systems
IMPAQ	Impoundment / River Management and Planning Assessment Tool for Water Quality Simulation
IPCC	Intergovernmental Panel on Climate Change
IPSL	France Institut Pierre Simon Laplace
IWRM	Integrated Water Resource Management
MIUB	Germany Meteorological Institute of the University of Bonn
MPI	Max-Planck Institute for Meteorology
MRI	Japan Meteorological Research Institute
NEAP	Nutrient Enrichment Assessment Protocol
PE	Potential Evapotranspiration
RCM	Regional Climate Models
SRES	Special Report on Emissions Scenarios
TDS	Total Dissolved Salts
TPCs	Thresholds of Potential Concerns
WAM	Watershed Assessment Model
WEAP	Water Evaluation and Planning Model
WMA	Water Management Area
WQSAM	Water Quality Systems Assessment Model
WRPM	Water Resources Planning Model
WRYM	Water Resources Yield Model
WR90	Water Resources Survey 1990
WR2005	Water Resources Survey 2005
WTW	Water Treatment Work
WWTW	Waste Water Treatment Work

CHAPTER 1. INTRODUCTION

Developing responses (or adaptation strategies) to future climate and development changes involves three key issues: 1) the *institutional framework* in which responses can be developed; 2) the *instruments for developing the responses* and; 3) the *information that is available to inform the responses*. The institutional framework includes the national strategies and legislative framework within which the water services delivery institutions operate, as well as the local framework and the specific functions of the individual institutions. In some areas, the functions of water services delivery are the sole responsibility of a water services authority, such as a municipality, while in other areas (such as the Amatole region), the functions and responsibilities are shared between the water services authority and a water board. The institutional framework therefore, includes the management relationships between these entities. In the Amatole region, the responsibilities are shared between Buffalo City Municipality (BCM) and Amatola Water.

The instruments for developing responses include the compilation of Water Services Development Plans (WSDP), Eastern Cape Provincial Spatial Development Plan (ECPSDP), and Integrated Development Plans (IDP), developed at the local level as well as the National Water Resources Strategy, the National Climate Change Response Strategy and the Water Resources Reconciliation strategies, developed by the Department of Water Affairs with national, regional and local inputs.

Any planning instrument must be informed by the most up-to-date and reliable information that is generated from the analysis of the available historical observed data and the application of models or estimation methods to fill in gaps in the observed data. With respect to developing responses to future situations, all of the information generated by prediction models is necessarily uncertain (we cannot predict the future with certainty). The generation of this type of information and its use for planning and decision-making represents the main objective of this report. Resultantly, the dominant issue is the need to recognise the uncertainties in future predictions and ensure that they are part of any planning instruments such that the links can be made between uncertain information and decision-making risk.

The overall objective that must be the focus while developing any planning instrument for water resources management is the aspiration of the South African National Water Act: Some for All Forever.

1.1 Background to climate change and water resources in South Africa

While the link between changing air temperatures and rainfall is still rather tentative, there have been some indications that rainfall patterns in South Africa are possibly starting to change. These changes have not been uniform across the country, with rainfall increases reported in Potchefstroom (Lynch et al., 2001), and decreases in the Western Cape (van Wageningen and du Plessis, 2007) and over Limpopo, the northwest and northern Cape (Warburton and Schultze, 2005) while Fauchereau et al. (2003) reported an increase in inter-annual rainfall variability.

In terms of projections for the African continent, the Intergovernmental Panel on Climate Change (IPCC) Fourth Assessment report (Parry et al., 2007: p. 59) states: "*Current stress on water in many areas of Africa is likely to be enhanced by climate variability and change. Increases in runoff in East Africa (possibly floods) and decreases in runoff and likely* *increased drought risk in other areas (e.g., southern Africa) are projected by the 2050s. Current water stresses are not only linked to climate variations, and issues of water governance and water-basin management must also be considered in any future assessments of water in Africa*."

The IPCC report lists some important findings on the impacts of climate change on freshwater resources. Those that are relevant to the present project are listed below:

- The impacts of climate change on freshwater systems and their management are mainly due to the observed and projected increases in temperature, evaporation, sea level and precipitation variability (very high confidence).
- Higher water temperatures, increased precipitation intensity and longer periods of low flows are likely to exacerbate many forms of water pollution, with impacts on ecosystems, human health and water system reliability and operating costs (high confidence).
- Climate change affects the function and operation of existing water infrastructure as well as water management practices (very high confidence).
- Adaptation procedures and risk management practices for the water sector are being developed in some countries and regions (e.g., Caribbean, Canada, Australia, Netherlands, UK, USA, Germany) that recognise the uncertainty of projected hydrological changes (*very high confidence*).

Recent modelling studies using downscaled climate change models indicate that there may be a reduction of rainfall over the West Coast and the adjacent interior (Schultze et al., 2005) which is consistent with the observed trend reported by van Wageningen and du Plessis (2007). Lumsden et al. (2009) investigated the downscaled results of six GCMs based on the A2 emissions scenario ("business-as-usual"), and found that generally, more rainfall is predicted for the eastern parts of the country and less rainfall along the West Coast and adjacent interior.

While most GCMs project consistently increasing temperatures in the future due to climate change, models are inconsistent in their predictions for rainfall changes. There are indications that changes to precipitation due to climate change will result in an increase in extremes rather than changes to average precipitation (Kabat and van Schaik, 2003). For the Southern African Development Community region, Davis and Joubert (2011) state that: "*Over southern Africa, there is good evidence to suggest that temperatures have been increasing over the last century. No clear evidence exists for a change in mean annual rainfall, which demonstrates year-to-year variability*." DEA (2011) agrees with this, and adds that "*there have been statistically significant increases in daily rainfall intensity and dry spell duration over the region*." Of concern is that the potential changes to precipitation due to climate change may affect water and food security of many countries.

1.2 Decision-making risk and uncertainties

It is widely accepted that water resources development and operational decisions need to be made in an environment of uncertainty associated with historical and future conditions. ***Uncertainty is not the same as not having confidence in the predictions, but rather it equates to having a probability associated with a specific prediction*** (Tadross et al., 2011). The explicit inclusion of uncertainty in decision-making is, however, a recent development, particularly in developing countries. The following quotation that is targeted at natural resource managers could equally be addressed to any water services delivery individual who needs to consider climate change uncertainty for future sustainable management of water resources.

> *The uncertainty in projected climate change impacts is one of the greatest challenges facing managers attempting to address global change. In order to*

> *select successful management strategies, managers need to understand the uncertainty inherent in projected climate impacts and how these uncertainties affect the outcomes of management activities. Perhaps the most important tool for managing ecological systems in the face of climate change is active adaptive management, in which systems are closely monitored and management strategies are altered to address expected and on-going changes.*
>
> Lawler et al., 2010: p. 35

In this regard, the adaptive capacity of the system is of concern, which is defined by the IPCC as "*the ability or potential of a system to respond successfully to climate variability and change, and includes adjustments in both behaviour and in resources and technologies*" (Adger et al., 2007: p. 727).

From a modelling point of view, in order to generate specific climate change projections at a regional level, the general projections for southern Africa need to be downscaled for the region. Researchers in southern Africa have been working on downscaling global models to a regional scale over the past few years (e.g. Lumsden et al., 2009). Assessment of the impacts and planning based on these regionalised projections is critical in the context of adaptation to climate change. This is because adaptation can only happen in view of expected changes, including an estimation of the uncertainty in these changes, specific to the area of interest.

Willows and Connell (2003) present an iterative eight-stage climate change risk-uncertainty-decision-making framework consisting of:

1. Identify problem and objectives.
2. Establish decision-making criteria.
3. Assess risk using qualitative and quantitative measures.
4. Identify options.
5. Appraise options.
6. Make decision.
7. Implement decision.
8. Monitor, evaluate and review.

Stages 1 and 2 of the framework help identify the structure of the problem i.e. its nature, what is at risk, and the objectives and criteria to be used to differentiate between options in the decision making process. Stages 3-5 analyse the problem in tiered stages. The authors note that climate risks need to be evaluated along with non-climate risks as part of stage 3. Vulnerability assessment is conducted in addition to the adaptive capacity of the system. The identified options are assessed in terms of the likelihood of meeting the objectives and criteria defined earlier in the process. Feasibility, suitability, acceptability and effectiveness are the measures by which the options are assessed for the local situation in terms of the environmental, political, social and economic conditions. The decision-making happens at stage 6, and post-decision actions on implementing, monitoring, evaluating and reviewing the selected option(s) are part of stages 7 and 8.

What complicates the above framework is the large uncertainty due to climate change under which the decision-making needs to be conducted. The options and their impacts on the system are not well defined under the climate change scenarios that decision makers are faced with (Polasky et al., 2011). This makes traditional decision theory, which requires probabilities for various alternatives, not feasible. Additionally, the traditional approach leads decision-makers to focus on issues for which data and understanding is currently available. Thus, Polasky et al. (2011) suggest combining classical decision theory with threshold approaches, scenarios planning and resilience thinking in order to better scope potential future states and outcomes. This is supported through adaptive management, which is an iterative process with feedbacks (as indicated in the risk-uncertainty-decision-making framework above), in which results of current decision generate information to make future decisions. Resilience of an ecosystem has been described as "*the capacity of an ecosystem* *to tolerate disturbance without collapsing into a qualitatively different state that is controlled by a different set of processes*" (Resilience Alliance: http://www.resalliance.org). It can be thought of as the buffering capacity of an ecosystem to maintain its functions in the face of disturbances. Resilience thinking is being applied to various disciplines such as engineering, economics and ecology.

1.3 Uncertainty framework

In order to generate specific climate change projections at a regional level, the general projections for southern Africa need to be downscaled for the region. Researchers in southern Africa have been working on downscaling global models to regional scale over the past few years (e.g. Lumsden et al., 2009). Assessment of impacts and planning based on these regionalised projections is critical in the context of adaptation to climate change. This is because adaptation can only happen in view of expected changes, including an estimation of the uncertainty in these changes, specific to the area of interest. It is widely accepted that water resources development and operational decisions need to be made in an environment of uncertainty associated with historical and future conditions. However, the explicit inclusion of uncertainty in decision-making is a recent development, particularly in developing countries. This project aims to quantify changes associated with climate change and the uncertainty linked to these changes in order to develop a decision support system that incorporates these uncertainties.

Figure 1.1 below provides an uncertainty framework for the water resource assessments for the expected developmental and climate change impacts. The framework includes uncertainty in:

- Natural hydrology in the past and in the future.
- Resource use (and abuse).
- Impacts of use on resource availability and quality.
- Influence of external factors on impacts and risk.

The figure summarises the challenges and complexity of water services delivery and management within climate change scenarios.

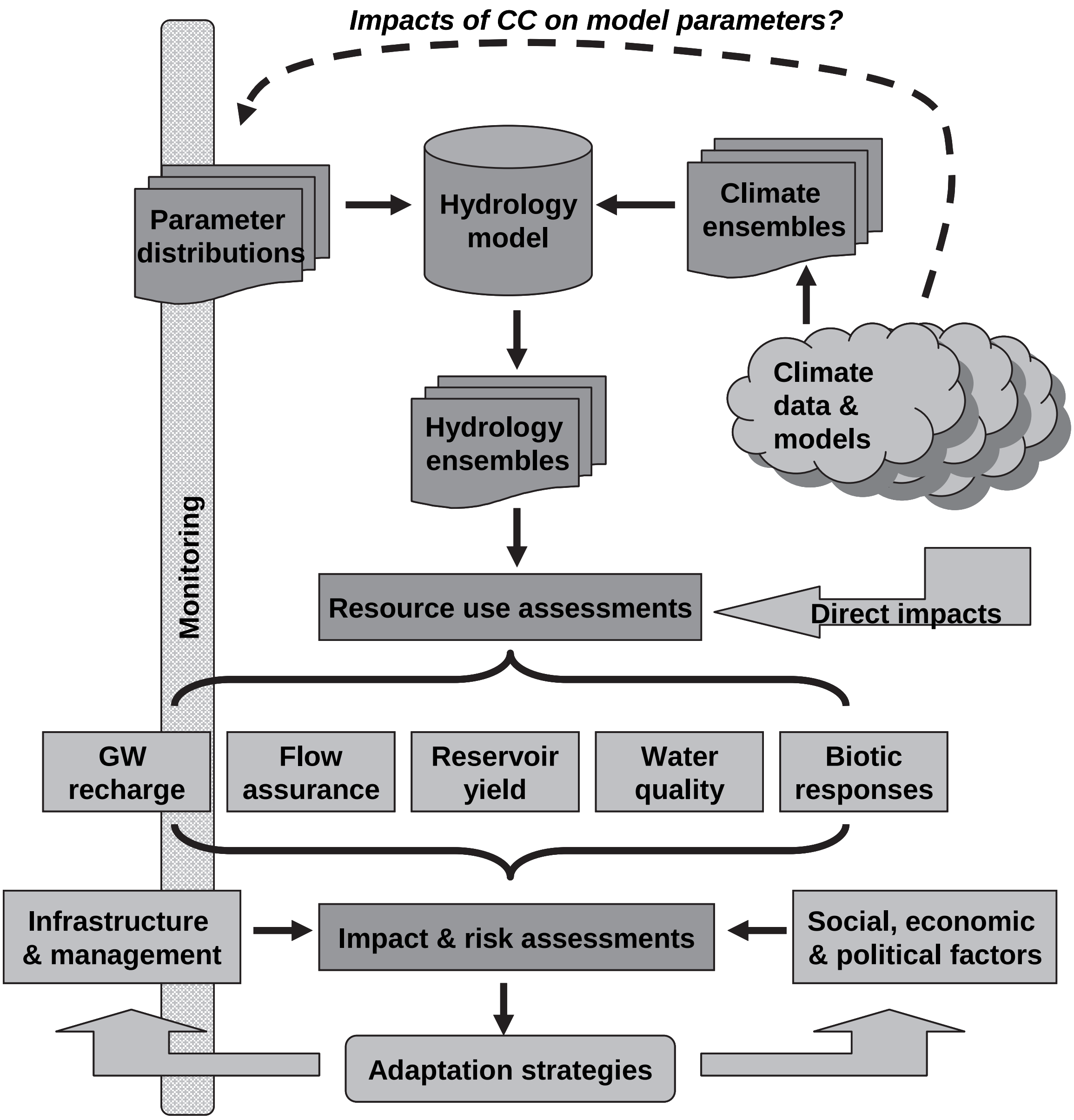


Figure 1.1 An uncertainty framework for development and climate change impact assessment.

1.4 Project rationale and aims

The IPCC reports have placed emphasis on freshwater resources, their vulnerability, adaptation and management as one of the priority areas in recognition of the fact that these resources are fundamental to basic human needs in addition to present and future planned development projects. Vulnerability to climate change has been defined by the IPCC as "*the propensity of human and ecological systems to suffer harm and their ability to respond to stresses imposed as a result of climate change effects*" (Adger et al., 2007: p. 720).

There is general agreement across climate change models in terms of expected temperature changes associated with climate change; however, there is less agreement about rainfall changes in the model predictions. In addition, it is speculated that changes related to socio-economic developments might be greater than those associated with climate change in developing countries and thus, adaptation strategies need to consider these changes in combination. The present project aimed to quantify changes associated with the near future climate change and socio-economic development, with inclusion of the uncertainty linked to both these changes in order to develop a decision support system that incorporates these uncertainties.

Climate change is expected to affect water availability through the effects on the water cycle. In general, higher temperatures are expected to increase evaporation from the oceans and thus, to increase the global average rainfall (Jackson et al., 2001). However, regional patterns would deviate from the global expected changes due to regional climatic differences, greater evapotranspiration due to a warmer climate and regional land-use and soil responses to higher temperatures. Importantly, the need for management actions for mitigating the impacts of climate change for river systems with dams on them is expected to be greater relative to those with free flowing rivers (Palmer et al., 2008).

Climate change adds an additional dimension of concern to the range of issues (such as development, mismanagement and pollution) that are already causing the deterioration of South African water resources. Climate is already of high variability in South Africa, and this, along with a limited capacity for preparedness makes South Africa very vulnerable. For some regions, changes in precipitation due to climate change may be negative with a reduced capacity of rivers to dilute pollutants because of lower natural flow, or increased pollutant loads due to catchment washoff during the predicted increase in extreme events (Bates et al., 2008).

The focus of the project was on the water supply area of two moderate size water boards, in particular the Buffalo River (for the Amatola Water Board area) and the Modder and Caledon River systems (for the Bloem Water Board area). Hydrological modelling for both the areas was conducted. However, the focus of the WEAP modelling has been on the Amatole system, as data for this system are more readily available from previous reports. Additionally, the project team did not receive any feedback from Bloem Water Board following the first workshop. Through the three years of this project, there was continuous interaction with stakeholders and reference group members through annual workshops, reference group meetings and attendance of Reconciliation Strategy meetings. The people consulted included the members of the water boards (Amatola, Bloem and Umgeni), DWA (regional and national), other university scientists, the WRC, and consultancy companies (UWP and CES). Their input was critical to the project and how it developed over time and we thank them for their support.

The aims for the WRC funded project K5/2018 were:

1. To identify potential impacts and threats to sustainable water services delivery posed by climate change, as well as the uncertainties associated with these, with regards to changes in water quantity, water quality and socio-economic developments. This will be done through application of existing or newly developed estimation tools that can be used to convert downscaled Global Climate Models (GCM) output data to likely changes (including uncertainties) in the variables that impact directly on the operations of water boards (water quantity and quality). Part of the estimation process will include timescales of the expected changes.
2. Develop a methodology for assessing risks and vulnerabilities (including uncertainties in predictions) to climate change for Water Boards and their capacity to fulfil their mandate on water services delivery.
3. Develop a strategy and monitoring network for water audits in order to monitor indicators of change.
4. Derive Thresholds of Potential Concerns (TPCs) for water quality and quantity issues for Water Boards related to raw and potable water, discharges, pricing effects, etc. based on the outputs of the climate models.
5. Develop a decision-support framework for an adaptive management strategy to assess and modify water services delivery and development plans of the Water

Boards in terms of infrastructure repair and developments, water conservation and demand management, water pricing changes and other associated issues.

Aim 1 is addressed in Chapters 4-6 and Appendix B that present the results of modelling using the Pitman and WEAP models with inputs of the downscaled GCMs and the socio-economic development uncertainties. Aim 2 was not directly met by the project due to the changed focus in the second year towards the development of the in-house water quality model (WQSAM) on which the decision support system is being built. The motivation for this change was the limitations of WEAP encountered during the water quality modelling stage (discussed in detail in Chapter 3). The monitoring network for Aim 3 is given in Chapters 8 (current network) and 10 (recommendations). The Thresholds of Potential Concern for Aim 4 were derived by the project team in consultation with the reference group members (particularly input from Amatola Water and DWA) and these are given in Chapter 2. For Aim 5, the Decision Support System, which is in a draft stage at present, will be based on the in-house water quality model (WQSAM) and it will use the TPCs (Chapter 2).

CHAPTER 2. AMATOLE AND CALEDON SYSTEMS

by

Denis Hughes, Andrew Slaughter and Sukhmani Mantel

The report focuses primarily on the Amatole system, for which modelling on hydrology, water availability and use, and water quality was conducted, while only the climate change uncertainty estimation was done for the Caledon system.

2.1 Background of the systems

2.1.1 Background of the Amatole system

The Buffalo, Nahoon and Kubusi Rivers fall under the Mzimvubu to Keiskamma Water Management Area (WMA) and the available yield in the WMA is greater than the requirements for the year 2000 (National Water Resource Strategy (NWRS); DWAF 2004a: Chapter 2). The expected availability of water for the year 2025 also has a positive balance, although demand for water is expected to increase primarily from economic activities. These economic activities go hand-in-hand with improved standards of living, which could increase water demand beyond what has been considered in the report. DWAF (2004a) notes that there are 570 000 people residing in the Buffalo River catchment and less than 500 m^3 per annum water is available per individual which is less than for some other parts of the country.

The State-of-River Report for the Buffalo River has identified various problems, including high population in a catchment with limited water resources, naturally high salinity (due to the marine origin of the geological formations), two dams that are downstream of large urban areas, blockages in the sewerage systems, inadequate treatment capacity and poor management (River Health Programme, 2004; AWB, 2010a). These problems, according to the report, have resulted in partially treated and untreated sewage being discharged into the river and the dams, which in turn results in algal blooms and high concentrations of faecal bacteria. Another major problem identified by the report is inadequately treated industrial effluents leading to poor water quality that poses risks to both river and human health. Illegal water connections are another problem facing Amatola Water (AWB, 2010a), and probably ADM and BCM. Figure 2.1 shows the main catchments, location of the rivers, dams and major towns in the Amatole system.

In terms of drinking water supply, the Buffalo City Metropolitan Municipality has received positive Blue Drop Status assessments. The Blue Drop Status Report is a regulatory tool created by the DWA to monitor the ability of municipalities to supply constant and safe domestic water. Comparison of the Blue Drop scores over the years (http://www.dwaf.gov.za/dir_ws/dwqr) shows the improvement and continued high Blue Drop status for this municipality (Table 2.1).

2.1.2 Background of the Caledon River system

The total area of the Caledon River basin (Figure 2.2) at its junction with the Orange River is 21 884 km^2, while this study focuses on the area (15 270 km^2) upstream of the Welbedacht Dam (D23J).

Table 2.1 Blue drop scores for East London and King William's Town for the years 2009-2011.

	2009	2010	2011
East London	67.5%	95.3%	95.1%
King William's Town	Not assessed	95.1%	95.0%

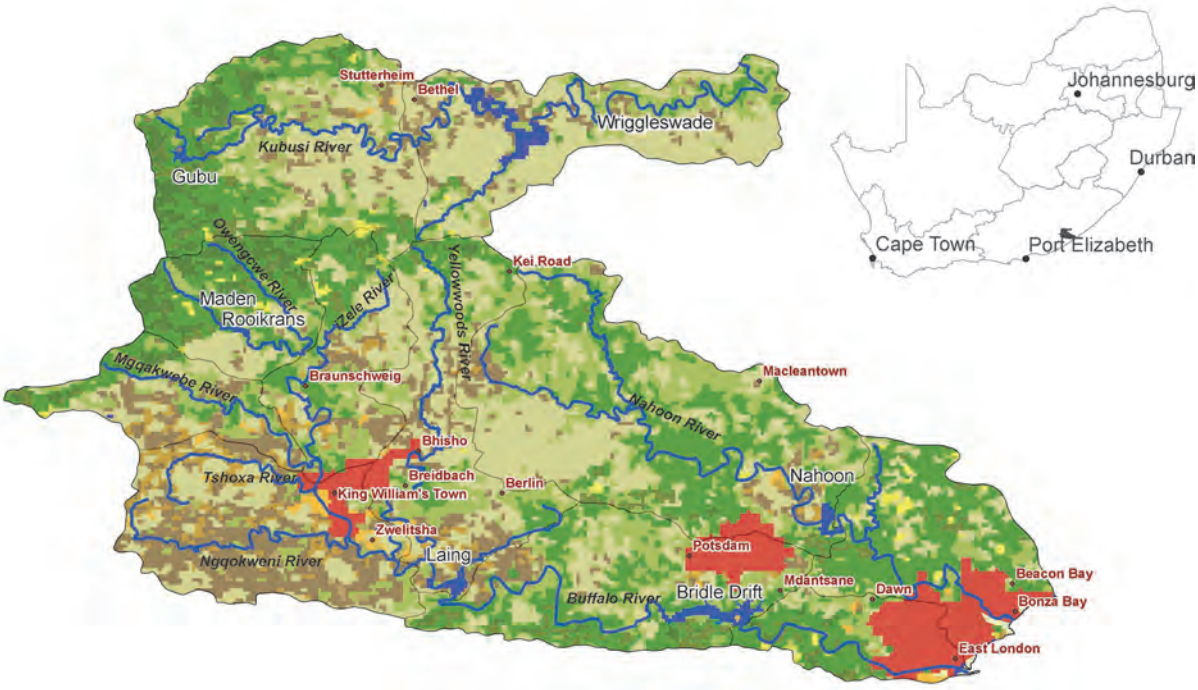


Figure 2.2 Map of the Buffalo, Nahoon and Kubusi River catchments in the Eastern Cape, showing the location of the rivers, dams, major towns (in red) and the land-cover derived from FAO (2009a).

The headwater sub-basins rising within Lesotho are characterised by steep slopes (the north-western edge of the Drakensberg Mountains) with grassland vegetation (Figure 2.3, P1). Land-use consists of extensive rain-fed cultivation and cattle grazing (mostly subsistence agriculture) on the valley sides and bottoms. The topography in most of the South African parts of the basin is undulating, while land-use is based on intensive cultivation with a mixture of rain-fed (mostly maize) and irrigated crops together with some cattle grazing (Figure 2.3, P2). The majority of the basin is underlain by sandstones and shales, while the south-western parts of the basin are underlain by shales and mudstones. Soil characteristics are highly variable both in terms of depth and texture. Mean annual precipitation varies from > 1 000 mm in the Drakensberg Mountains to < 600 mm in the lower parts of the basin. Potential evaporation ranges from < 1 300 mm in the headwaters to 1 600 mm downstream. The rainfall regime is highly seasonal with approximately 70% of the rain falling between November-March.

The water resources of the Caledon River basin (Figure 2.4) are important locally to sustain water supplies for many small towns as well as the Lesotho capital city of Maseru and for irrigated agriculture in the South African parts of the basin. They are also important regionally through an inter-basin transfer scheme abstracting water from the Welbedacht Dam for the city of Bloemfontein located in the Modder River basin to the northwest. As a consequence, many small farm dams as well as a number of much larger dams exist within the basin (Figure 2.3, P3). Midgley et al. (1994) list a total of 53 impoundments with a combined storage capacity of approximately 202 x 10^6 m^3, compared with their estimate of the mean annual runoff of 1 244 x 10^6 m^3.

There are, however, many more small storage dams with unknown capacities that are not included in the Midgley et al. (1994) list. While there are six stream flow gauging stations (Figure 2.2) within the study area, the data records are short and cover different periods, rarely measure the full range of high flows and are impacted by poorly quantified upstream abstractions. The combined uncertainties in the observed data make the basin effectively ungauged. The observed data may be useful for constraining some aspects of simulated flow data, but are not useful for conventional model calibration.

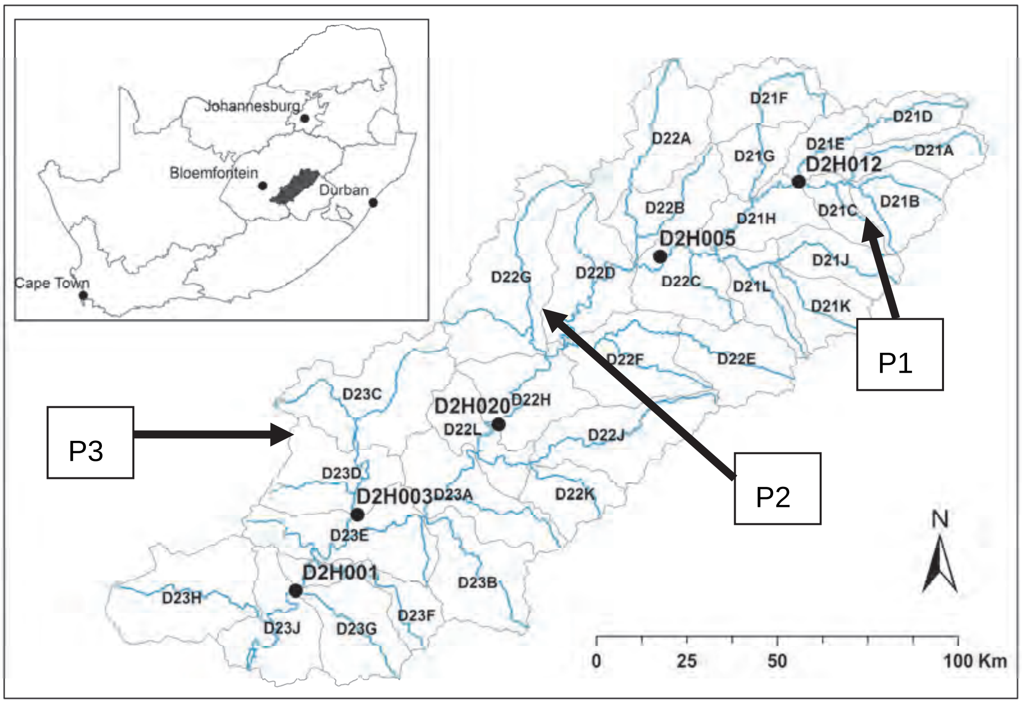
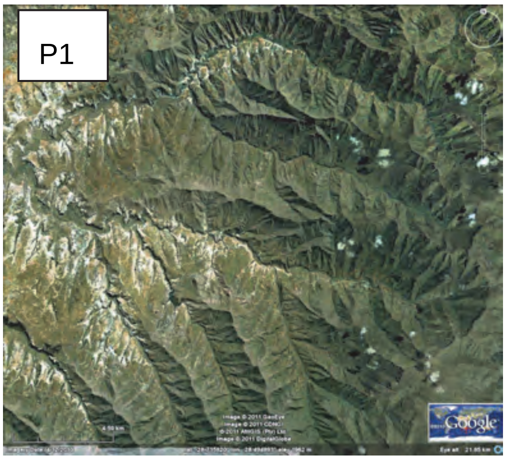


Figure 2.3 The Caledon River basin showing modelled sub-basins and stream flow gauging stations (P1-P3 refer to the Google Earth Images in Figure 2.3).



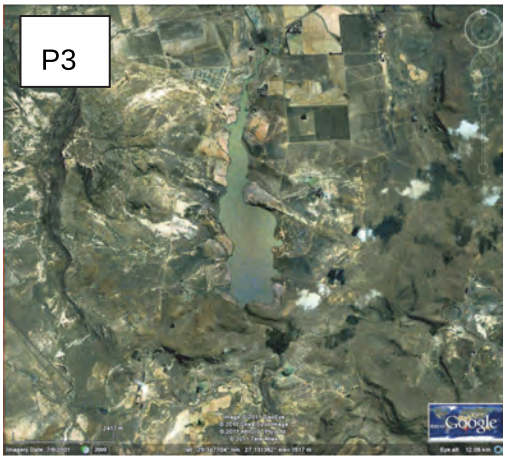


Figure 2.4 Google Earth images of the upper parts of the basin in Lesotho (P1), the middle parts of the basin on the border between Lesotho and South Africa (P2) and a reservoir (P3) on one of the tributaries in the lower part of the basin.

Figure 2.5 Map of the Caledon and Modder River catchments in the Free State, showing the location of the rivers, dams, major towns (in red) and the land-cover derived from FAO (2009a, 2009b).

2.2 Previous water resources modelling in the Amatole area

Three major studies in recent years have modelled the water resources in the Amatole area. A previous comprehensive study on the Amatole system, labelled the *Amatole Water Resources System Analysis Phase 2* report, conducted water quantity (WRYM and WRPM models) and water quality modelling for the Amatole catchments – including non-point source washoff from catchment land-use, point source discharges to rivers, transport and assimilation of constituents in river reaches, and assimilation of constituents in impoundments – based on 16 year monthly flow and water quality data (DWAF, 1998). The analysis was conducted for the catchments of the Buffalo, Nahoon, Kubusi, Genubie and Toise rivers which included the Maden, Rooikrantz, Laing, Bridle Drift, Nahoon, Gubu and Wriggleswade reservoirs. The Phase 2 Analysis used three water quality modelling approaches: 1) a monthly decision support model; 2) a daily reservoir simulation model and; 3) a WQT-hydro-salinity model. The Phase 2 Analysis modelled TDS, suspended solids, soluble phosphorus (particulate and total), chlorophyll *a* (in impoundments) and *E. coli*.

Bath et al. (1997) used the CE-QUAL-W2 model to simulate the stratification patterns of Laing Dam and the influence of the water transfer from Wriggleswade Dam on the TDS levels within Laing Dam. The authors recommended the use of CE-QUAL-W2 and the Dynamic Reservoir Simulation Model (DYRESM) to develop operating rules for water releases from the Wriggleswade Dam, and also continual collection of reservoir and meteorological data in addition to the implementation of management and monitoring strategies for reservoirs requiring water quality management in future.

Ninham Shand in 2006, as part of a study on four selected systems for examining the development of “Generic Guidelines for Operation and Management of Bulk Water Supply Systems under both normal and drought conditions”, developed operating rules for the Amatole Water Supply system (DWAF, 2006a). The results included operating rules for dams developed using a water quality model (IMPAQ) that was linked to the WRYM and WRPM models for managing both water quality and quantity under drought situations. The IMPAQ model has not been previously used under future climatic predictions for Amatola Water. Also, there is limited user support for this model (Nico Rossouw, Ninham Shand, *pers. comm.*). Therefore, for the present project, the WEAP model has been used as a system level model that provides results for water use and availability analyses under present and future water demands as well as under future climate scenarios. It can also model water quality through simple models included in WEAP and through connections with CE-QUAL-K2.

2.3 Water quantity and quality problems in the Amatole system

2.3.1 Water quantity problems

Effluent flow comprises the majority of flow within the Middle Buffalo during low flows. The artificial flow within the Middle Buffalo between King Williams Town and Laing Dam is likely to increase due to the regionalised WWTW at Zwelitsha, while the Yellowwoods River is likely to return to naturally ephemeral flow due to the decommissioning of WWTWs (BCM, 2011; DEDEA, 2011). Encroachment by alien vegetation has also been noted as a problem within the Buffalo River catchment (ECPSDP, 2010), which may decrease runoff to the river.

2.3.2 Water quality problems

Eutrophication and salinisation appear to be the most problematic water quality issues within the Amatole system, especially within the reservoirs where water is extracted for municipal use. This is especially true of the Laing and Bridle Drift dams in the Middle and Lower Amatole (DWAF, 2004b; O’Keeffe et al., 1990). The presence of a closed loop within the Middle Amatole has been noted, with water abstracted from the Laing Dam returning as WWTWs effluent flow from upstream of the dam (DWAF, 2001). The proposed regionalised WWTW at Zwelitsha and the decommissioning of three smaller WWTWs on the Buffalo and Yellowwoods rivers should moderately improve water quality within the Middle Buffalo River, Yellowwoods River and the Laing Dam over the long term (BCM, 2011; DEDEA, 2011). This development will not however solve the problem of a ‘closed loop’ effect within the Middle Amatole and it remains to be seen whether this development will have dramatic long-term effects on water quality. At present, the WWTWs operating in the Middle Amatole are over-loaded beyond capacity (ECPSDP, 2010; DEDEA, 2011), which has an effect on the quality of effluent released. While DWAF implemented a PO_4 concentration effluent standard of 1 mg ℓ^{-1} in the 1980s (O’Keeffe et al., 1990), historical monitoring data show that effluent released by WWTWs in the Middle Amatole region are rarely below this standard (see Figure 2.5) and nutrient concentrations within effluent show a high degree of temporal variability (see Figures 2.5 and 2.6). Hopefully, the regionalisation of the Zwelitsha WWTW will prove to mediate this problem, depending on what type of a sink the Laing Dam is and how much nutrients are taken out by the hyacinth and the impact of removing the hyacinth (Dr Nikite Muller, *pers. comm.*).

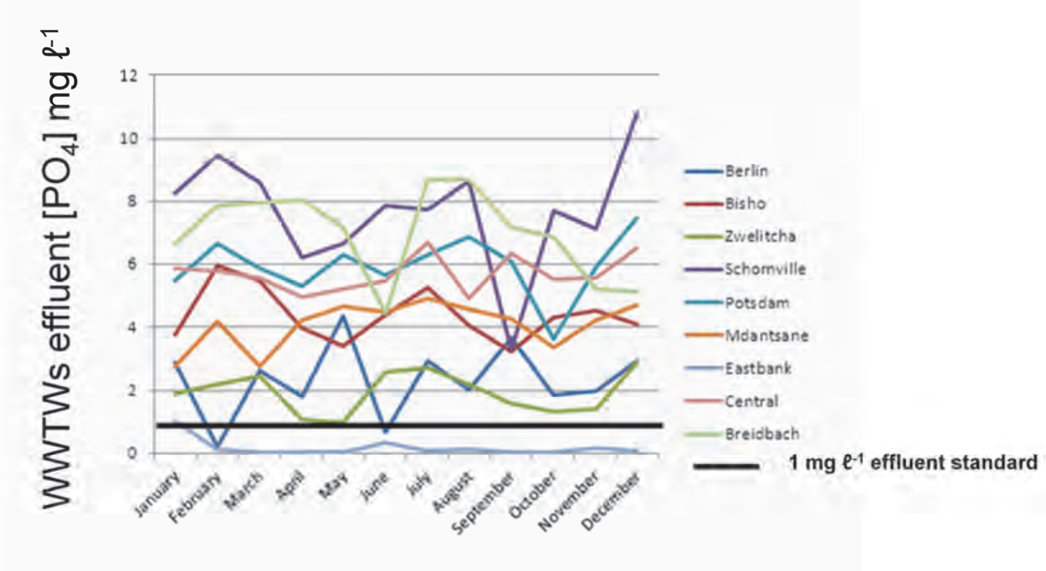


Figure 2.5 Average monthly PO_4 concentrations found in effluent released from WWTWs within the Amatole system

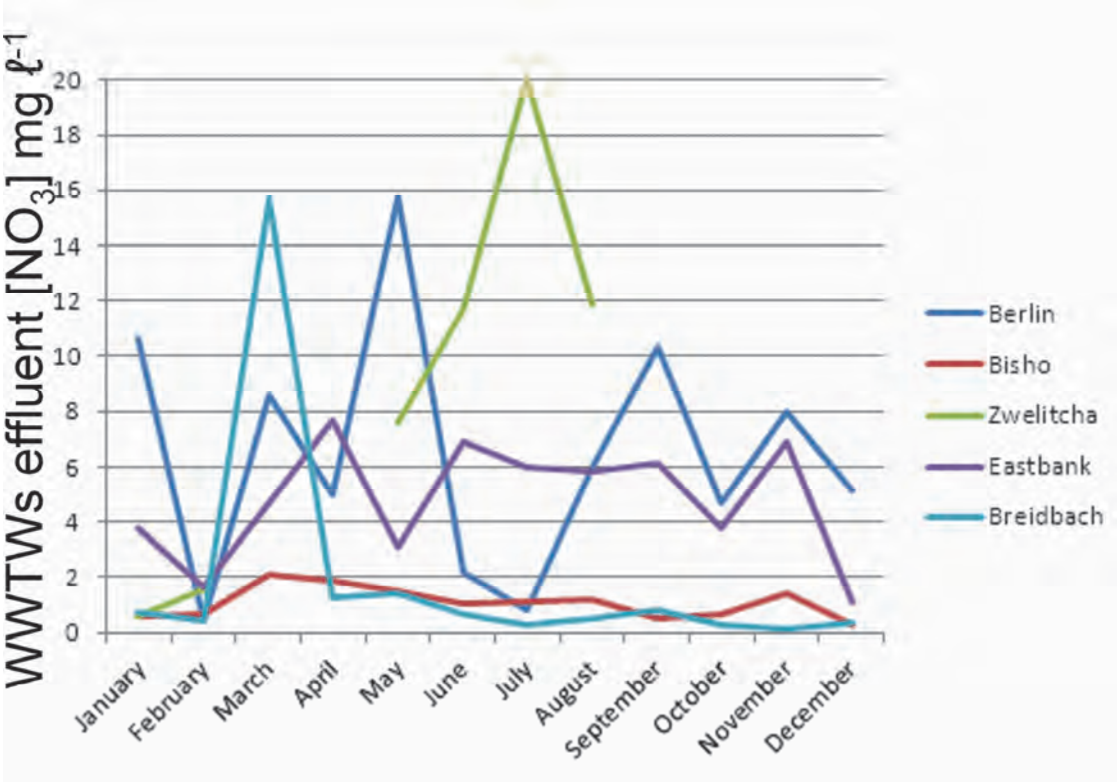


Figure 2.6 Average monthly NO_3 concentrations found in effluent released from WWTWs within the Amatole system

While effluent within the Middle Buffalo is the major source of pollutants during low flow, runoff from urban areas may contribute a significant amount of nutrients during rainfall events (up to 65% of the total load; O'Keeffe et al., 1990). A major source of diffuse nutrients into the Middle Amatole is from tributaries running from Mdantsane into the Laing Dam (O'Keeffe et al., 1990).

Currently, the Laing Dam acts to improve water quality downstream. Firstly, the dam acts as a nutrient trap (Palmer and O'Keeffe, 1990). The possible reasons for this may be uptake of nutrients by hyacinth which can proliferate in the dam. High turbidity in the dam could also be contributing to rapid sedimentation of phosphorus, and has been noted as a possible factor restricting eutrophication (Palmer and O'Keeffe, 1990). While Hyacinth growth can remove nutrients from within the dams, hyacinth deaths can release nutrients and cause anoxic conditions. There have also been reports of growth of *Mycrocystis* colonies within Bridle Drift Dam in 1973, causing a deterioration of water taste and odour (Walmsley and Butty, 1980). While the dams do act as sinks in regards to certain water quality variables, they do alter the natural temperature regime, with reservoirs in the upper Amatole increasing water temperatures, and those in the Middle and Lower Amatole decreasing temperatures, relative to natural conditions.

The Amatole system also is naturally highly saline, especially within the middle reaches (DWAF, 2004b; O'Keeffe et al., 1990). While some salt input can be attributed to irrigation return flows, runoff from urban areas and effluent, most of the salt input (~60%) can be attributed to natural geological structures.

Other water quality problems experienced in the reservoirs include sedimentation that decreases dam capacity (ECPSDP, 2010), anoxic conditions that can result in the release of iron and manganese compounds from the sediments to the water column (DWAF, 2004b), and faecal contamination as result of broken sewers (O'Keeffe et al., 1990).

2.4 Thresholds of Potential Concern (TPCs)

Thresholds of Potential Concern (TPCs) are ranges of change which trigger investigation when they are exceeded at upper or lower limits, resulting in either management action or a revision of the threshold (Rogers and Bestbier, 1997; McLoughlin et al., 2011). Since the initial data availability may be limited, auditing of the thresholds could be facilitated by a monitoring program to collect additional data.

TPCs should be guided by the seven attributes of good indicators, particularly for biological monitoring (based on Noss, 1990), listed as following in Rogers and Bestbier (1997):

1. Sufficiently sensitive to provide an early warning of change.
2. Widely applicable or distributed over an appropriate geographic range.
3. Capable of providing continual assessment over a wide range of stress.
4. Relatively independent of sample size.
5. Easy and cost effective to measure.
6. Enables discrimination between natural fluxes and anthropogenic stress.
7. Relevant to ecologically significant phenomena and processes.

2.4.1 Water quantity

Within the Amatole system, EWRs have been conducted: for the Buffalo River downstream of Rooikrantz, Laing and Bridle Drift dams; along the Kubusi River and; below the Nahoon Dam and the Nahoon estuary. The DWAF (2008) Amatole Reconciliation Strategy review of the EWR shows that there are various factors preventing the EWR from being implemented. The review of the EWR at site 1 was conducted with updated hydrological information, and noted that the EWR had not been implemented as it would reduce the system yield by up to 25%. Currently, finalisations of the river classifications and EWRs are still in progress (DWA, 2011).

It is estimated that high flow components of the EWR might not be met due to discharge limitations of the dam outlets. In addition, reservoir operating rules would have to be developed to facilitate the ecological flows. It has been noted that the Wriggleswade Dam transfer to the Laing Dam via the Yellowwoods River should be facilitated at a lower flow rate than the transfer capacity, so as to avoid ecological and structural damage to the river due to higher than normal flows (DWAF, 2008: DWA, 2011).

Some points raised within the 3rd reference meeting are relevant to flow TPCs. Firstly, the Middle Buffalo (King William's Town to Laing Dam) is regarded as being too modified to justify application of environmental flow TPCs. Secondly, the proposed upgrading of the existing Zwelitsha WWTW and the decommission of three smaller WWTWs along the Middle Buffalo and the Yellowwoods River (DEDEA, 2011), will have a fairly dramatic effect on flow in both rivers. Firstly, flow within the Yellowwoods River will return to an ephemeral nature, as the relatively constant effluent flow input will cease, although there will be intermittent artificial high flows due to the releases from the Wriggleswade transfer. Flow in the Middle Buffalo River between King Williams Town and Laing Dam will increase due to the increased treatment capacity of the Zwelitsha WWTW.

The EWRs for the various regions of the Amatole system can be regarded as flow TPCs. To interpret the flow TPC value, the modified flow duration curve (due to human use) can be compared to the IFR duration curve, for a particular region and month of interest. Figure 2.7 shows the natural flow and IFR flow duration curves for the ecological category C for the month of October on the Kubusi River below Wriggleswade Dam. If the actual flow within the river were to drop below the IFR duration curve, this would be a cause for concern and should trigger management action.

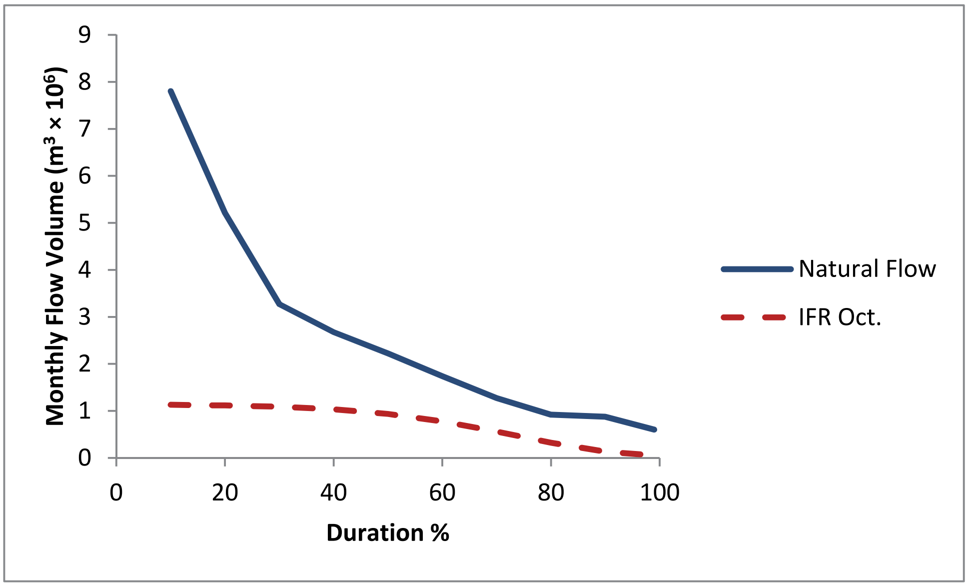


Figure 2.7 Flow duration curves of natural and IFR flow calculated for the ecological category C within the Kubusi River below Wriggleswade Dam for the month of October.

2.4.2 Water quality

Amatole system TPCs have been used within resource management in South Africa in the case of the Kruger National Park (Rogers and Bestbier, 1997). The process used here to develop TPCs was useful for guiding the development of TPCs for the Amatole system, although some major differences are evident, such as the emphasis on the preservation of near natural conditions of water resources within the Kruger National Park, whereas much of the Amatole system has become drastically altered due to human influences. What the Kruger example demonstrates is that the TPCs can only be developed in the context of a 'desired state' and operational goals. Within a Reserve determination, the desired state can be linked to the desired class for the catchment investigated. TPCs can then be linked to the ecological Reserve determined for quantity and quality. The Kruger example demonstrates that TPCs are not static, and can evolve over time with changing knowledge and management needs (McLoughlin et al., 2011).

Within the Kruger National Parks example, original TPCs used a percentile of observed water quality conditions (as indicated by historical monitoring data), with the specific percentile determined by the water quality variable in question. In the case of the Amatole system, the desired state was guided by the intermediate Reserve determination (DWAF, 2001). DWAF (2001) outline the present ecological state (PES), and the intermediate TPCs for river reaches within the Amatole system were determined using the PES. More specifically, depending on the specific variable, a proportion of the PES value is increased by a certain amount to indicate a TPC (such as 75% of the PES plus 10% in the case of salinity), or in the case of pH, the TPCs would be 25% of the PES minus 0.5 units as a lower (acidic) TPC, and 75% of the PES plus 0.5 units as an upper (alkaline) TPC. At the third reference group meeting, the point was made that moderate improvements to the water quality of the middle Buffalo River, the Yellowwoods River and the Laing Dam are expected, due to the proposed upgrading of the Zwelitsha WWTW and the decommission of three smaller WWTWs on the Buffalo and Yellowwoods rivers (also see DEDEA, 2011). Updated TPCs for the Middle Buffalo River are presented here, taking into account that a moderate improvement in water quality is expected. Since available reports on the proposed regionalisation of the Zwelitsha WWTW do not give information on actual expected water quality of the effluent (BCM, 2011; DEDEA, 2011), this had to be estimated. To estimate the in-stream water quality variable concentration range downstream of the regionalised Zwelitsha WWTW, expected treatment efficiencies were obtained from published research (Sötemann et al., 2002), given that the proposed regionalised Zwelitsha WWTW will most likely use the University of Cape Town (UCT) Biological Nutrient Removal (BNR) process (BCM, 2011). The expected effluent concentrations were input into a nutrient point source mass balance model (Slaughter and Hughes, In Press), to determine the in-stream water quality variable concentrations of nutrients. The results of this model can be seen in Figure 2.8.

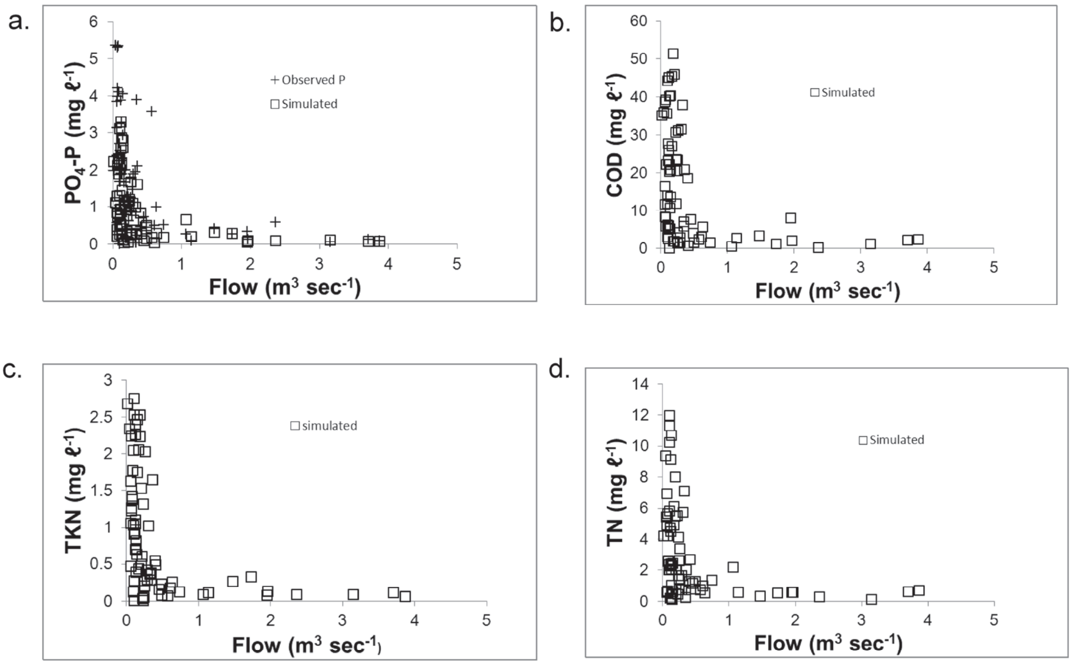


Figure 2.8 Expected range of in-stream concentrations of various water quality variables in relation to flow in the Buffalo River immediately downstream of the proposed regionalised Zwelitsha WWTW: a) in-stream phosphate; b) chemical oxygen demand; c) total Kjeldahl nitrogen and; d) total nitrogen.

While the proposed regionalisation of the Zwelitsha WWTW will most likely improve the quality of water in Laing Dam in relation to pollutants treated within a WWTW, the proposed TPCs for impoundments do not use the PES, but rather the DWAF (1998) objectives for water quality, as water from impoundments is required to meet certain standards for municipal and industrial use. The objectives were derived by using the South African Water Quality Guidelines (DWAF, 1996), and requirements of water users, cost of water treatment, and the observed water quality in the dams. While WTWs could potentially treat water of worse quality than the objectives, this would increase costs of treatment. Therefore, expected improvements to water quality within the Laing Dam because of the regionalisation of the Zwelitsha WWTW would not affect the TPCs constructed for the Laing Dam. In addition, the transfers of water from Wriggleswade Dam could potentially improve water quality within Laing Dam.

The TPCs presented here also take into account the suggestions at the 3rd reference group meeting, and provide region specific TPCs for the reaches of the Nahoon River above and below the Nahoon Dam.

Temperature, pH and salinity are given as monthly values. This follows the format of the Present Ecological State (PES) values given by DWAF (2001) for the various regions. For all regions, TPCs for pH are given as the range of permissible values. Measured pH below or above this range would be a reason for concern. The pH TPCs were constructed by taking the 25th percentile and 75th percentile PES values given by DWAF (2001) and subtracting 0.5 pH units from the 25th percentile as the lower limit, and adding 0.5 pH units to the 75th percentile as the upper limit. Temperature TPCs were constructed by taking the 95th percentile values given for the PES by DWAF (2001) and adding 2 °C to each value. Salinity TPCs were constructed by taking the 75th percentile values given for the PES by DWAF (2001) and increasing that value by 10%. The extent of increase (or decrease in the case of pH) is rather arbitrary, although the water quality guidelines for aquatic ecosystems (DWAF, 1996) use similar methods for specifying the Target Water Quality Ranges (TWQRs) for these three water quality variables. Within river reach regions, the nutrient TPCs are specified by inorganic PO_4 concentrations as given by the PES (DWA, 2001), increased by 10%, as well as the TIN:PO_4 ratio as given by the PES (DWAF, 2001) decreased by 10%. Since the Buffalo River is PO_4 limited, the TIN:PO_4 ratio is interpreted as indicating higher potential for eutrophic conditions with lower ratio values, and hence the TIN:PO_4 TPC was decreased by 10% relative to the PES. Salinity TPCs in reservoirs are typically lower than those of upstream tributaries, as is noticeable in particular for Nahoon Dam. Highly saline water would typically sink to the bottom of reservoirs, while water is typically extracted from the surface for human use, explaining the discrepancy. The final TPCs for water quality are listed in Table 2.2

Table 2.2 Water quality TPCs for the Amatole system by region.

Table 2.2: Region 1: Rooikrantz Dam

Water Quality Variable	Suggested TPCs	Current and Future Monitoring	Possible Management Action
Salinity DWAF (1998) TDS Objective	> 100 mg ℓ^{-1}	Monthly medians of salinity from R2R002Q01 on Rooikrantz Dam.	Identify diffuse source of salinity and initiate management intervention.
Nutrients DWAF (1998) PO_4 and Chlorophyll a objectives	$PO_4 > 0.050$ mg ℓ^{-1} and Chlorophyll a > 0.005 mg ℓ^{-1}	Monthly medians of PO_4 from R2R002Q01 on Rooikrantz Dam. Initiate measures of Chlorophyll a at R2R002Q01*.	Identify diffuse sources of nutrients and implement management action.
DWAF (1998) *E. coli* objective	> 150 (#/100 ml)	Initiate microbial water quality measures at R2R002Q01*.	Identify source of diffuse contamination and implement management intervention.
Sediment	Settling of sediment into Rooikrantz Dam and decreasing of dam capacity	Yearly measures of dam capacity*.	Identification of land practices upstream that are causing sediment transport such as grazing causing erosion, and the implementation of intervention management.

* - Additions to monitoring network needed

Table 2.2 continued: Region 2: Buffalo River between Rooikrantz Dam and R2H005

Water Quality Variable	Suggested TPCs												Current and Future Monitoring	Possible Management Action
	Jan	**Feb**	**Mar**	**Apr**	**May**	**Jun**	**Jul**	**Aug**	**Sep**	**Oct**	**Nov**	**Dec**		
Salinity in TDS (mg ℓ^{-1}) 75% of DWAF(2001) PES + 10%	178	162	209	267	382	449	506	563	584	599	567	301	DWA monitoring point R2H005Q01. Monthly medians.	Identify diffuse sources of nutrients and implement management action. Possible restriction of irrigated cultivation.
pH range of DWAF(2001) PES from 25%-75% ± 0.5	7.1 – 8.6	7.2 – 8.5	7.3 – 8.5	7.4 – 8.6	7.4 – 8.7	7.4 – 8.7	7.5 – 8.8	7.7 – 8.9	7.6 – 8.9	7.6 – 8.9	7.2 – 8.9	7.3 – 8.8	DWA monitoring point R2H005Q01. Monthly medians.	Identification and management of problem.
Temperature range of DWA (2001) PES 95% + 2 °C	23	28	25	23	21	19	20	19	18	22	22	22	DWA monitoring point R2H005Q01 as well as some point between the outlet of Rooikrantz Dam and R2H005Q01*. Monthly medians.	Management to alter release mechanism of Rooikrantz Dam to allow mixing of water of different depths and temperatures.
DWAF (1996) median summer PO_4 and TIN threshold for onset of Eutrophic conditions	$PO_4 > 0.025$ mg ℓ^{-1} and TIN > 2.5 mg ℓ												DWA monitoring point R2H005Q01. Monthly medians.	Identify diffuse sources of nutrients and implement management action.
Sediment	Perceived loss of riffle environments, increase in turbidity, or narrowing of river channel												Initiate measurement of turbidity at R2H005Q01*; identify physical changes over time of the river channel using satellite images*.	Identify land management practices that may be leading to erosion and implement management action.

* - Additions to monitoring network needed

Table 2.2 continued: Region 3: Buffalo River between R2H005 and Laing Dam

Water Quality Variable	Suggested TPCs	Current and Future Monitoring	Possible Management Action
PO_4 – P Median concentration[1]+ 10% Median TIN[1]:PO_4[1] ratio - 10% Chlorophyll a	$PO_4 > 0.77$ mg ℓ^{-1} and TIN:$PO_4 < 2.55$ together with increase in Chlorophyll a	DWA monitoring points R2H010Q01 on Buffalo River, R2H009Q01 on Ngqokweni River and R2H015Q01 on Yellowwoods River. Monthly medians. Inclusion of Chlorophyll a monitoring at above mentioned monitoring points*. Inclusion of NO_3 monitoring at the Zwelitsha WWTW on the Buffalo River*. Monitoring of nutrients released from the Da Gama textile factory through R2H016Q01 on the Malakalaka Stream.	Identify diffuse sources of nutrients and implement management action. If monitoring of WWTWs or industrial effluent indicates problem, initiate management options at point source.
Antecedent conditions for nutrients	Protracted period of little or no rainfall in Middle Buffalo affected by urban runoff with a forecasted near future large rainfall event.	Monitoring of rainfall in Middle Buffalo and near future rainfall forecasting.	Preparations for large input of nutrients to Laing Dam with next forecasted large rainfall event.
Sediment	Perceived loss of riffle environments, increase in turbidity, or narrowing of river channel	Initiate measurement of turbidity at R2H010Q01 on the Buffalo River*, R2H009Q01 on the Ngqokweni River* and R2H015Q01 on Yellowwoods River*; identify physical changes over time of the river channels using satellite images*.	Identify land management practices that may be leading to erosion and implement management action.

* - Additions to monitoring network needed

[1] - As simulated by a point source nutrient model (Slaughter and Hughes, In Press) taking into account capacity and treatment efficiencies of the regionalised WWTW at Zwelitsha

Table 2.2 continued: Region 3: Buffalo River between R2H005 and Laing Dam

Water Quality Variable	Suggested TPCs	Current and Future Monitoring	Possible Management Action
TKN[1]	TKC > 0.64 mg ℓ^{-1}	Initiate measurement of TKN at R2H010Q01 on Buffalo River*, Monthly medians.	If monitoring of WWTWs indicates problem, initiate management options at point source.
TN[1]	TN > 2.18 mg ℓ^{-1}	Initiate measurement of TKN at R2H010Q01 on Buffalo River*, Monthly medians.	If monitoring of WWTWs indicates problem, initiate management options at point source.

* - Additions to monitoring network needed

[1] - As simulated by a point source nutrient model (Slaughter and Hughes, In Press) taking into account capacity and treatment efficiencies of the regionalised WWTW at Zwelitsha

Table 2.2 continued: Region 3: Buffalo River between R2H005 and Laing Dam

Water Quality Variable	Suggested TPCs												Current and Future Monitoring	Possible Management Action
	Jan	**Feb**	**Mar**	**Apr**	**May**	**Jun**	**Jul**	**Aug**	**Sep**	**Oct**	**Nov**	**Dec**		
Salinity in TDS (mg ℓ $^{-1}$) 75% of DWA(2001) PES + 10%	340	300	481	548	612	680	733	784	855	832	748	609	DWA monitoring points R2H010Q01, R2H009Q01 and R2H015Q01. Monthly medians	Management of urban runoff.;
pH range of DWA(2001) PES from 25% -75% ± 0.5	7.1 – 8.6	7.3 – 8.6	7.5 – 8.7	7.4 – 8.6	7.5 – 8.8	7.6 – 8.8	7.6 – 8.8	7.5 – 8.9	7.5 – 8.9	7.4 – 8.8	7.4 – 8.9	7.3 – 8.8	DWA monitoring points R2H010Q01 on Buffalo River, R2H009Q01 on Ngqokweni River and R2H015Q01 on Yellowwoods River. Monthly medians.	Identification and management of problem. DWA monitoring data of Schornville and Zwelitsha WWTWs on Buffalo River and Bhisho WWTW on Yellowwoods River can be analysed. Industrial effluent from Da Gama Textiles can be analysed: R2H016Q01 on the Malakalaka Stream
Temperature range of DWA (2001) PES 95% + 2 °C	23	28	25	23	21	19	20	19	18	21.5	22	22	DWA monitoring points R2H010Q01 on Buffalo River, R2H009Q01 on Ngqokweni River and R2H015Q01 on Yellowwoods River. Monthly medians. Inclusion of temperature measures for effluent from the Scholand and Zwelitsha WWTWs on the Buffalo River and the Bhisho WWTW on the Yellowwoods River*.	Identify problem. WWTWs effluent piped to sea.

* - Additions to monitoring network needed

Table 2.2 continued: Region 4: Laing Dam

Water Quality Variable	**Suggested TPCs**	**Current and Future Monitoring**	**Possible Management Action**
Salinity DWAF (1998) TDS Objective	> 400 mg $ℓ^{-1}$	DWA monitoring points R2R001. Monthly medians.	Identify land-use practices or management inefficiencies at the Zwelitsha WWTW and implement appropriate management action. Identify possible inflow source of problem.
Nutrients DWAF (1998) PO_4 and Chlorophyll a objectives	PO_4 > 0.100 mg $^{-l}$ and Chlorophyll a > 0.015 mg $ℓ^{-1}$	DWA monitoring points R2R001. Initiate measurement of Chlorophyll a at R2R001*. Monitoring of Zwelitsha WWTW effluent affecting Laing Dam. Monthly medians.	Identify diffuse sources of nutrients and implement management action. If monitoring of WWTWs or industrial effluent indicates problem, initiate management action at point source.
Nutrients Laing Dam nutrient sink function	Perceived loss of nutrient sink function	Monitoring of nutrient concentration entering Laing Dam (sum of R2H010Q01 and R2H015Q01) and that leaving Laing Dam (R2R001).	Initiate investigation to determine reason for loss of 'nutrient sink' function.
Eutrophication inhibited by high turbidity in Laing Dam	A decrease in turbidity relative to normal that may result in increased eutrophication	Initiate measurement of turbidity at R2H010Q01 on the Buffalo River*, R2H009Q01 on the Ngqokweni River*, R2H015Q01 on Yellowwoods River* and R2R001 on Laing Dam*.	Management action to prevent eutrophication, such as artificial inhibition of eutrophication.
Uptake of nutrients by Hyacinth on Laing Dam	An indication that the Hyacinth population in the dam is going to suffer a die-off.	Active assessment of Hyacinth health within Laing Dam*, monitoring of nutrients at R2R001 indicating whether nutrients are becoming limiting to Hyacinth growth.	Physical removal of Hyacinth from Laing Dam.

* - Additions to monitoring network needed

Table 2.2 continued: Region 4: Laing Dam

Water Quality Variable	Suggested TPCs	Current and Future Monitoring	Possible Management Action
Toxins in Laing Dam	Detection of toxins of unacceptable concentration in WWTWs effluent or industrial effluent that enter Laing Dam. Detection of anoxic conditions within Laing Dam that may cause the release of toxic metals from the sediments (manganese and iron). Detection of toxins within the sediment profile of Laing Dam. Detection of Persistent Organic Pollutants (POPs) within Laing Dam.	Initiate monitoring for toxins within the effluent of the Zwelitsha WWTWs on the Buffalo River* and the effluent released industries operating in the area *. Monitoring of oxygen status at the bottom of Laing Dam*. Periodic assessment of the toxin profile of sediment within Laing Dam*. Measures of POPs in Laing Dam.	Initiate management intervention at WWTWs or industries releasing effluent containing toxins. Management of agriculture if POPs detected.
Sediment	Settling of sediment into Laing Dam and decreasing of dam capacity	Yearly measures of dam capacity*.	Identification of land practices upstream that are causing sediment transport such as grazing causing erosion, and the implementation of intervention management.
DWAF (1998) *E. coli* objective	> 300 (#/100 ml)	Initiate microbial water quality measures within Laing Dam at R2R001*, R2H010Q01 on the Buffalo River*, R2H009Q01 on the Ngqokweni River* and R2H015Q01 on Yellowwoods River*. Initiate microbial water quality measures within effluent from the Zwelitsha WWTW on the Buffalo River*.	Identify source of diffuse contamination and implement management intervention. If derived from a point source, initiate management intervention at the point source.

* **-** Additions to monitoring network needed

Table 2.2 continued: Region 5: Buffalo River between Laing Dam and Bridle Drift Dam

Water Quality Variable	Suggested TPCs												Current and Future Monitoring	Possible Management Action
	Jan	**Feb**	**Mar**	**Apr**	**May**	**Jun**	**Jul**	**Aug**	**Sep**	**Oct**	**Nov**	**Dec**		
Salinity in TDS (mg ℓ $^{-1}$) 75% of DWA(2001) PES + 10%	340	352	283	301	353	459	486	513	546	553	522	436	DWA monitoring point R2H027Q01 on the Buffalo River. Monthly medians	Identification of diffuse or point source of salinity and initiation of management intervention
pH range of DWA (2001) PES from 25%-75% ± 0.5	7.4 – 8.8	7.3 – 8.8	7.2 – 8.7	7.3 – 8.6	7.5 – 8.6	7.5 – 8.8	7.6 – 8.9	7.2 – 8.8	7.5 – 8.9	7.8 – 9	7.8 – 9	6.9 – 8.4	DWA monitoring point R2H027Q01 on Buffalo River. Monthly medians.	Identification of problem and initiation of management intervention
Temperature range of DWA (2001) PES 95% + 2 °C	23	28	25	23	21	19	20	19	18	21.5	22	22	DWA monitoring point R2H027Q01 on Buffalo River, as well as an intermediate location closer to the outflow from Laing Dam*.	Initiate mixing of water layers of different temperatures within the release mechanism of Laing Dam
DWA (2001) Median PO_4 + 10% and TIN:PO_4 ratio - 10%	$PO_4 > 0.031$ mg ℓ $^{-1}$ and TIN:$PO_4 < 7.33$												DWA monitoring point R2H027 on the Buffalo River	Identify diffuse sources of nutrients and implement management action.
Sediment	Perceived loss of riffle environments, increase in turbidity, or narrowing of river channel												Initiate measurement of turbidity at R2H027Q01 on the Buffalo River* ; identify physical changes over time of the river channels using satellite images *	Identify land management practices that may be leading to erosion and implement management action

* - Additions to monitoring network needed

Table 2.2 continued: Region 6: Bridle Drift Dam

Water Quality Variable	**Suggested TPCs**	**Current and Future Monitoring**	**Possible Management Action**
Salinity DWAF (1998) TDS Objective	> 350 mg ℓ^{-1}	Initiate measures of salinity within Bridle Drift Dam*. Monitor salinity within tributaries leading to Bridle Drift Dam.	Identify point or diffuse source of salinity and initiate management intervention.
Nutrients DWAF (1998) PO_4 and Chlorophyll a objectives	$PO_4 > 0.035$ mg ℓ^{-1} and Chlorophyll a > 0.030 mg ℓ^{-1}	Initiate measures of nutrients and Chlorophyll a within Bridle Drift Dam*. Monitor nutrients within tributaries leading to Bridle Drift Dam.	Identify diffuse sources of nutrients and implement management action.
Toxins in Bridle Drift Dam	Detection of toxins of unacceptable concentration within the tributaries leading to Bridle Drift Dam. Detection of anoxic conditions within Bridle Drift Dam that may cause the release of toxic metals from the sediments (manganese and iron). Detection of toxins within the sediment profile of Bridle Drift Dam. Detection of Persistent Organic Pollutants (POPs) within Laing Dam.	Initiate monitoring for toxins within tributaries leading to Bridle Drift Dam*. Monitoring of oxygen status at the bottom of Bridle Drift Dam*. Periodic assessment of the toxin profile of sediment within Bridle Drift Dam*. Measures of POPs in Laing Dam.	Initiate management intervention controlling land-use that may be leading to diffuse sources of toxins. Management of agriculture if POPs detected.
Sediment	Settling of sediment into Bridle Drift Dam and decreasing of dam capacity	Yearly measures of dam capacity*.	Identification of land practices upstream that are causing sediment transport such as grazing causing erosion, and the implementation of intervention management.
DWAF (1998) *E. coli* objective	> 200 (#/100 ml)	Initiate microbial water quality measures within Bridle Drift Dam* and tributaries leading to Bridle Drift Dam*.	Identify source of diffuse contamination and implement management intervention. If derived from a point source, initiate management intervention at the point source.

* - Additions to monitoring network needed

Table 2.2 continued: Region 7: Buffalo River between Bridle Drift Dam and the estuary

Water Quality Variable	Suggested TPCs												Current and Future Monitoring	Possible Management Action
	Jan	Feb	Mar	Apr	May	Jun	Jul	Aug	Sep	Oct	Nov	Dec		
Salinity in TDS (mg ℓ $^{-1}$) 50% of DWA (2001) PES + 30%	481	462	398	335	400	530	530	567	533	555	430		DWA monitoring point R2H002Q01 on the Buffalo River. Monthly medians	Identification of diffuse or point source of salinity and initiation of management intervention
Temperature range of DWA (2001) PES 95% + 2 °C	23	28	25	23	21	19	20	19	18	21.5	22	22	DWA monitoring point R2H002Q01 on Buffalo River, as well as an intermediate location closer to the outflow from Bridle Drift Dam*.	Initiate mixing of water layers of different temperatures within the release mechanism of Bridle Drift Dam
Sediment	Perceived loss of riffle environments, increase in turbidity, or narrowing of river channel												Initiate measurement of turbidity at R2H002Q01 on the Buffalo River* ; identify physical changes over time of the river channels using satellite images *	Identify land management practices that may be leading to erosion and implement management action

* - Additions to monitoring network needed

Table 2.2 continued: Region 8: Gubu Dam

Water Quality Variable	**Suggested TPCs**	**Current and Future Monitoring**	**Possible Management Action**
Salinity DWAF (1998) TDS Objective	> 100 mg ℓ^{-1}	Monthly medians of salinity from S6R001Q01 on Gubu Dam.	Identify point or diffuse source of salinity and initiate management intervention.
Nutrients DWAF (1998) PO_4 and Chlorophyll a objectives	$PO_4 > 0.050$ mg ℓ^{-1} and Chlorophyll a > 0.035 mg ℓ^{-1}	Monthly medians of PO_4 from S6R001Q01 on Gubu Dam. Initiate measures of Chlorophyll a at S6R001Q01*.	Identify diffuse sources of nutrients and implement management action.
DWAF (1998) *E. coli* objective	> 150 (#/100ml)	Initiate microbial water quality measures at S6R001Q01*.	Identify source of diffuse contamination and implement management intervention.
Sediment	Settling of sediment into Gubu Dam and decreasing of dam capacity	Yearly measures of dam capacity*.	Identification of land practices upstream that are causing sediment transport such as grazing causing erosion, and the implementation of intervention management.

* - Additions to monitoring network needed

Table 2.2 continued: Region 9: Kubusi River above Wriggleswade Dam

Water Quality Variable	**Suggested TPCs**												**Current and Future Monitoring**	**Possible Management Action**
	Jan	**Feb**	**Mar**	**Apr**	**May**	**Jun**	**Jul**	**Aug**	**Sep**	**Oct**	**Nov**	**Dec**		
Salinity in TDS (mg ℓ^{-1}) 75% of DWA(2001) PES + 10%	74	73	69	83	92.4	108	109	101	102	94.6	89	80	DWA monitoring point S6H001Q01 on the Kubusi River. Monthly medians	Identification of diffuse or point source of salinity and initiation of management intervention
pH range of DWA(2001) PES from 25%-75% ± 0.5	7.6 – 8.8	7.6 – 8.9	7.6 – 8.8	7.5 – 8.7	7.6 – 8.8	7.6 – 8.8	7.6 – 8.8	7.6 – 8.8	7.8 – 8.9	7.6 – 9.1	7.8 – 9.1	7.6 – 8.9	DWA monitoring point S6H001Q01 on Kubusi River. Monthly medians.	Identification of problem and initiation of management intervention
DWA (2001) Median PO_4 + 10% and TIN:PO_4 ratio - 10%	PO_4 > 0.021 mg ℓ^{-1} and TIN:PO_4 < 10.18												DWA monitoring point S6H001Q01 on the Kubusi River	Identify diffuse sources of nutrients and implement management action.
Sediment	Perceived loss of riffle environments, increase in turbidity, or narrowing of river channel												Initiate measurement of turbidity at S6H001Q01 on the Kubusi River* ; identify physical changes over time of the river channels using satellite images *	Identify land management practices that may be leading to erosion and implement management action

* - Additions to monitoring network needed

Table 2.2 continued: Region 10: Wriggleswade Dam

Water Quality Variable	Suggested TPCs	Current and Future Monitoring	Possible Management Action
Salinity DWAF (1998) TDS Objective	> 200 mg ℓ^{-1}	Monthly medians of salinity from S6R002Q01 on Wriggleswade Dam.	Identify point or diffuse source of salinity and initiate management intervention.
Nutrients DWAF (1998) PO_4 and Chlorophyll a objectives	PO_4 > 0.050 mg ℓ^{-1} and Chlorophyll a > 0.015 mg ℓ^{-1}	Monthly medians of PO_4 from S6R002Q01 on Wriggleswade Dam. Initiate measures of Chlorophyll a at S6R002Q01*.	Identify diffuse sources of nutrients and implement management action.
DWAF (1998) *E. coli* objective	> 200 (#/100ml)	Initiate microbial water quality measures at S6R002Q01*.	Identify source of diffuse contamination and implement management intervention.
Sediment	Settling of sediment into Wriggleswade Dam and decreasing of dam capacity	Yearly measures of dam capacity*.	Identification of land practices upstream that are causing sediment transport such as grazing causing erosion, and the implementation of intervention management.

* - Additions to monitoring network needed

Table 2.2 continued: Region 11: Kubusi River between Wriggleswade Dam and confluence with the Kei River

Water Quality Variable	**Suggested TPCs**												**Current and Future Monitoring**	**Possible Management Action**
	Jan	**Feb**	**Mar**	**Apr**	**May**	**Jun**	**Jul**	**Aug**	**Sep**	**Oct**	**Nov**	**Dec**		
Salinity in TDS (mg ℓ^{-1}) 75% of DWA(2001) PES + 10%	208	200	210	219	218	190	201	205	220	205	239	197	DWA monitoring point S6H002Q01 on the Kubusi River. Monthly medians	Identification of diffuse or point source of salinity and initiation of management intervention
pH range of DWA(2001) PES from 25%-75% ± 0.5	7.1 – 8.6	7.3 – 8.5	7.4 – 8.7	7.2 – 8.4	7.3 – 8.5	7.2 – 8.4	7.3 – 8.4	7.2 – 8.6	7.1 – 8.4	7.3 – 8.6	7.2 – 8.5	7.4 – 8.7	DWA monitoring point S6H002Q01 on Kubusi River. Monthly medians.	Identification of problem and initiation of management intervention
DWA (2001) Median PO_4 + 10% and TIN:PO_4 ratio - 10%	PO_4 > 0.022 mg ℓ^{-1} and TIN:PO_4 < 2.79												DWA monitoring point S6H002Q01 on the Kubusi River	Identify diffuse sources of nutrients and implement management action.
Sediment	Perceived loss of riffle environments, increase in turbidity, or narrowing of river channel												Initiate measurement of turbidity at S6H002Q01 on the Kubusi River* ; identify physical changes over time of the river channels using satellite images *	Identify land management practices that may be leading to erosion and implement management action
* - Additions to monitoring network needed														

Table 2.2 continued: Region 12: Nahoon Dam

Water Quality Variable	Suggested TPCs	Current and Future Monitoring	Possible Management Action
Salinity DWAF (1998) TDS Objective	> 400 mg ℓ^{-1}	Monthly medians of salinity from R3R001Q01 on Nahoon Dam.	Identify point or diffuse source of salinity and initiate management intervention.
Nutrients DWAF (1998) PO_4 and Chlorophyll a objectives	PO_4 > 0.070 mg ℓ^{-1} and Chlorophyll a > 0.007 mg ℓ^{-1}	Monthly medians of PO_4 from R3R001Q01 on Nahoon Dam. Initiate measures of Chlorophyll a at R3R001Q01*.	Identify diffuse sources of nutrients and implement management action.
DWAF (1998) *E. coli* objective	> 200 (#/100 ml)	Initiate microbial water quality measures at R3R001Q01*.	Identify source of diffuse contamination and implement management intervention.
Sediment	Settling of sediment into Nahoon Dam and decreasing of dam capacity	Yearly measures of dam capacity*.	Identification of land practices upstream that are causing sediment transport such as grazing causing erosion, and the implementation of intervention management.

* - Additions to monitoring network needed

Table 2.2 continued: Region 13: Nahoon River upstream of dam: upper reaches

Water Quality Variable	Suggested TPCs		Current and Future Monitoring	Possible Management Action
	Summer	**Winter**		
Salinity in TDS (mg ℓ $^{-1}$) 75% of observed DWA data + 10%	831.35	686.4	Increase frequency of monitoring of salinity on the upper Nahoon River*. Monthly medians	Identification of diffuse or point source of salinity and initiation of management intervention
pH range of DWA observed data from 25%-75% ± 0.5	6.99-8.45	7.2-8.56	Increase frequency of monitoring of pH on the upper Nahoon River*. Monthly medians	Identification of problem and initiation of management intervention
DWA observed Median PO_4 + 10% and TIN:PO_4 ratio - 10%	PO_4 > 0.044 mg ℓ $^{-1}$ and TIN:PO_4 < 4.5		Increase frequency of monitoring of PO_4, TIN and Chlorophyll a on the Nahoon River*. Monthly medians	Identify diffuse sources of nutrients and implement management action.
Sediment	Perceived loss of riffle environments, increase in turbidity, or narrowing of river channel		Initiate measurement of turbidity on the Nahoon River* ; identify physical changes over time of the river channels using satellite images *	Identify land management practices that may be leading to erosion and implement management action

* - Additions to monitoring network needed

Table 2.2 continued: Region 14: Nahoon River upstream of dam (excluding dam): middle reaches

Water Quality Variable	Suggested TPCs		Current and Future Monitoring	Possible Management Action
	Summer	**Winter**		
Salinity in TDS (mg ℓ^{-1}) 75% of observed DWA data + 10%	936.65	822.25	Increase frequency of monitoring of salinity on the middle Nahoon River*. Monthly medians	Identification of diffuse or point source of salinity and initiation of management intervention
pH range of DWA observed data from 25%-75% ± 0.5	7.20-8.86	7.20-8.86	Increase frequency of monitoring of pH on the middle Nahoon River*. Monthly medians	Identification of problem and initiation of management intervention
DWA observed Median PO_4 + 10% and TIN:PO_4 ratio - 10%	$PO_4 > 0.055$ mg ℓ^{-1} and TIN:$PO_4 <$ 4.27		Increase frequency of monitoring of PO_4, TIN and Chlorophyll a on the Nahoon River*. Monthly medians	Identify diffuse sources of nutrients and implement management action.
Sediment	Perceived loss of riffle environments, increase in turbidity, or narrowing of river channel		Initiate measurement of turbidity on the Nahoon River* ; identify physical changes over time of the river channels using satellite images *	Identify land management practices that may be leading to erosion and implement management action

* - Additions to monitoring network needed

Table 2.2 continued: Region 15: Nahoon River downstream of dam (excluding dam): lower reaches

Water Quality Variable	Suggested TPCs		Current and Future Monitoring	Possible Management Action
	Summer	**Winter**		
Salinity in TDS (mg ℓ^{-1}) 75% of observed DWA data + 10%	843.7	815.1	Increase frequency of monitoring of salinity on the middle Nahoon River*. Monthly medians	Identification of diffuse or point source of salinity and initiation of management intervention
pH range of DWA observed data from 25%-75% ± 0.5	7.10-8.3	7.00-8.7	Increase frequency of monitoring of pH on the middle Nahoon River*. Monthly medians	Identification of problem and initiation of management intervention
DWA observed Median PO_4 + 10% and TIN:PO_4 ratio - 10%	$PO_4 > 0.055$ mg ℓ^{-1} and TIN:$PO_4 < 14.20$		Increase frequency of monitoring of PO_4, TIN and Chlorophyll a on the Nahoon River*. Monthly medians	Identify diffuse sources of nutrients and implement management action.
Sediment	Perceived loss of riffle environments, increase in turbidity, or narrowing of river channel		Initiate measurement of turbidity on the Nahoon River* ; identify physical changes over time of the river channels using satellite images *	Identify land management practices that may be leading to erosion and implement management action

* - Additions to monitoring network needed

CHAPTER 3. SELECTION OF QUANTITY AND QUALITY MODELS USED

by

Sukhmani Mantel, Andrew Slaughter and Denis Hughes

3.1 Use of modelling in management of water resources

Various authors have promoted decision-making based on modelling for resource management and operation over the alternative of decision-making based on historical recorded data (Bath et al., 1997; Coleman et al., 2007). This is due to the limited and incomplete dataset of conditions available under historical conditions. In addition, these data might not be representative of future climate and of expected supply and demand scenarios. Modelling has the advantage of simulating the water resource situation under various scenarios of physical, chemical and biological processes and it can be useful in evaluating the relative effectiveness of various management options for specific local conditions. Modelling also allows for future planning by revealing gaps in present data gathering that can be the focus for future remediation (Coleman et al., 2007). Modelling water resources however, gives rise to modelling uncertainty that needs to be considered in addition to climate change model uncertainty (i.e. the uncertainty arising from different predictions of various climate change models).

Given that climate change and development impacts on both water quantity and quality are of interest within this project, it was necessary to select the main model for use as one that could simulate both of these components of water resources. However, it is possible that the selected model would not have been previously applied either in the region or in South Africa. For this reason, it was decided to also make use of the Pitman model to simulate the water quantity components of the two basins. The justification for this is based on the extensive experience of the use of this model within the country as well as the relatively high confidence that can be typically expressed in the model outputs. The Pitman model has been applied in this project within an uncertainty framework (Kapangaziwiri et al., 2009). For the Buffalo River basin, the model has only been applied in the simulation of natural hydrology (with and without climate change impacts), while in the Caledon it has been applied to the simulation of both natural and developed conditions (with and without climate change impacts).

3.2 Criteria for selecting water availability and water quality models for the project

At the start of the project, it was decided that the water availability and water quality model should be an off-the-shelf model that has been tested elsewhere. The model should assist in the assessment of the effects of climate change scenarios on the water availability and water quality of the rivers and the reservoirs in the catchments being modelled. For the model to be useful for water management and planning, it should ideally be capable of accepting five primary sets of input data:

- **Meteorological data** – air temperature and climate data obtainable from the South African Weather Service and the outputs of the General Circulation Models (GCMs) that have been downscaled by the Climate Systems Analysis Group (CSAG) to the catchment area being modelled.

- **Water quantity/hydrology data** – flow data available from the South African Department of Water Affairs (DWA) for calibration purposes.
- **Water user demands** – by various sectors under the present conditions and under future development scenarios. These data can be obtained from the regional and national DWA and municipality planning documents.
- **Reservoir data** – the model should ideally be able to model for reservoir stratification using data on reservoir dimensions, volume, and water quality and it should be capable of producing reservoir operating rules for the management of the water supply system. The reservoir data can be obtained from the Department of Water Affairs (DWA) and the local water board who might conduct additional monitoring of the system.
- **Water quality data for river and water treatment works** – the model should be able to accept data on the water quality of the river and the water treatment works. These data are available from the DWA, the water board and/or the local municipality.

The state of the system has been summarised in Chapter 2 above. Presently the Amatole system faces two major water quality problems, that of waste water treatment works (WWTWs) being frequently located upstream of water supply reservoirs and secondly, the issues of poor management and ageing infrastructure contributing to excessive nutrient inputs and high potential for eutrophication. From a water quality point of view, some of the future climate scenarios that were considered useful to investigate are whether the changes to water flow will affect the residence time of pollutants in the system, whether air temperature increases will exacerbate potential eutrophication problems, and also, if the model is able to realistically simulate these effects.

A literature review of water quality models applied in the past to South Africa indicated four possible models that were considered for use under this project:

- **IMPAQ model** (Impoundment/ River Management and Planning Assessment tool for water Quality simulations). This model has been used across various rivers and reservoirs in South Africa including Mgeni River, Duzi River (Inanda Dam in KZN), Great Kei River and the Amatole Water Supply Area (DWAF, 2006b).
- **WEAP model** (Water Evaluation and Planning Model) developed by the Stockholm Environment Institute (SEI) (Sieber and Purkey, 2007). WEAP has been applied to various sub-catchments of the Olifants River (Lévite et al., 2003; McCartney and Arranz, 2007).
- **CE-QUAL-W2 model** developed at the Environmental and Hydraulics laboratories, U.S. Army Engineer Waterways Experiment Station, has been applied to model the Vaal Barrage in addition to the Laing and Inanda dams (Görgens and de Clercq, 2006).
- **DYRESM model** (Dynamic Reservoir Simulation Model) developed by the Centre for Water Research, University of Western Australia. DYRESM has been used for modelling the Inanda, Roodeplaat and Hartbeespoort dams in South Africa (Bath et al., 1997).

Table 3.1 shows an assessment of the four models in terms of the selection criteria listed above. The IMPAQ model has been previously applied to the Amatole system (DWAF, 2006b), although not using future climatic predictions. Although the IMPAQ and WEAP models do not fit all the criteria for this study, they are simple models that have been widely used and that can provide insight into model setup and outputs for the other two models that are more complex.

The major advantage of a system level model like WEAP is that it provides results on water availability for the system that the reservoir models do not provide. Thus, the WEAP model (Version 3.3) was considered in this project as a system level model since it provides results for system level water use and availability (in addition to river water quality modelling) under the present and future water demands as well as under future climate scenarios.

Table 3.1 Comparison of the four models being considered for water quality modelling for the project.

Water Quality Model	**Input data**	**Outputs**	**Model limitations for the project**
IMPAQ	Physical, chemical and microbial parameters, hydrological data, pollution sources data and meteorological data	Operating rules and management of surface water sources	No modelling for dam stratification
WEAP	Meteorological data, hydrological data, water user demands, physical, chemical and microbial parameters, pollution sources, treatment and discharges data, priorities of downstream requirements and reservoir operating rules	System level water demand and supply management	No modelling for dam stratification or reservoir water quality, but can be linked to CE-QUAL-K2.
CE-QUAL-W2	Meteorological data, stratification, physical, chemical and microbial parameters data, hydrological data, reservoir depth-area, volume, spillway and off-take characteristics data	Management of water quantity and quality to develop system operation rules	Fits the criteria for this study, except only applicable to reservoir modelling.
DYRESM	Meteorological data, physical, chemical and microbial parameters data, hydrological data, stratification, and off-take characteristics data	Management of water quantity and quality to develop system operation rules	Fits the criteria for this study, except only applicable to reservoir modelling.

3.3 Discussion of water quality models available

While there are many water quality models available, the above requirements, as well as the limits of available observed data, restrict the number of suitable models available (see Table 3.1). As part of the process of investigating existing models, the Impoundment Management and Planning Assessment Model (IMPAQ), was investigated. The hydrology of IMPAQ is driven by the Pitman (Pitman, 1973) and the Water Resources Yield (WRYM) models. While this model would seem suitable, study of the model showed some shortcomings including: 1) the model works on a monthly time step, which is not ideal for water quality simulation; 2) the model incorporates no indication of uncertainty; 3) the model does not simulate nitrogen, which is an important nutrient affecting eutrophication; 4) methods of simulating point and diffuse sources of water quality variable loads, as well as in-stream fate of water quality variables, could be improved with more updated science and better methods.

The Water Evaluation and Planning (WEAP) model (Sieber and Purkey, 2007) also includes rudimentary water quality simulation. These include facilities to simulate conservative and non-conservative water quality constituents. Non-conservative water quality variables such as nutrients are simulated using a single model rate coefficient, which encompasses all processes, such as chemical speciation, sedimentation and uptake by plants if nutrients are taken as an example. WEAP does not simulate water quality within reservoirs.

Two dedicated reservoir models exist in CE-QUAL-W2 and the Dynamic Reservoir Simulation Model (DYRESM). These reservoir models typically simulate reservoir processes to a high degree of detail, and require a large amount of data for calibration.

The Water Quality Systems Assessment Model (WQSAM) has been developed to an initial preliminary stage, due to the perceived need for a dedicated water quality model that directly links to the yield models (WRYM or WReMP), and provides simulations that are useful to water resource management. WQSAM is described in greater detail in in Chapter 7 of this report.

3.4 WEAP model: A brief literature review

The Water Evaluation And Planning (WEAP) model was developed by the Stockholm Environmental Institute (SEI). WEAP is a water accounting model and an Integrated Water Resource Management (IWRM) tool to investigate different scenarios of human water use and resource development (Yates et al., 2005) while considering many competing users of water (Sieber and Purkey, 2007) and facilitating trade-off analysis. WEAP simulates water supply and demand, flow, storage, pollution generation, treatment and discharge (Sieber and Purkey, 2007). WEAP is also able to incorporate environmental flows as a water demand (Sieber and Purkey, 2007) and has simple water quality modelling functionality. As a water quality model, WEAP is much simpler, and simulates fewer processes than more complicated models such as QUAL2E, but has the advantage of supporting management scenario functionalities, as the model explicitly represents waste water and water treatment infrastructure by their capacities and cost (Assaf and Saadeh, 2008). WEAP is capable of modelling the concentration of water quality constituents in a river using simple mixing, first-order decay equations or by linking to the US EPA water quality model QUAL2K.

WEAP has found some past application in South Africa, although no published studies as yet have attempted to simulate water quality using WEAP. Lévite et al. (2003) used WEAP to simulate water demand scenarios in a tributary of the Olifants River. The study focussed on the Steelpoort River as a relatively simple basin with no large dams or inter-basin transfers. The researchers found the process of quantifying the demand difficult as information was hard to come by, and users found it difficult to quantify their usage. The study also incorporated environmental flow requirements for the Olifants into the study. Arranz and McCartney (2007) outline the application of WEAP to the whole Olifants River catchment, which is a complicated task as the catchment contains many different users, such as rural communities, mining, agriculture, forestry and power generation. The Olifants catchment also contains many reservoirs, and the presence of many boreholes required the explicit inclusion of ground water into the model. The presence of an inter-basin transfer scheme also complicated the modelling process. The study was done by Arranz and McCartney (2007) to investigate future development impacts on the Olifants catchment. Here, water quantity was simulated, with unmet demand being the main output variable to gauge model results. This study also explicitly modelled the environmental flow requirements through the Kruger National Park. Similar to the current study, three development scenarios of higher growth, medium growth and lower growth were investigated. This model did not simulate water quality, and this allowed urban and mining demands to be entered as net water demands.

International applications of WEAP include that of Yates et al. (2005), Yates et al. (2009), Assaf and Saadeh (2008) and Jenkins et al. (2005). Assaf and Saadeh (2008) modelled Biological Oxygen Demand (BOD) in the Litani River in Lebanon. Yates et al. (2005) applied WEAP to two small sub-catchments of the Sacramento watershed in California, USA. Yates et al. (2005) found that the hydrological model within WEAP simulated most of the variability and low flows in the investigated watersheds, but did not give good simulations of the extreme low flows. Yates et al. (2009) investigated the application of WEAP to the Sacramento basin which supports extensive irrigation. Jenkins et al. (2005). Applied the WEAP model to a watershed in Kenya as a tool to encourage stakeholder involvement.

3.5 Reservoir models previously used in South Africa

In order to simulate the dynamics of the reservoir, a hydrodynamic model is necessary. WEAP does not have this capability, and thus, the project team investigated other reservoir models that have been used in South Africa in the recent past for use in the present project.

Rossouw et al. (2008) describe the use of the NEAP (Nutrient Enrichment Assessment Protocol) internet-based model for modelling phosphorus loading in reservoirs. The authors focused on phosphorus as it can be managed by modifying land-use practices or by controlling point sources. Total Phosphorus is also the key element that regulates primary production and thus eutrophication of reservoirs. The NEAP model is a coarse level model with an annual time-step that is not useful for the present project.

Bath et al. (1997) investigated the adaptation and use of two reservoir dynamic models to selected South African water bodies. The one-dimensional DYRESM (Dynamic Reservoir Simulation Model) was applied to the Inanda, Roodeplaat and Hartbeespoort dams for simulating temperature and salinity. As this is a one-dimensional model, it presumes that lateral variations are relatively small and therefore, it is most useful for small lakes and reservoirs where the vertical dimension needs to be modelled. This model has been developed by the Centre for Water Research, University of Western Australia, and recently the developers have changed their software policy and have started charging an annual membership fee to receive user support. The project team decided not to use this model as this model, and particularly the user support services are not available freely.

The hydrodynamic and water quality model CE-QUAL-W2 has been developed by the United States Corps of Engineers (http://www.ce.pdx.edu/w2/; accessed on 30 March 2011; Cole and Wells, 2008) and in South Africa it has been used by Bath et al. (1997) for modelling the Vaal Barrage, the Inanda Dam and the Laing Dam. The model is capable of modelling the vertical and the lateral dimensions for temperature and various water quality constituents. In the case of Laing Dam, Bath et al. (1997) used the CE-QUAL-W2 model to simulate the stratification patterns in the dam and the influence of the water transfer from the Wriggleswade Dam on the TDS levels in Laing Dam. The authors recommended the use of CE-QUAL-W2 and DYRESM to develop operating rules for water release from Wriggleswade Dam, and also continual collection of reservoir and meteorological data in addition to the implementation of management and monitoring strategies for reservoirs requiring water quality management in future. Kamish and Petersen (2007) provide a summary of the application of CE-QUAL-W2 to the Voëlvlei Dam (to simulate algal blooms) and the Berg River Dam (to simulate temperature of environmental releases). The CE-QUAL-W2 model is being used by Golder Associates (WRC project K5-2028) to model the Voëlvlei Dam.

3.6 Discussion and conclusion on models chosen

3.6.1 Water availability and use models

WEAP model has been utilised across the world as indicated by the publications on the website (http://www.weap21.org/index.asp?doc=16), including various sub-catchments of the Olifants River (Lévite et al., 2003; McCartney and Arranz, 2007, 2009). The primary use of the model in other studies has been for water quantity modelling, although in the past couple of years, the water quality modelling component of this model has been used by some researchers. The model is relatively simple to set up if required data (water demand, input flow or rainfall data, water quality, pollution sources, etc.) are available.

Some points to consider when using the WEAP model are:

- The model does not accept time series data with missing periods of data. Therefore, the project team had to use data patching for both water quantity and quality data. Patching introduces model uncertainty to the results.
- The effective precipitation equations that were used in the WEAP model were generated in order to calibrate the model. The effective precipitation that was used would incorporate the geology, soils and other catchment characteristics. The calibration results were acceptable, although not exact, and therefore, this factor adds to the overall uncertainty in the results.
- The water demand for alien vegetation is deducted from the river runoff, similar to other water user demands. In reality, alien vegetation affects river runoff and thus, there could be a situation created by the model where alien vegetation demand is not met, which cannot occur in reality.
- There is no facility to model a Water Treatment Work as an entity that has a specific treatment capacity and whose input and output have different water quality values. Discussion with SEI programmers confirmed that the only way to model a WTW is as a transmission link. In this project, WTWs have been modelled as a demand entity that supplies water to other demand sites (population, industry).
- As noted earlier, WEAP does not have the capability to model water quality in the reservoirs.

3.6.2 Water quality models

While the WEAP model does provide rudimentary water quality simulation that is relatively easy to use, the simulation methods for water quality are perhaps too simple. The lumping of all process rates for non-conservative water quality variables into one coefficient is perhaps too simplistic, and limits water quality simulation. WEAP could possibly be suitable for simulating conservative water quality constituents such as salinity. However, as seen from previous WEAP results for salinity, unrealistic spikes in salinity were simulated for the Upper Amatole region that were most likely linked to the irrigation return flow simulation by WEAP.

In addition, the inability of the model to simulate water quality within reservoirs is a serious shortcoming. Within the application of WEAP in this project to historical, development and climate change scenarios, simulated water quality from upstream to downstream reverted back to historical observed seasonal water quality when the model had to deal with reservoirs.

While IMPAQ showed the right approach to meet water quality modelling needs in water resource management in South Africa by explicitly using the results of yield model outputs, previously mentioned shortcomings of the model (see Section 3.2) preclude the realistic use of the model. WEAP has also been shown to be inadequate in regards to water quality modelling. Since South Africa’s water management needs in the context of water quality modelling require estimates of risk associated with management decisions, rather than time series estimates of a particular water quality variable, it was decided that a new water quality systems assessment model should be developed, based on the work done with IMPAQ, but improving on the limitations identified. This gave rise to the development of the Water Quality Systems Assessment Model (WQSAM). Chapter 7 of this report gives more information on WQSAM.

3.6.3 Watershed Assessment Model (WAM)

An MSc candidate, Bret Whiteley, has been looking at the application of the WAM model, which has been used widely in the USA, to the Buffalo River. WAM is a deterministic, distributed and physically based hydrologic watershed model, which represents the complex water quantity and quality responses within the terrestrial portion of the hydrological cycle, based on detailed characterisation data. His preliminary results are presented in Appendix A.

CHAPTER 4. MODELLING OF CLIMATE CHANGE IMPACTS ON HYDROLOGY WITH THE PITMAN MODEL

by

Denis Hughes

4.1 Climate change models and downscaling

Global Circulation Models (GCMs) have been found to produce bias in simulated climate across the African continent and thus, some studies for southern Africa have utilised downscaling to produce Regional Climate Models (RCMs) that provide more focused and relevant results for the region in comparison to GCMs (Christensen et al., 2007: 867). This allows the regional authorities and communities to focus on adaptive measures relevant to the specific predictions for their area.

Two South African research papers that have used downscaled GCMs to generate rainfall predictions and the associated uncertainty are relevant to this study. Hewitson and Crane (2006) used three empirically downscaled GCMs and mean atmospheric fields to generate future rainfall predictions over South Africa. They showed some convergence in precipitation predictions (although the magnitude of the prediction varied) with results indicating increased summer (December-February) rainfall in the central and eastern part of the country and decreased rainfall in the western section. A recent article on intermediate and future climate scenarios, using six GCMs of the IPCC 3rd and 4th Assessment Reports that were empirically downscaled for South Africa, reinforced this uncertainty in rainfall predictions (Lumsden et al., 2009).

The climate change data that have been used in this project are derived from the data generated by the Climate Systems Analysis Group (CSAG) based at the University of Cape Town. The data consist of daily rainfall, maximum and minimum temperatures for three scenarios; the baseline situation (1961-2000), the near future (2046-2065) and the far future (2081-2100). The estimates are based on downscaled data from nine GCMs using the Special Report on Emissions Scenarios (SRES) A2 emission scenario. Table 4.1 lists the GCMs that are part of the CSAG standard data product set and that have been used in this study. The downscaling approach used by CSAG is documented in Hewitson et al. (2005) and Hewitson and Crane (2006) and is not described here. The most important issue from the point of view of this study is that the GCM outputs are all down-scaled using a consistent approach and that the baseline scenarios represent the recent past and can therefore be compared with historical data.

Table 4.2 GCMs used in the study.

GCM abbreviation	Source of GCM
CCCMA	Canadian Centre for Climate Modelling and Analysis
CNRM	France Centre National de Recherches Meteorologiques
CSIRO	Australian CSIRO Atmospheric Research
GFDL	USA NOAA Geophysical Fluid Dynamics Lab
GISS	USA Goddard Institute for Space Studies
IPSL	France Institut Pierre Simon Laplace
MIUB	Germany Meteorological Institute of the University of Bonn
MPI	Max-Planck Institute For Meteorology
MRI	Japan Meteorological Research Institute

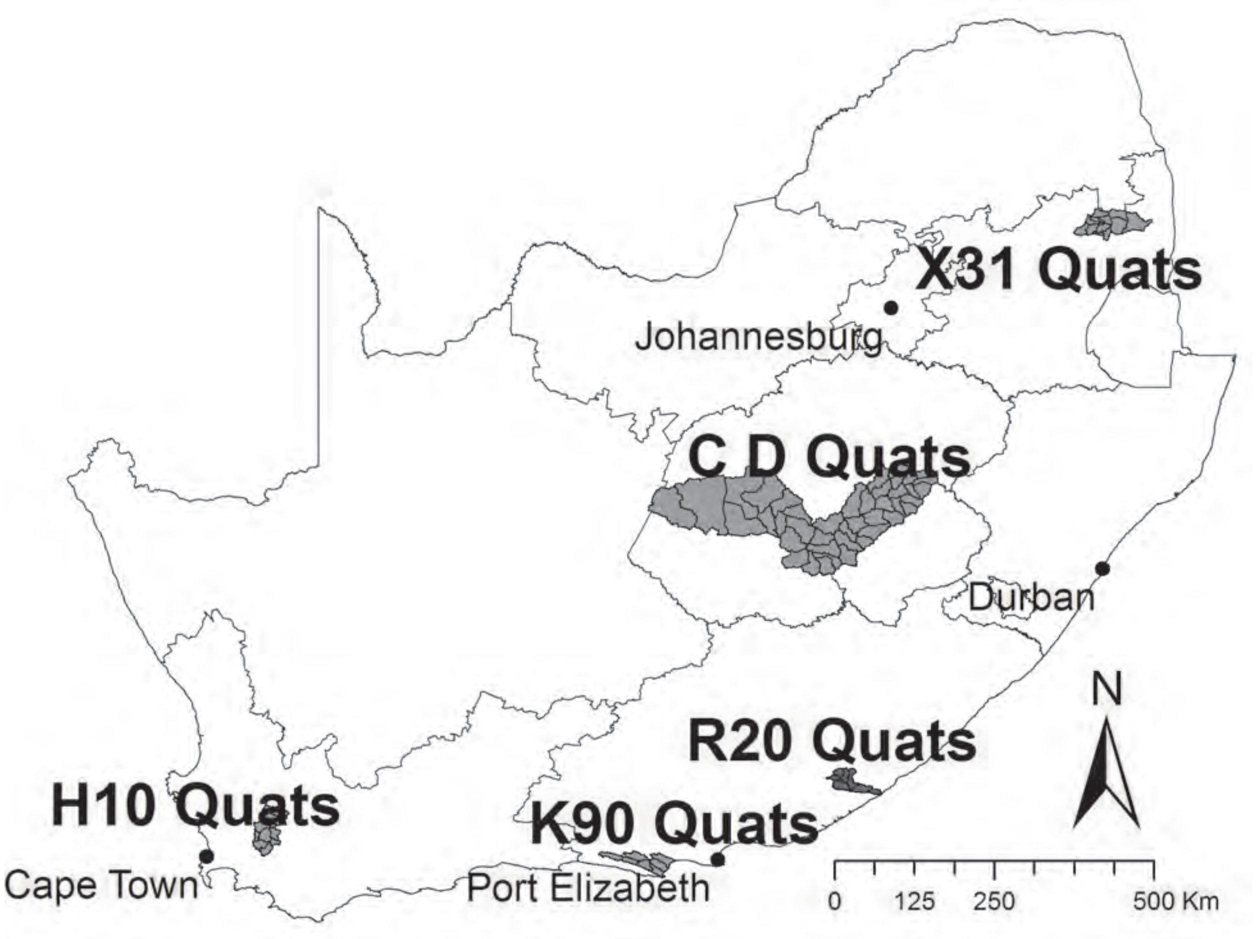


Figure 4.1 Areas across South Africa that are being investigated as part of the uncertainty analyses.

4.2 Processing data

4.2.1 Processing the down-scaled climate model data

To date, the IWR have received the data for the Buffalo River catchment area. The daily time series generated by CSAG are for so-called quinary catchments, which are smaller than the quaternary catchments that are typically used for water resources analysis in South Africa. Within the Amatole region (Buffalo, Nahoon and upper Kubusi River catchments) there are 11 quaternary catchments (R20A-G, R30E and F, S20A and B; Figure 4.1) and 36 quinary catchments. The first step in the process to compile monthly rainfall time series at the quaternary scale was therefore to compute catchment average monthly rainfall time series from the quinary daily data. This was achieved using the SPATSIM standard point-to-area method (based on inverse distance weighting) after creating a GIS coverage of points representing the centroids of the quinary catchments. The degree of spatial variation in the temperature data did not justify using an equivalent approach and the temperature (and subsequent evaporation demand estimates) were based on representative quinary values.

4.2.2 Processing the rainfall data

One of the immediate observations is that the baseline rainfall data outputs from the down-scaled GCMs are not consistent with historical observed rainfall data and that some correction process would be required before the near and far future rainfall data could be used as input to the hydrological model and the outputs compared with simulations based on historical data.

Figure 4.2 illustrates the situation for one of the climate models. The solid black line represents the seasonal distribution of mean monthly rainfall based on historical data using the period 1961-2000 (the same as the climate model baseline data). The data that have been used are taken from the WR2005 study and are based on spatial interpolation of gauged rainfall data (the data plotted are for the upper reaches of the Buffalo River catchment). The black vertical lines represent one standard deviation either side of the historical mean. The blue line represents the climate model baseline estimates of the monthly means and it is clear that there are substantial differences between this model and the historical data. The same applies to the other models, to differing degrees. It is also apparent that the frequency distribution characteristics of the climate models' baseline data are quite different to the frequency characteristics of the historical data.

The near future rainfall projections have to be seen in relation to the baseline estimates for the same model (red and blue lines in Figure 4.2). For the near future data to be comparable to the historical data and to each other, they require some form of standardisation. Several approaches to standardising the data were attempted, and the method that appeared to generate the most sensible results was based on correcting the main statistical distribution characteristics of the baseline data to the historical data and then applying the same correction to the near future data to remove bias in both means and standard deviations.

The method used to remove this bias from the future (near and far) rainfall estimates has been to express the future monthly rainfalls as standard deviates of the baseline monthly distributions (using log values) and to scale the standard deviates with the monthly distribution statistics of the historical rainfall data (Equation 1):

$$FRC_{ijk} = EXP\ (LWRM_j + LWRSD_j * (LFR_{ijk} - LBRM_{jk}) / LBRSD_{jk}) \qquad \text{Equation 1}$$

Where:

FRC_i = Future rainfall after correction for month i and calendar month j in the time series of GCM k.

LFR_i = Logarithm of future rainfall for month i and calendar month j in the time series of GCM k.

$LBRM_j$ = Mean of the logarithms of baseline rainfalls for GCM k and calendar month j.

$LBRSD_j$ = Standard deviation of the logarithms of baseline rainfalls for GCM k and calendar month j.

$LWRM_j$ = = Mean of the logarithms of WR2005 rainfalls for calendar month j.

$LWRSD_j$ = Standard deviation of the logarithms of WR2005 rainfalls for calendar month j.

The objective of the transformation is to remove the bias in the monthly means and variations between the historical and GCM baseline estimates, while preserving the differences between the GCM baseline and future scenarios. Several other transformation approaches (such as using the cumulative frequency distributions of rainfall) did not preserve the seasonality and structure of the down-scaled future rainfalls. The dashed line in Figure 4.2 illustrates the results of the bias removal for the down-scaled CCCMA data. It should be evident that bias has been removed and that the 'corrected' near future rainfall distribution can be used to compare with historical rainfall data. A facility to perform these calculations has been added to the SPATSIM modelling framework.

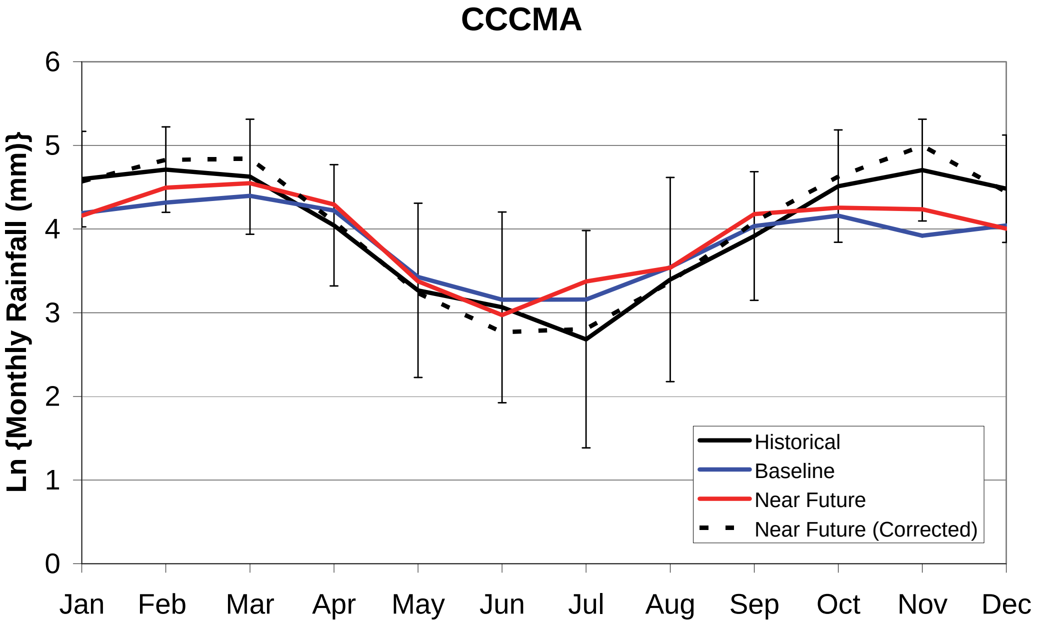


Figure 4.2 Comparisons of the seasonal distributions of mean monthly rainfall data.

4.2.3 Processing the temperature data

There are different ways in which temperature data can be converted to evaporation demand data, and these typically involve assumptions about other variables in the evaporation estimation equations. The historical runs of the hydrological model are based on fixed mean monthly evaporation demands (PE: potential evapotranspiration) taken from studies such as WR90 or WR2005. There is no allowance for time series variations in PE, although these can be catered for by including time series inputs of deviations from the monthly means.

A relatively simple approach has been adopted here. It was decided to use the maximum and minimum temperature data for the baseline and future climate model scenarios to determine the temperature component of the Hargreaves (Allen et al., 1998) Equation (Equation 2). The percentage increases in these values, from baseline to future, were then used to scale the historical seasonal distributions of potential evaporation when running the model for future scenarios.

$$HC_k = (TMax_k + TMin_k) / 2 \times SQRT(TMax_k - TMin_k) \qquad \text{Equation 2}$$

Where:

HC_k = Temperature component of the Hargreaves equation for GCM k, calculated for baseline and future conditions.

$TMax_k$ = Daily maximum temperature for GCM k.

$TMin_k$ = Daily minimum temperature for GCM k.

This approach ignores the other components of the Hargreaves equation (relative humidity and wind speed), which are assumed to be unchanged between the baseline and future scenarios. While this assumption may not be valid, no information is currently produced through the standard down-scaled products to estimate the differences in these effects between baseline and future conditions. The daily values are used to compute mean monthly values (MHC_{jk}, where j is the month) for all calendar months and the seasonal scaling factor computed from the ratio of the HC_k values for the individual GCMs future scenarios to their baseline scenarios.

Figures 4.3 and 4.4 illustrate the results for two of the GCMs and compare the Hargreaves based evaporation demand results with simple temperature change results. The diagrams illustrate that there are substantial differences in the patterns of temperature change between the different models.

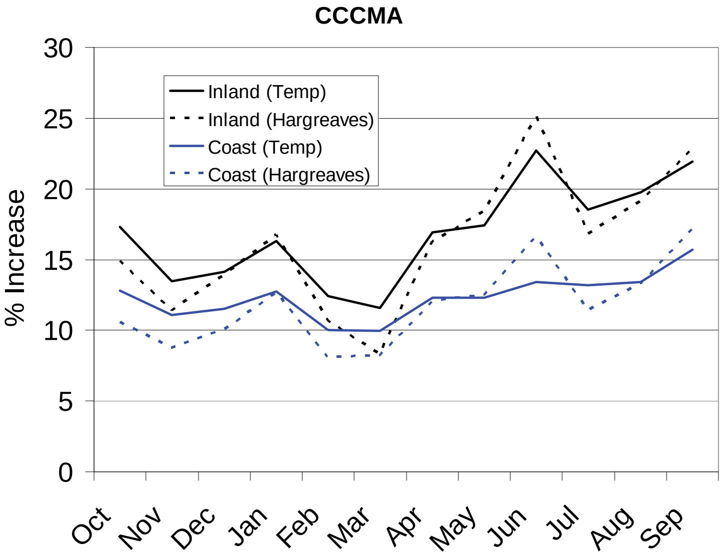


Figure 4.3 Temperature and evaporation demand changes for two quinary catchments (coast and inland) – CCCMA climate model results.

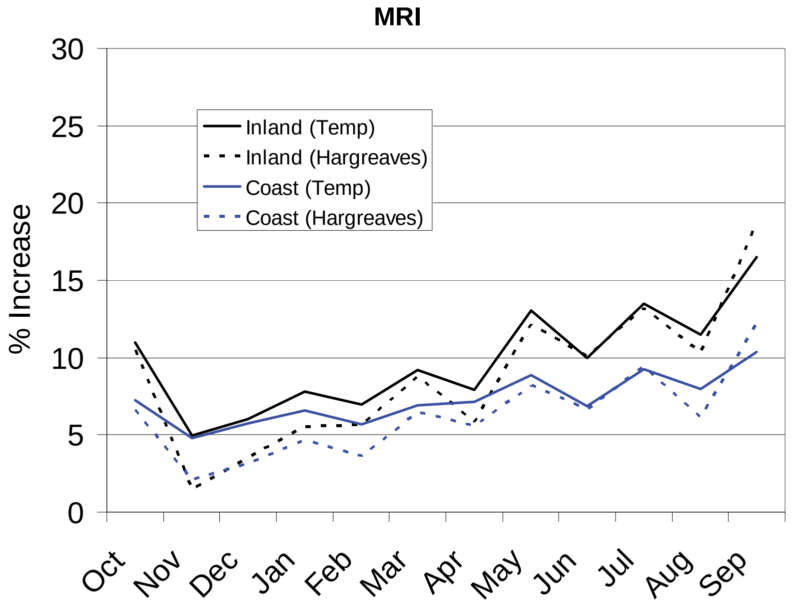


Figure 4.4 Temperature and evaporation demand changes for two quinary catchments (coast and inland) – MRI climate model results.

4.3 Running the hydrological model

As noted earlier in this report, it was always intended to run the hydrological model within an uncertainty framework (Kapangaziwiri et al., 2009). The first step in setting up the model for the Buffalo River catchment has been to identify the frequency distributions of parameter values that would give realistic uncertainty ranges in the simulated flow ensembles. These parameter frequency distributions have been based on the methods developed by the IWR (Kapangaziwiri and Hughes, 2008 and Kapangaziwiri, 2010) and modified by taking into consideration the limited amount of observed stream flow data that are available, as well as the uncertainties in those data. The observed stream flow data uncertainties are associated with the many existing development impacts within the catchment.

Figure 4.5 illustrates the results for the middle to upper part of the Buffalo River catchment (quaternary R20B). The grey band represents the outputs from the model uncertainty ensembles for this study, the solid line represents the simulation results that are used within the current version of the water resources yield model and the dotted line represents the observed flows as impacted by upstream developments and land-use (alien vegetation). The bottom axes markers have been excluded, but cover the whole range of percentage points (99.9 on the right to 0.1 on the left). Figures 4.6-14 show the equivalent results for the hydrological model outputs based on the downscaled and corrected data for the near future scenario and all nine GCMs. The shaded areas are the results based on using the near future rainfall data, while the solid colour band shows the results using combined changes in rainfall and potential evapotranspiration. The lines showing the observed flows and the current data used for yield modelling are included on all diagrams for reference purposes. Figure 4.15 illustrates the total uncertainty across all of the downscaled GCMs.

The model results can be summarised as follows:

- The inclusion of future evaporation demand effects are quite substantial for most of the GCMs.
- In most cases, the uncertainty bands with and without evaporation demand effects are overlapping. The exception is the result for the CNRM model, where the inclusion of evaporation effects creates a separation of the uncertainty bands.

- While the band of uncertainty across all GCMs is narrower than results that have been reported for other climate change studies around the world and specifically within southern Africa, the band remains quite wide compared to the uncertainty in the historical flow regime. The band also includes projections of runoff increases and decreases.

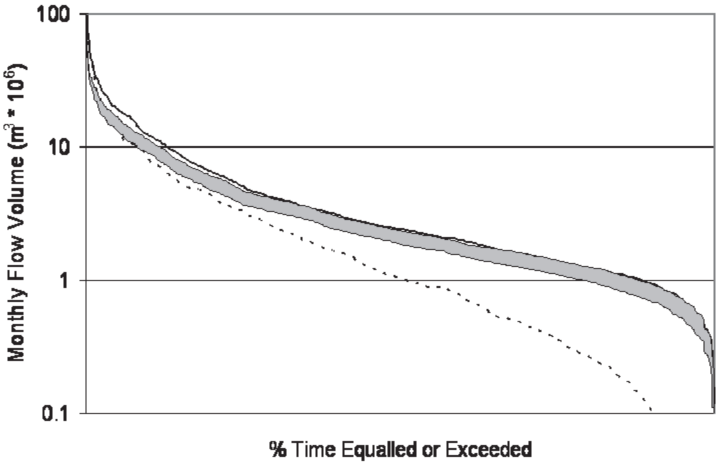


Figure 4.5 Simulation results (shown as a flow duration curve) using historical rainfall data.

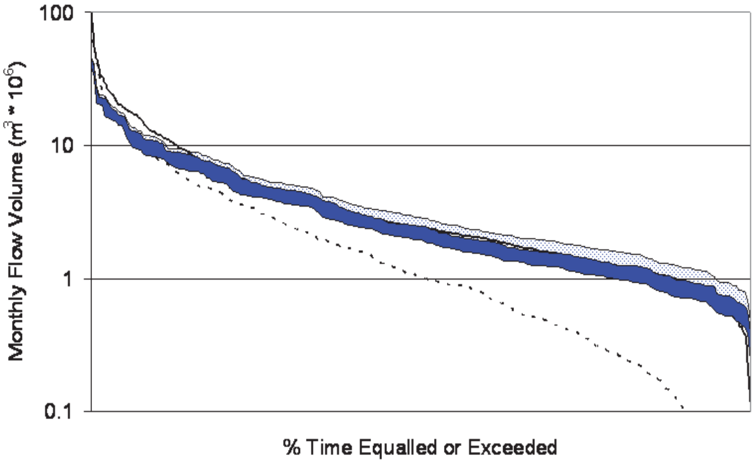


Figure 4.6 Simulation results (shown as a flow duration curve) using CCCMA near future rainfall and evaporation demand data.

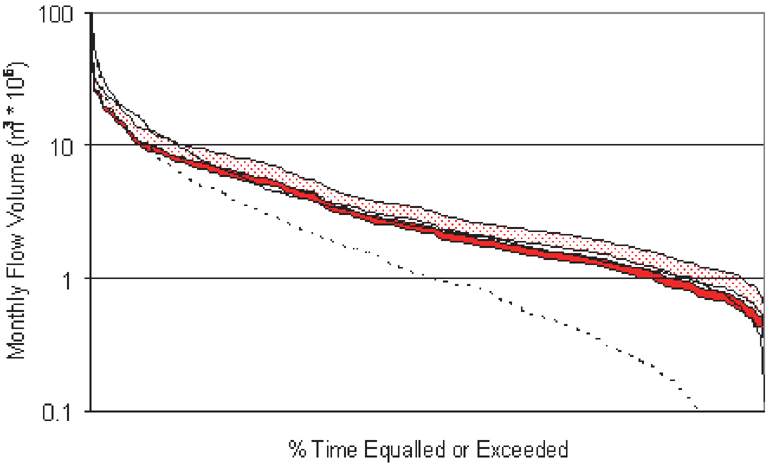


Figure 4.7 Simulation results (shown as a flow duration curve) using CNRM near future rainfall and evaporation demand data.

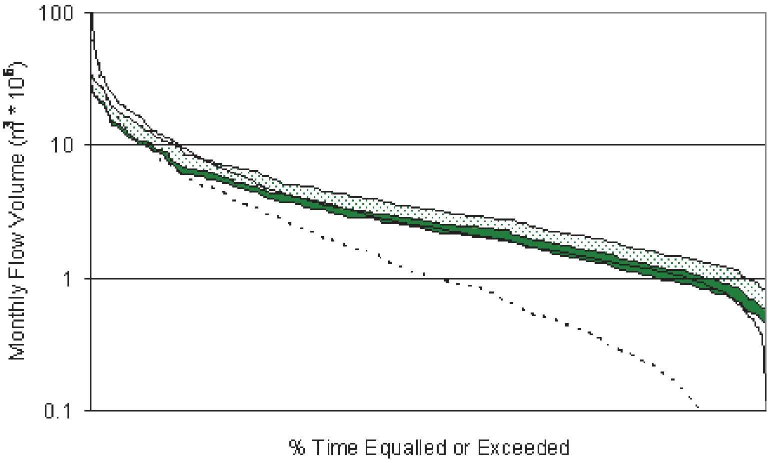


Figure 4.8 Simulation results (shown as a flow duration curve) using CSIRO near future rainfall and evaporation demand data.

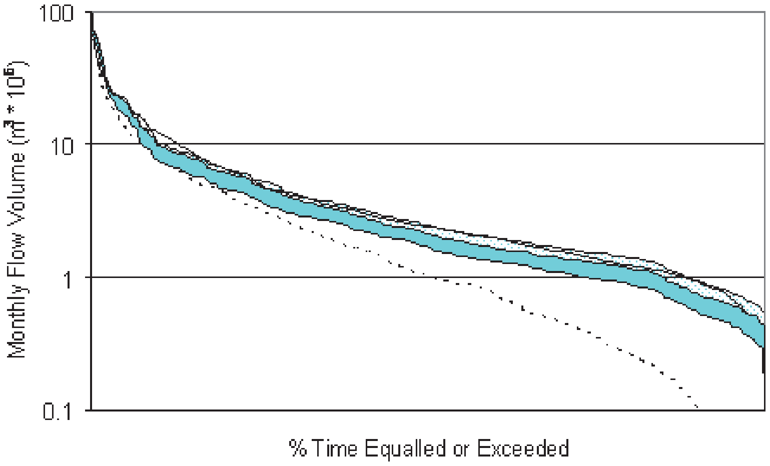


Figure 4.9 Simulation results (shown as a flow duration curve) using GFDL near future rainfall and evaporation demand data.

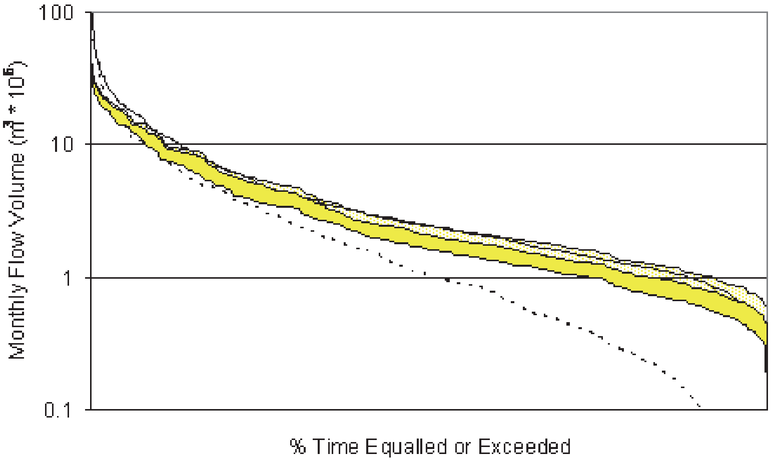


Figure 4.10 Simulation results (shown as a flow duration curve) using GISS near future rainfall and evaporation demand data.

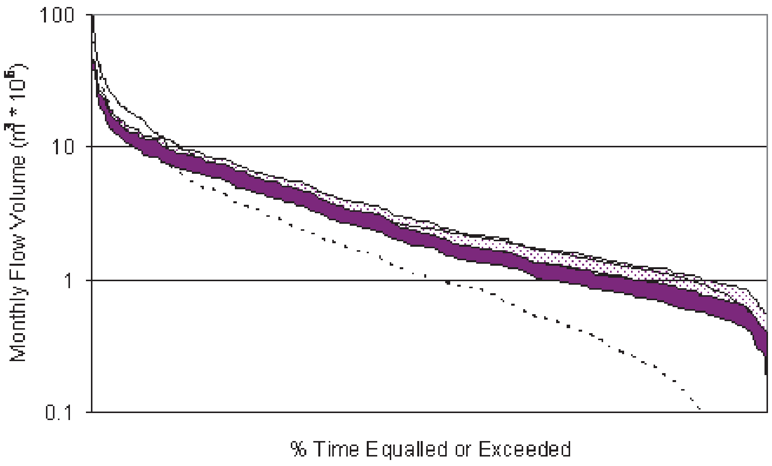


Figure 4.11 Simulation results (shown as a flow duration curve) using IPSL near future rainfall and evaporation demand data.

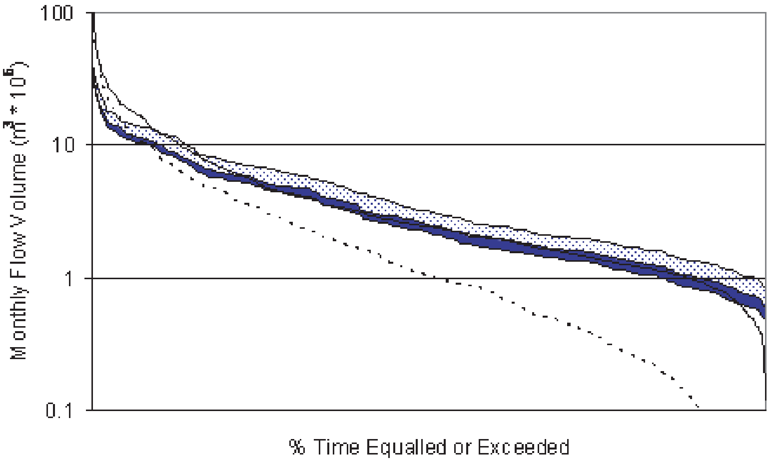


Figure 4.12 Simulation results (shown as a flow duration curve) using MIUB near future rainfall and evaporation demand data.

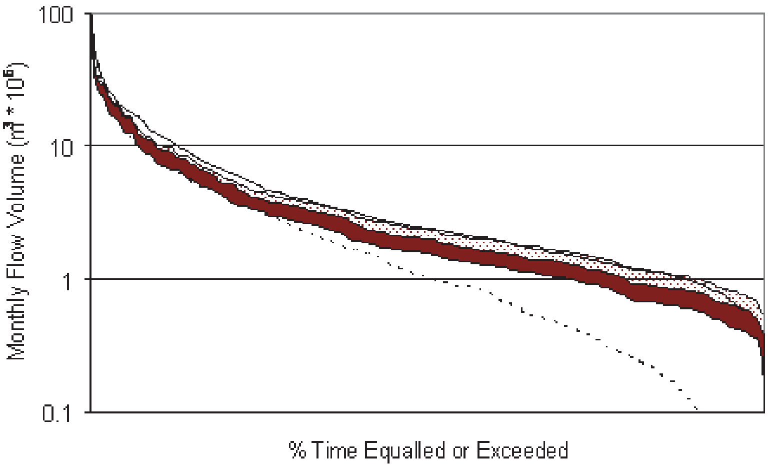


Figure 4.13 Simulation results (shown as a flow duration curve) using MPI near future rainfall and evaporation demand data.

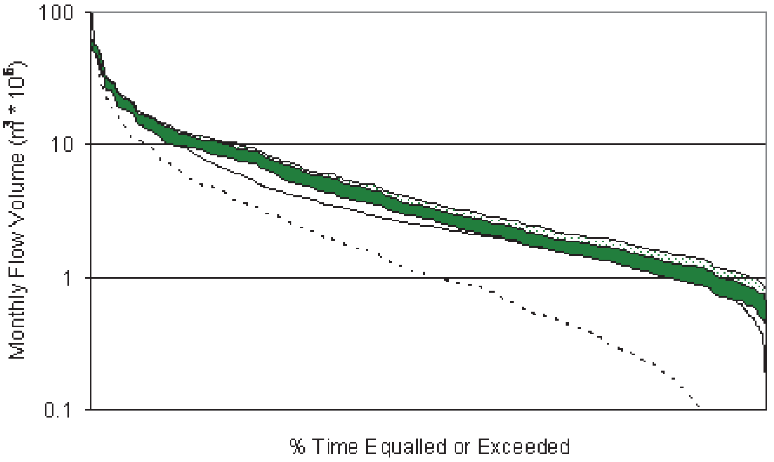


Figure 4.14 Simulation results (shown as a flow duration curve) using MRI near future rainfall and evaporation demand data.

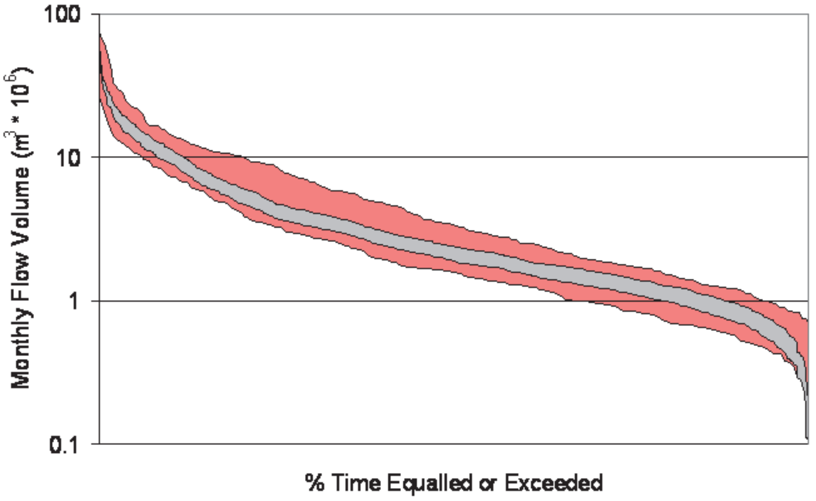


Figure 4.15 Comparison of the historical range of uncertainty (based on model parameter uncertainty) and future uncertainty (based on parameter uncertainty and future climate uncertainty across all nine GCMs).

4.4 Reducing the uncertainty

4.4.1 Development of measures of GCM 'skill'

There are very big differences between the nine baseline rainfall time series and the WR2005 (Middleton and Bailey, 2008) rainfall data that are typically used in water resources analyses in South Africa and are based on all available gauged data. While the WR2005 data are less than perfect, largely because of relatively low densities of measurement stations, they are the best available representation of historical rainfall patterns. The purpose of this section is to report on the development of an approach that can be used to assess the relative skill of the nine monthly baseline rainfall time series compared with the WR2005 data. While this is applied in a single catchment, the approach should be equally applicable to anywhere within South Africa where the same type of data (historical and climate model outputs) are available.

It is essential to recognise that the down-scaled rainfall products are not expected to adequately reproduce individual monthly values and that the time series sequencing skill is also likely to be poor. Conventional time series comparison approaches such as the Nash and Sutcliffe (1970) efficiency, the coefficient of determination (R^2) or any other measures based on comparisons of individual monthly values cannot therefore, be used – all of the climate model results would give poor results (low R^2 and negative Nash-Sutcliffe efficiency values). It is therefore necessary to select comparative skill measures that are useful from a water resources availability assessment point of view.

Part of the rainfall transformation process relies on the WR2005 and baseline data for the different GCMs both having similar skewness values for the distribution of rainfall depths within each calendar month and that the logarithmic transformation is appropriate. An assessment of skill based on the differences in skewness is therefore appropriate. A skill measure was therefore based on the absolute relative difference in skewness between the GCM baseline and WR2005 data (Equation 3):

$$\text{Skewskill}_k = \Sigma \text{ ABS}((\text{Skew}_{jk} - \text{skewWR}_j) / \text{skewWR}_j) \qquad \text{Equation 3}$$

Where:

$Skew_{jk}$ = Skewness of the monthly rainfalls for calendar month j and GCM k.

$SkewWR_{j}$ = Skewness of the WR2005 monthly rainfalls for calendar month j.

$Skewskill_{k}$ = Annual sum of the absolute relative differences.

The seasonality of the rainfall regime is clearly of great importance in hydrological modelling, and during the initial phases of the study it had already been observed that some of the down-scaled rainfall data did not appear to reproduce historical seasonality patterns very well. A skill measure was therefore adopted that would measure the relative differences between the GCM seasonal rainfall distributions and the WR2005 data, but with the overall depth bias removed (Equation 4):

$Seasskill_{k} = \Sigma\ ABS((BR_{jk} * (BRMAR_{k} / WRMAR) - WR_{j}) / WR_{j})$ Equation 4

Where:

BR_{jk} = Baseline mean monthly rainfall for month j and GCM k.

$BRMAR_{k}$ = Baseline mean annual rainfall for GCM k.

WR_{j} = WR2005 mean monthly rainfall for month j.

WRMAR = WR2005 mean annual rainfall.

$Seasskill_{k}$ = Annual season skill score.

The equivalent of Equation 4 has also been used to calculate a seasonality skill measure for the potential evaporation data. Equation 2 was applied to some historical temperature data (Schulze and Maharaj, 2004) as well as the baseline temperature data for the nine down-scaled GCMs. The mean monthly values for the historical and GCM data were then used in Equation 4 (replacing mean monthly rainfall with the MHC_{jk} values and the mean annual rainfall values with the evaporation equivalents).

The rainfall seasonality skill measure does not adequately account for the variation in rainfalls across different years for the same calendar month and therefore, an additional skill measure has been added to account for this, based on the coefficient of variation of the ratio of standard deviation to the mean (Equation 5):

$CVskill_{k} = \Sigma\ ABS((CV_{jk} - CVWR_{j}) / CVWR_{j})$ Equation 5

Where:

CV_{jk} = Coefficient of variation of the monthly rainfalls for calendar month j and GCM k.

$CVWR_{j}$ = Coefficient of variation of the WR2005 monthly rainfalls for calendar month j.

$CVskill_{k}$ = Annual sum of the absolute relative differences.

The final skill measure has been based on calculations of serial auto-correlation within the individual time series using lags of 1, 2, 11, 12 and 13 months. These lags were chosen on the basis of the serial correlation patterns observed in the WR2005 data that demonstrated weak intra-season persistence (0.25 and 0.10 for lags 1 and 2, respectively), as well as weak persistence across two adjacent seasons (0.19, 0.22, 0.16 for lags 11, 12 and 13, respectively). The baseline rainfall time series for all nine GCMs exhibited similar patterns, but with quite different correlation values. The serial correlation skill measure was therefore simply the sum (for all five lags) of the absolute differences in serial correlation (Equation 6):

$SCskill_{k} = \Sigma\ ABS(SC_{lk} - SC_{l})$ Equation 6

Where:

SC_{lk} = Serial correlation coefficient for lag l and GCM k.

SC_{l} = Serial correlation coefficient for lag l, WR2005 monthly rainfalls.

$SCskill_k$ = Sum of the skill values for all five lags.

4.4.2 Results of 'skill' analysis

Figure 4.16 illustrates the differences in the skewness of the different GCM baseline time series compared with WR2005. All of the models tend to under-estimate skewness and in some models and some calendar months, it is apparent that a logarithmic transformation to achieve a more normal distribution is not necessarily appropriate. They all under-estimate skewness during the main dry season (June-August), while the excessive skewness of the MIUB data during April contributes to the overall low skill level of this GCM (Table 4.2, column 2).

Figure 4.17 presents the results of the comparisons based on seasonality and it is immediately apparent that the greatest relative differences lie within the dry season, while most of the GCMs show similar results for the main wet season (October-March). The largest exceptions to this general observation are the CNRM (over-estimates of the late wet season), IPSL and MIUB (under-estimates of the late wet season) GCMs. The latter two models are also the least skillful during the dry season, which leads them to have the lowest overall skill level (Table 4.2, column 3).

Figure 4.18 presents the differences in values of the monthly coefficient of variation (CV) of the different GCM baseline time series compared with WR2005. With the exception of the IPSL and MIUB models, the wet season CVs are reasonably well represented, while the late dry season CVs are generally under-estimated. This region infrequently experiences high rainfalls during the otherwise normally dry season, which contributes to the high CVs. These are clearly not being adequately represented by the GCMs. Table 4.2 column 4 indicates that, once again, the IPSL and MIUB models do not appear to very skillful.

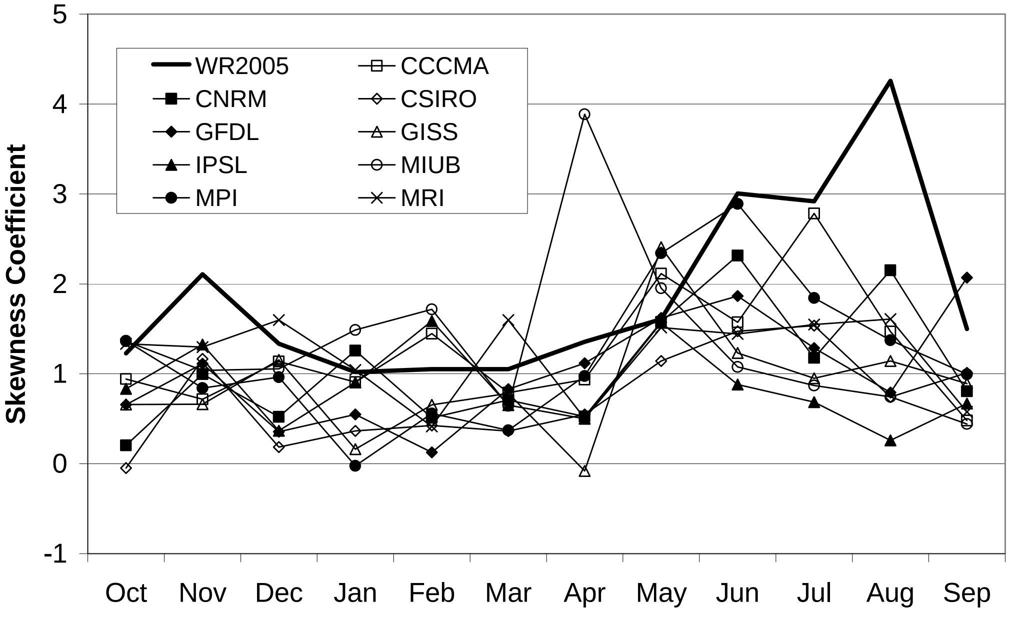


Figure 4.16 Calendar month skewness values for WR2005 and baseline data for all nine GCMs.

Table 4.2 Rankings of the GCMs for the different measures of rainfall skill

GCM	Measure of Skill				Cumulative measures and ranking				
	Skew	Season	CV	SC	Total multiplied	Rank	Total summed	Rank	Mean rank
CCCMA	1	6	2	7	84	4	16	4	4
CNRM	4	7	4	9	1 008	7	24	6	6.5
CSIRO	8	4	5	4	640	5	21	5	5
GFDL	5	1	6	1	30	1	13	2	1.5
GISS	7	2	8	8	896	6	25	7	6.5
IPSL	6	9	7	3	1 134	8	25	7	7.5
MIUB	9	8	9	5	3 240	9	31	9	9
MPI	3	3	3	2	54	2	11	1	1.5
MRI	2	5	1	6	60	3	14	3	3

Column 5 of Table 4.2 presents the rankings based on a comparison of the serial correlation coefficients, which are often quite different from the other skill measures. However, when the rankings across the four skill measures are combined, either by multiplication or summation, the result is quite clear. The IPSL and MIUB models are quite consistently ranked low in skill and end up with the lowest mean rank. The CNRM and GISS models may also be considered less skillful than the remaining models, despite the fact that GISS ranks 2nd on the important seasonality measure.

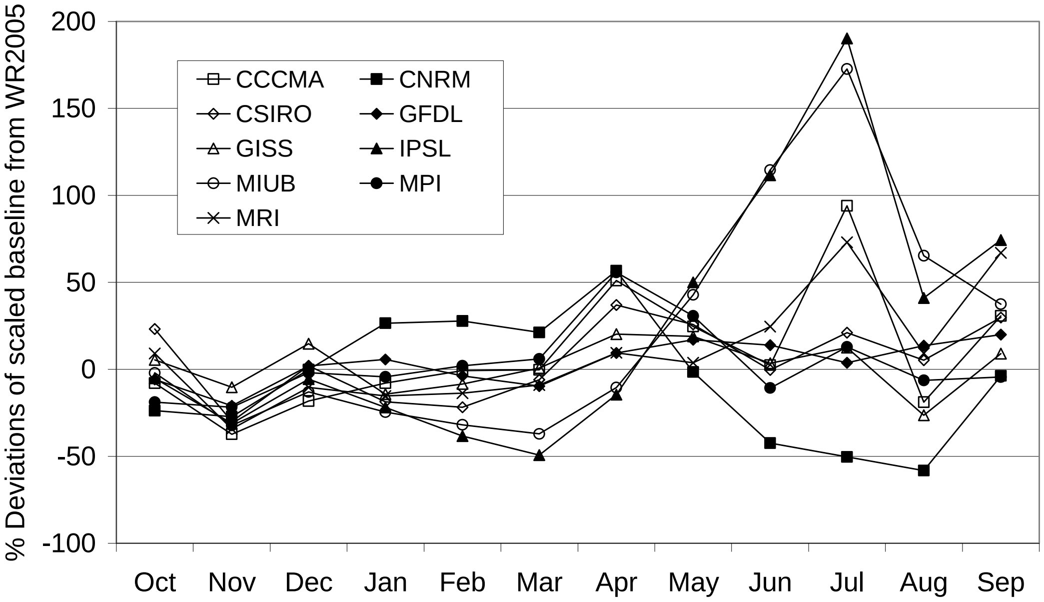


Figure 4.17 Calendar month measures of the rainfall seasonality skill for the baseline data for all nine GCMs.

Table 4.3 lists the seasonality skill values and the ranking of the nine GCMs, based on Equation 4 for rainfall and the equivalent equation for potential evaporation. It is immediately evident that the rankings are very different when rainfall skill is compared to evaporation skill. However, it is also evident that the rainfall skill is far more important because the rainfall skill values (the relative degree of departure of the GCM baseline estimates from the historical data) are far greater than the evaporation skill values. A comparison of the individual month deviations for rainfall seasonality (Figure 4.17) and evaporation seasonality (Figure 4.19) confirms that the down-scaled GCM rainfalls are far less skillful than the potential evaporation estimates based on temperature data.

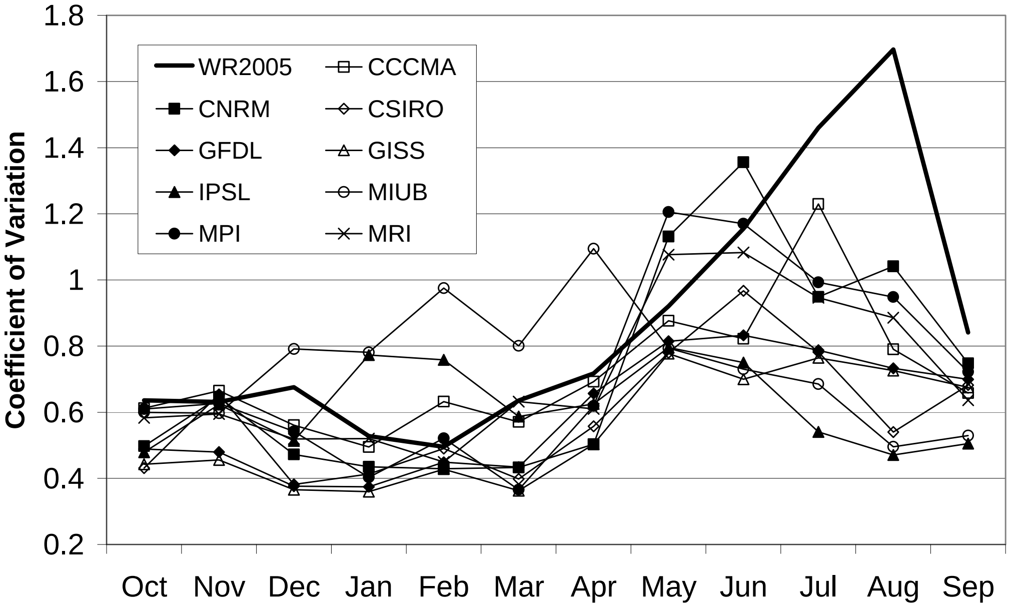


Figure 4.18 Calendar month coefficient of variation values for WR2005 and baseline data for all nine GCMs.

Table 4.3 Skill values and rankings of the GCMs for the seasonality measures of rainfall and potential evaporation skill.

GCM	Rainfall		Evaporation	
	Skill value	Rank	Skill value	Rank
CCCMA	294.0	6	27.5	6
CNRM	339.7	7	14.7	1
CSIRO	220.9	4	20.2	3
GFDL	125.7	1	44.9	9
GISS	144.7	2	24.4	5
IPSL	632.9	9	30.6	7
MIUB	584.1	8	22.2	4
MPI	175.8	3	20.1	2
MRI	279.0	5	41.7	8

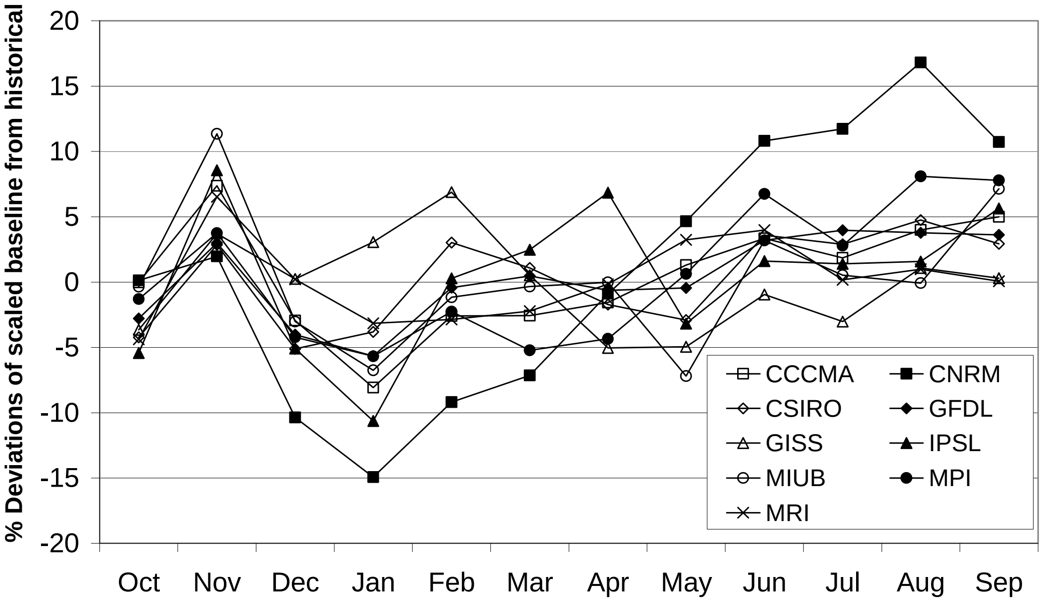


Figure 4.19 Calendar month measures of the evaporation seasonality skill for the baseline data for all nine GCMs.

4.4.3 Revised stream flow simulations using only 'skillful' GCMs

Figure 4.20 shows the seasonal distribution of climate change effects on mean monthly simulated runoff for all of the nine GCMs. The data plotted are the percentage deviations of the GCM monthly means from the historical equivalents and the median simulation ensembles are used in all cases. The overall impression is that the wet season runoff is increased, but that the dry season runoff is decreased. There is, however, a substantial amount of variation in the changes across the nine GCMs, and it is very difficult to identify any pattern differences between the more skillful GCMs based on Table 4.2 (CCCMA, GFDL, MPI and MRI) and the less skillful models (those with a mean rank in column 10 of Table 4.2 of 5 or greater).

Figure 4.21 shows the envelopes of flow duration curves for three sets of simulations: 1) the ensembles of simulations using historical data; 2) the range of ensemble results for all GCMs and; 3) the range of ensemble results for the four GCMs identified as being more skillful for rainfall data. The results of this comparison suggest that there are very small changes with respect to the uncertainty in future runoff predictions, and there are only minor reductions in the width of the uncertainty bands.

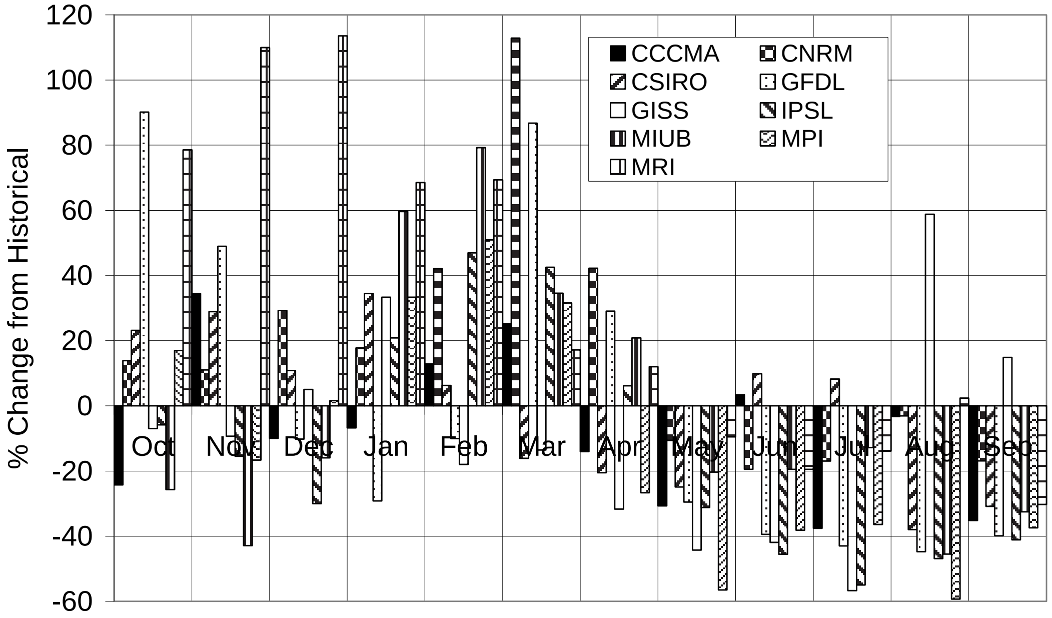


Figure 4.20 Seasonal distribution of climate change monthly means expressed as a percentage change from historical monthly means for all nine GCMs.

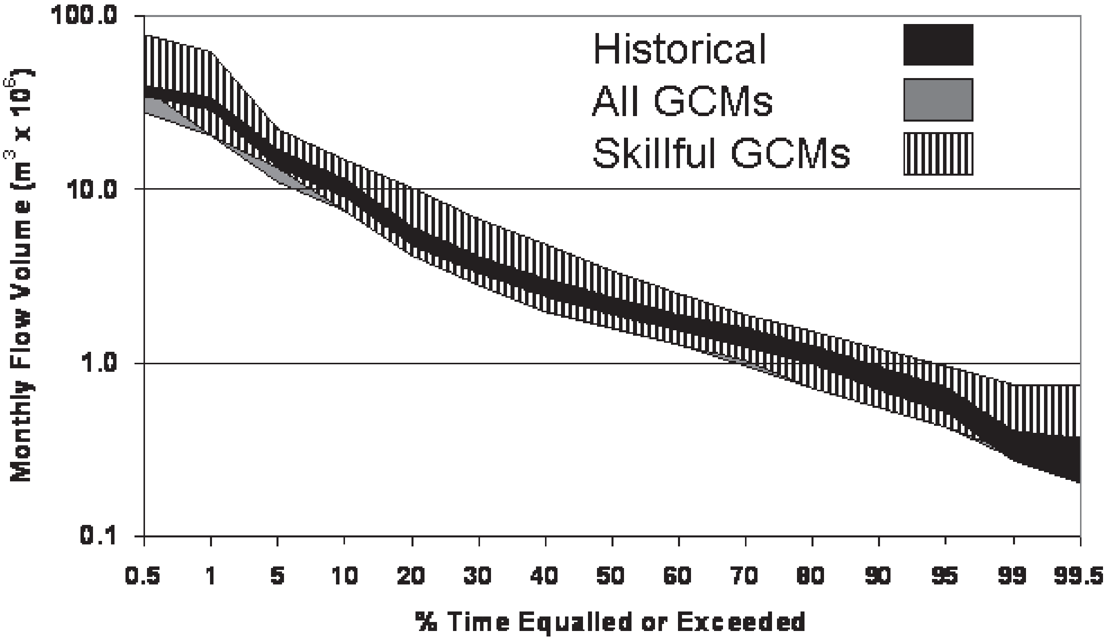


Figure 4.21 Flow duration curve envelopes (including the upper and lower bounds of 90% of the simulation ensembles) for the near future for all GCMs and the four most skillful GCMs (based on the mean rank in Table 4.2) and the simulations using historical data.

4.5 Discussion

This report has focused on quantifying the changes in water quantity and quality associated with nine climate change scenarios for the near future. The data used in the models consisted of daily rainfall and maximum and minimum temperatures for two scenario situations: the baseline situation (1961-2000) and the near future (2046-2065). The estimates are based on downscaled data from nine GCMs (listed in Table 4.1) using the SRES A2 emission scenario. The percentage increase in temperature and evaporation demands under the various scenarios was noted to be quite different. The following results were noted for the uncertainty associated with the runoff results using the Pitman model:

- The inclusion of the effects of future evaporation demand is quite substantial for most of the GCMs.
- In most cases, the uncertainty bands with and without evaporation demand effects are overlapping. The exception is the result for the CNRM model, where the inclusion of evaporation effects creates a separation of the uncertainty bands.
- While the band of uncertainty across all GCMs is narrower than results that have been reported for other climate change studies around the world and specifically within southern Africa, the band remains quite wide compared to the uncertainty in the historical flow regime. The band also includes projections of runoff increases and decreases.
- An innovative technique of developing measures of GCM ‘skill’ was developed to reduce the uncertainty. The ‘skill’ analysis indicated that four GCMs (CCCMA, GFDL, MPI and MRI) were more skillful than the others. However, the results found very small changes with respect to the uncertainty in future runoff predictions made by the Pitman model. There was only minor reduction in the width of the uncertainty bands noted.

4.6 Application of the uncertainty version of the Pitman model for the Caledon river basin

The objective of this part of the study on the Caledon River was to establish an appropriate parameter set (including uncertainty bounds) for both natural and present day conditions based on historical climate data as well as investigating the impacts of future climates on the present day flow regime. An introduction to the uncertainty framework is presented in Section 1.3.

4.6.1 Parameter estimation

The Pitman model (the version with revised surface-groundwater interaction routines used at Rhodes University – Hughes, 2004 and Hughes et al., 2006) parameter sets are traditionally established through calibration at a limited number of gauging sites, followed by regionalisation using a relatively subjective approach based on perceived basin similarity. Midgley et al. (1994) provide parameter values for the 1 946 sub-basins covering the whole of South Africa, Lesotho and Swaziland. Of these, 31 sub-basins (D21A-L, D22A-L and D23A-J) form the Caledon River study area (Figure 4.1). Kapangaziwiri and Hughes (2008) and Kapangaziwiri et al. (2009) report on an alternative approach to parameter estimation for the Pitman model that does not rely on calibration, includes uncertainty and is based on the use of estimation equations using physical sub-basin properties (topography, soils, geology and vegetation) available from various sources (e.g. AGIS, 2007). The parameter uncertainty is estimated from the spatial variation in the physical sub-basin properties and expressed as means and standard deviations of normal distributions or maximum and minimum values of uniform distributions (Kapangaziwiri et al., 2009). In this study, a combined approach has been used. The Kapangaziwiri et al. (2009) approach has been applied to selected representative sub-basins (steep headwater areas of the northeast, less steep headwaters in the northwest and flatter downstream sub-basins) to establish the likely ranges of parameter values and their uncertainty distributions across the whole basin. The Midgley et al. (1994) parameter sets were used as a guide to extrapolating from the sample sub-basins to establish uncertain parameter sets for the whole basin.

The current uncertainty version of the Pitman model being used within the IWR at Rhodes University assumes that the uncertainties in the model parameters are grouped according to similarities across the sub-catchments of the basin being simulated. This means that all uncertainties within a group are considered to be dependent (i.e. parameter values vary together and in the same direction during the Monte Carlo sampling process), while the uncertainties between groups are considered independent (i.e. separate Monte Carlo samples generated for parameter uncertainties in different groups). The starting point for setting up the uncertainty version of the model is therefore to determine how many groups there should be and to identify the sub-catchments which fall into the different groups. The intention is that this process should be driven by the natural physical characteristics of the sub-catchments and Table 4.4 lists the five groups that have been established for the Caledon.

Table 4.5 provides some information about the stream flow gauging stations that are available for the basin and that have been used (when possible) to constrain the model outputs and uncertainties. It is clear from Table 4.5 that there are a very limited amount of data that can be used to 'calibrate' a hydrological model under natural conditions. There are also many problems with some aspects of the gauged records, notably with respect to the frequency with which high flows are accurately monitored. These have been attended where there is additional information available from the break-point raw stream flow data, however, a large amount of uncertainty remains within the observed data. There is also not enough information available to naturalise the stream flow records to account for upstream water use.

The rainfall data inputs to the model have been based on WR2005, and there are no real indications of how accurate or representative these data are. However, it is recognised that there are a limited number of rainfall gauging stations in the Lesotho parts of the basin, which are expected to be one of the areas of dominant runoff generation. This introduces a source of uncertainty into the whole modelling exercise. Unfortunately, this uncertainty is almost impossible to quantify in a realistic manner.

Table 4.4 Uncertainty groups for the Caledon basin.

Zone	Sub-basins	Mean annual rainfall (mm)	Characteristics
1	D21A, B, C, D, J, K, L	839-1 021	Steep eastern headwaters in the Lesotho Maluti mountains. Possibly some stock grazing.
2	D21E, F, G, H D22A, B, C, D	682-782	Undulating topography in the northern headwaters with some steep areas. Intensive agriculture in the valley bottoms.
3	D22G D23C, D, H	519-688	Dry south-western tributaries with undulating to flatter topography and intensively cultivated.
4	D22E, F, H, J, K D23B, F, G	705-817	Undulating topography with some steep headwater areas. Extensively cultivated in South Africa and dense rural populations with over-grazing in Lesotho.
5	D22H, L D23A, E, J	541-730	Lower basin valley bottom areas with generally flatter topography and intensively cultivated.

Table 4.5 Stream flow gauging stations

Gauge No.	Catchment area (km^2)	Records	Zones	Details
D2H012	518	1968-2011	1 & 2	High flows poorly quantified; some farm dam and land-use change effects.
D2H005	3 857	1941-1956	1 & 2	High flows moderately well quantified; many farm dams, abstractions and land-use impacts; some domestic return flows.
D2H020	8 399	1982-2010	1, 2 & 4	High flows moderately well quantified; large and poorly quantified impacts of Maseru city abstractions plus all upstream impacts.
D2H003	1 424	1934-1954	3	High flows well quantified; some agricultural abstractions but assumed to be relatively small (note that the period of record is before the construction of a large dam).
D2H022	12 852	1988-2010	All	Stable river section and subject to many uncertainties.
D2H001	13 421	1926-1978	All	High flows very badly quantified in early parts of record; many accumulated upstream abstraction impacts.

4.6.2 Results – Natural simulations (WR2005 climate data)

After some initial model runs, it was noted that the band of low flow uncertainty was generally too high and that the upper uncertainty bound suggested low flows that are too high. A similar observation was made regarding the moderate and higher flows, particularly in the headwater areas represented by gauge D2H012. The final uncertainty run of the model was therefore based on parameter sets that reflected these observations and are given in Table 4.6.

The results are presented in Figure 4.22 and the overall conclusion is that the uncertainty simulations for D21E (D2H012) and D23D (D2H003) appear to be acceptable representations of natural conditions. The other gauging stations are of little value for assessing the natural flow simulations of low to moderate flows. The results for D23F (D2H001) suggest that there is reasonable confidence of the high flow simulations, but this is not supported by some of the other gauges (D22H and D2H020; D22C and D2H005). The extent to which these issues are related to poor observed data or unrepresentative model simulations cannot be resolved without additional information.

Table 4.6 Uncertain parameter sets of the key model parameters used in the final uncertainty runs (where the uncertainty factor is given in parenthesis, a Normal distribution is used and the value is the standard deviation. Where a range of values is given these represent the minimum and maximum values of a uniform distribution).

Parameter	**Mean (St. Dev.) of Normal distributions for zones**				
	1	**2**	**3**	**4**	**5**
Zmin (mm)	50 (5)	50 (5)	60 (5)	50 (5)	60 (5)
Zmax (mm)	600 (10)	600 (10)	800 (10)	600 (10)	800 (10)
ST (mm)	120 (5)	140 (5)	175 (5)	130 (5)	180 (5)
FT (mm month^{-1})	6 (1.0)	3 (0.5)	1 (0.25)	3 (0.5)	2 (0.5)
POW	3 (0.3)	3 (0.3)	3 (0.3)	3 (0.3)	3 (0.3)
GW (mm month^{-1})	30 (2.0)	12 (1.5)	20 (1.5)	20 (1.5)	15 (1.5)
GPOW	4.0-6.0	4.0-6.0	4.5-5.5	4.0-6.0	4.0-6.0
R	0.3-0.7	0.3-0.7	0.3-0.7	0.3-0.7	0.3-0.7
Riparian GW Losses (%)	0.2-2.0	0.2-2.0	0.2-2.0	0.2-2.0	0.2-2.0

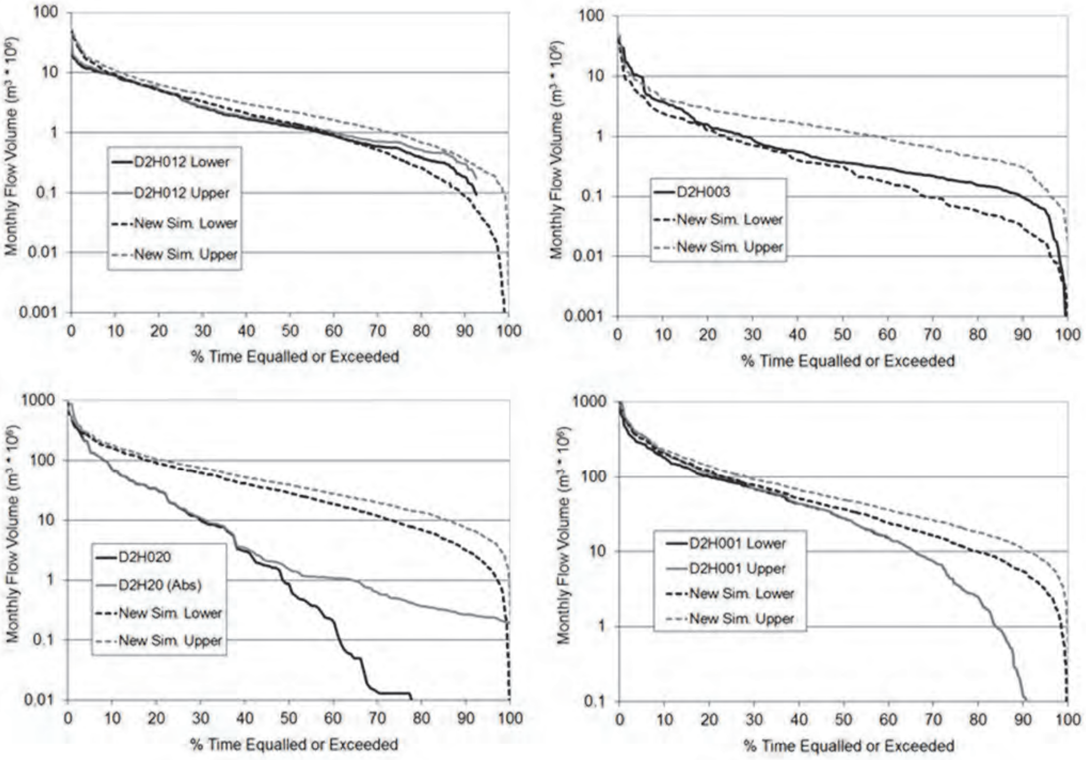


Figure 4.22 Final uncertainty bounds under natural conditions for example sub-basins.

4.6.3 Results – Present day simulations (WR2005 climate data)

It was found to be very difficult to identify and quantify the water use within the Caledon River basin. There are many conflicting sources of information (e.g. differences between WR90 and WR2005) and the information that was available is very incomplete (almost no data for the Lesotho parts of the basin). The basis for quantifying the water use parameters of the Pitman model was therefore highly uncertain, and many of the parameters have been approximately quantified using a spatial coverage of farm dams and associated surface areas, combined with interpretation of Google Earth images to identify areas of potential water use. The water use information used is divided up into the four main water use components of the SPATSIM version of the Pitman model; farm dams and irrigation use from the dams, direct abstractions for irrigation, direct abstractions for other uses and large reservoirs (and associated water use) on the main channel. The farm dam function can only use water generated within an incremental area, while the others can use water generated within upstream areas and routed through the current sub-catchment. Evidence from the DWA website on the location of boreholes suggests that there is not a great deal of groundwater abstraction in the basin, but this needs to be further checked.

Farm dam water use: Figure 4.23 shows the extent of dams in the total basin area and it is very clear that almost all parts of the South African area of the basin contain many farm dams. The surface areas of the dams have been converted into approximate full-supply volumes using a power function with parameters (Scale and Power) that vary with the area (Table 4.7):

$\text{Volume} = \text{Scale} * \text{Area}^{\text{Power}}$

A SPATSIM utility has been used to sum all of the estimate volumes for each sub-basin (excluding large dams on the main channel which are treated differently in the model set-up – see below) and the assumption has been made that the estimated volumes represent the mean of a normally distributed uncertainty distribution with a standard deviation of 10% of the mean (except for some of the larger dam volumes). The values for each of the quaternary catchment are listed in Tables 4.8-10.

The mean irrigation area (km^2) supplied by the farm dams has been approximately estimated as 0.835 × full supply volume based on an assumed water demand depth and the likely yield of the dams. This is a highly uncertain approach and Google Earth images were consulted to determine whether the estimated irrigation areas were reasonably sensible. It was found that these checks could be carried out quite effectively in some parts of the catchment, but were not really possible in the areas with large irrigation schemes. The mean irrigation area was used as an uncertain parameter with a normal distribution having a standard deviation of 10% of the mean. A seasonal distribution of demand has been based on a mixture of crops that appear to be grown in this whole region (early and late maize, some fruit crops) and using crop factors given in WR90.

The final parameter value required is the percentage of the incremental catchment area that supplies the combined farm dam storage with runoff. This was estimated from the farm dam coverage and was largely based on the density of farm dams and their position within the sub-catchments.

Table 4.7 Parameters of the farm dam area to volume conversion equation.

Threshold	Area	Scale	Power
1	0.001	0.8	0.6
2	0.01	0.8	0.6
3	0.1	0.8	0.6
4	2	2.4	1.1
5	100	2.8	0.9

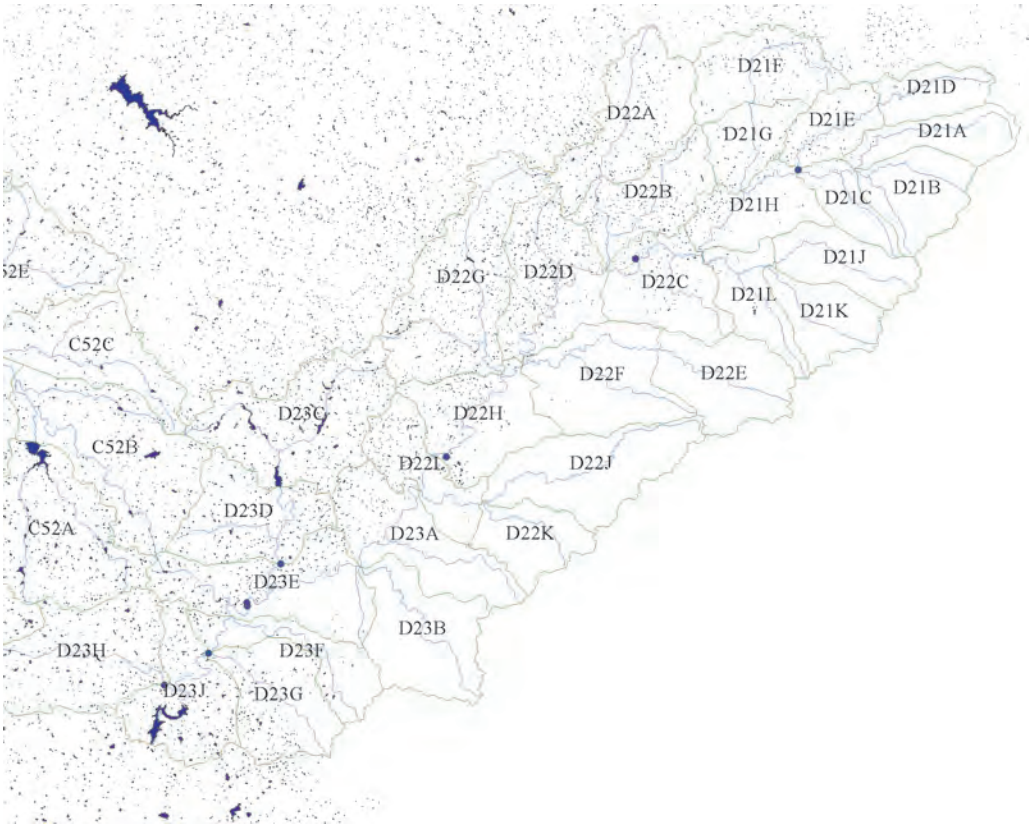


Figure 4.23 Farms dams in the Caledon River basin.

Direct irrigation abstractions: There is evidence from Google Earth of centre pivot irrigation close to the main Caledon River channel in some sub-catchments without evidence of being supplied from farm dams. It has therefore been assumed that there is some limited direct abstraction for irrigation. A uniform uncertainty distribution has been assumed and the minimum and maximum values are given in Tables 4.8-10 and it has been assumed that the irrigation return flow is 20% of the abstraction. The seasonal distribution of water use is based on the same crop mixture as used for the irrigation from farm dams and no allowance is made for effective rainfall to reduce the demand (i.e. the demand values used are net irrigation).

Direct abstractions for other uses: Other uses include water use by rural villages within Lesotho, a number of small to medium sized towns in South Africa and the city of Maseru. It is not very clear what the rural or town populations are, and therefore, all of these estimates are very approximate. It is also not clear how many of the South African towns (Clarens, Fouriesburg, Ficksburg, Ladybrand, Wepener, etc.) abstract directly from the channel or rely on local dams. Patterns of abstraction for Maseru are also difficult to determine despite having water consumption data for the city as a whole (i.e. from Google Earth it would appear that the city may use an off-channel storage facility and therefore, there may be no match between river abstractions and water consumption).

The volumes of use for the rural areas and South African towns have been based on very rough estimates of population coupled with consumptions figures of 25 and 100 ℓ person^{-1} d^{-1}, respectively. However, the project team is not at all confident about the population estimates. A uniform uncertainty distribution has been assumed and the minimum and maximum values are given in Table 4.8-10. The seasonal distribution of use has been slightly biased toward summer, partly to account for influxes of tourists in some of the SA towns and partly based on an assumption of garden watering during the hot summer months (also very uncertain assumptions).

Main channel reservoirs: There are five quaternaries where large (relative to the farm dams) reservoirs have been added as part of the present day model set up. D22B has a reservoir with 2.6×10^6 m^3 storage and 3×10^6 m^3 annual water use to account for a dam (Meulspruit) that possibly supplies Ficksburg, while D23C has a reservoir (Newbury) with 5.6×10^6 m^3 storage and 2×10^6 m^3 annual water use that is assumed to be used for downstream irrigation. A small storage (1×10^6 m^3) has been allocated to D22H to allow for the fact that Maseru may pump some water from river pools, even when the river stops flowing. Annual water use has been set to 12×10^6 m^3, but this would not be obtainable from the available storage and this value has been used to ensure that the pool storage is pumped dry. Reservoir storages have also been added to D23H (Knellpoort Dam with 137×10^6 m^3 storage) and D23J (Welbedacht Dam with 30.5×10^6 m^3 storage). However, no attempt has been made to simulate the operation of these dams to supply the inter-basin transfer scheme to the Riet River and Bloemfontein at this stage. The evaluation of the present day flow simulations stopped at the gauging station D2H001 at the outlet of D23F as the main purpose was to simulate the inflows to Welbedacht Dam. The operation and yield estimates of the Welbedacht Dam will be investigated at a later stage in the project through the application of uncertainty inputs into a yield model.

Other parameter changes: Two other parameter changes have been made to the present day version of the uncertainty model. The first has been made in all quaternary catchments that are dominated by agriculture and is based on the assumption that even dryland agriculture will result in greater ‘green’ water consumption. The natural range for the evaporation parameter R of 0.3-0.7 used in all areas has been changed to 0.2-0.5 to reflect increased evaporative losses. The second change has been applied to those Lesotho sub-catchments (mostly in the south east of the basin) where Google Earth suggests quite extensive riparian agriculture. In these quaternaries, the groundwater riparian losses parameter has been increased. However, this is unlikely to have a great deal of impact on the model results as the groundwater contribution from these catchments is quite low. The impacts of this change will be negligible compared to the other water use parameters.

Table 4.8 Water use parameters for the upper Caledon (D21)

Quat.	Dam volume (m^3 × 10^3)		% area above dams	Dam irrig. area (km^2)		Direct abstraction (10^3 m^3 y^{-1})		Irrig. direct abstraction (km^2)	
	Mean	St. Dev		Mean	St. Dev	Min.	Max	Min.	Max.
D21A	391	39	50	0.35	0.03	80	120	0	0
D21B	0	0	0	0	0	80	120	2.0	2.5
D21C	240	24	20	0.2	0.02	80	120	0	0
D21D	630	60	50	0.5	0.05	300	500	0	0
D21E	2 660	250	70	2.2	0.20	0	0	0	0
D21F	4 440	400	70	3.5	0.30	0	0	0	0
D21G	2 200	200	50	1.8	0.18	0	0	0	0
D21H	3 130	300	20	2.5	0.25	240	310	0	0
D21J	35	3	5	0.03	0.003	60	100	0	0
D21K	90	9	5	0.07	0.007	60	100	0	0
D21L	1 200	120	20	1.0	0.1	80	120	0	0

Table 4.9 Water use parameters for the middle Caledon (D22)

Quat.	Dam volume (m^3 × 10^3)		% area above dams	Dam irrig. area (km^2)		Direct abstraction (m^3 × 10^3 y^{-1})		Irrig. direct abstraction (km^2)	
	Mean	St. Dev		Mean	St. Dev	Min.	Max	Min.	Max.
D22A	10 595	900	90	8.8	0.8	0	0	0	0
D22B	8 300	800	85	6.5	0.4	0	0	0	0
D22C	4 000	400	90	3.0	0.3	100	140	0	0
D22D	12 000	1 000	85	12.5	1.0	80	100	9.0	12.0
D22E	0	0	0	0	0	50	80	0	0
D22F	280	28	10	0.22	0.02	200	250	0	0
D22G	21 000	2 000	90	15.0	1.5	0	0	0	0
D22H	7 900	700	70	6.0	0.6	12 000	16 000	0	0
D22J	0	0	0	0	0	100	120	0	0
D22K	0	0	0	0	0	100	120	0	0
D22L	6 600	600	60	5.5	0.5	4 000	6 000	0	0

Table 4.10 Water use parameters for the lower Caledon (D23)

Quat.	**Dam volume ($m^3 \times 10^3$)**		**% area above dams**	**Dam irrig. area (km^2)**		**Direct abstraction ($m^3 \times 10^3 y^{-1}$)**		**Irrig. direct abstraction (km^2)**	
	Mean	**St. Dev**		**Mean**	**St. Dev**	**Min.**	**Max**	**Min.**	**Max.**
D23A	10 000	1000	80	6.0	0.6	0	0	0	0
D23B	20	2	`5	0.012	0.002	50	80	0	0
D23C	36 000	1000	95	30.0	3.0	0	0	0	0
D23D	22 000	1000	85	19.0	1.9	0	0	0	0
D23E	14 500	1000	60	10.0	1.0	800	1200	0	0
D23F	3 500	300	80	3.2	0.32	0	0	0	0
D23G	9 600	500	70	6.0	0.6	180	220	0	0
D23H	19 000	1000	85	15.0	1.5	0	0	0	0
D23J	14 000	1000	85	10.0	1.0	0	0	0	0

Figures 4.24-26 illustrate the simulation results for present day conditions using the three gauging stations: D2H012 (outlet of D21E), D2H022 (within D23E) and D2H021 (outlet of D23F). It should be noted that all of the observed data represent different record lengths and different periods of record. It is therefore extremely difficult to use them to assess the validity of the simulation results. Unfortunately, there are no alternative data that can be used for this purpose.

D21E / D2H012: Figure 4.24 illustrates that the uncertainty bounds for low flows bracket the observed low flows very well, and it would seem that the model and water use parameters used are appropriate for this headwater area of the basin. There remain some uncertainties with respect to high flows, however, this could partly be related to the differences in the periods of record, as well as uncertainties in the method that has been used to correct the inadequacies of the high flow gauging.

D23E / D2H022: Figure 4.25 illustrates the results at D23E, which is much further downstream and incorporates a large proportion of the assumed water use within the Caledon upstream of Welbedacht Dam. Once again, the observed records are highly uncertain in terms of the length of record and its ability to represent longer term variations, as well as the accuracy of the flow measurements based on a rated section. At this site, the present day uncertainty ensembles for moderate to low flows are all quite substantially lower than the observed data, which is in stark contrast to the situation at the next downstream gauging site at D2H001 (D23F). This is very difficult to explain, particularly given that the record for D2H022 represents the more recent period (1988-2010) when water use might be expected to be higher than within the period represented by D2H001 (1926-1978). Without any overlap between these two gauges, it is impossible to assess the differences between the two gauged records.

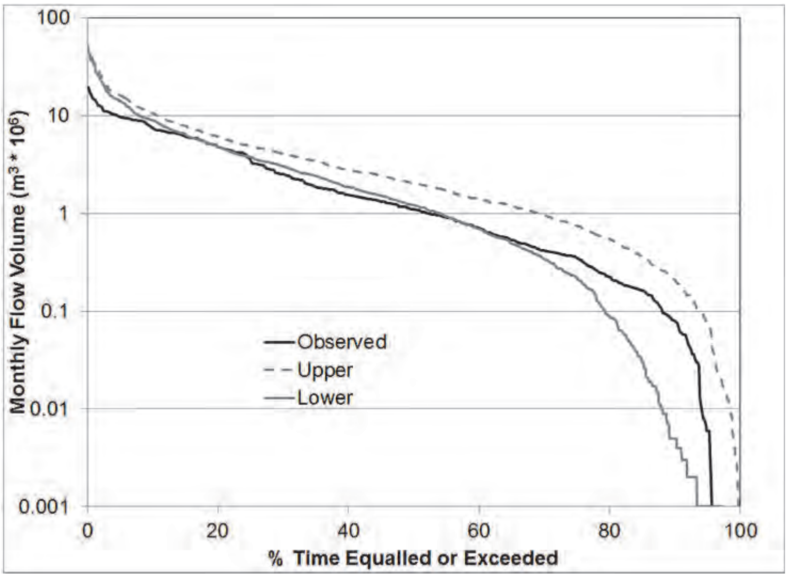


Figure 4.24 Present day uncertainty bounds for D21E compared with observed data at D2H012.

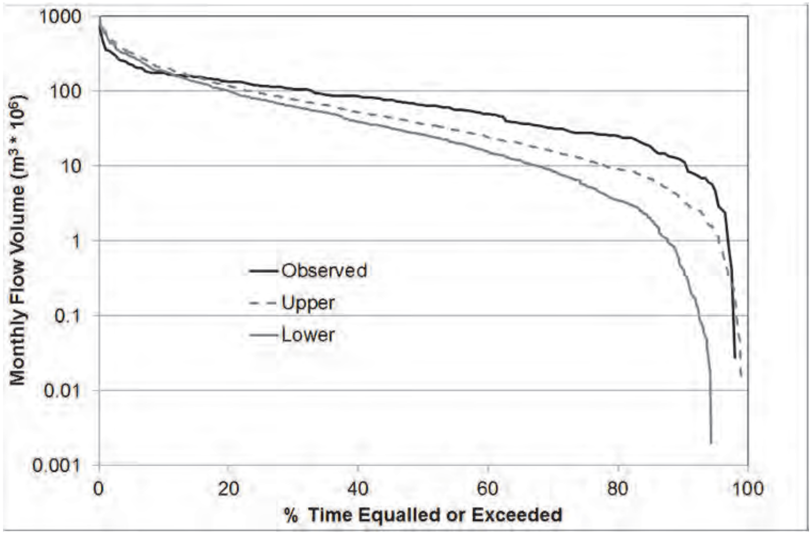


Figure 4.25 Present day uncertainty bounds for D23E compared with observed data at D2H022.

D23F / D2H001: The gauging record at D2H001 appears to be of reasonably good quality (and it is very surprising that such a key gauging station is no longer in operation) and represents the longest record period of all of the flow gauging stations in the basin. Figure 4.26 illustrates that apart from some of the lower flows, the correspondence between the lower uncertainty bound and the observed flows is reasonably good. An initial comparison of the low flow simulations at D23E and D23F suggested that the incremental flows between these two has substantially affected the length of time of zero flows (reduced from 6% to 1%) and these effects are solely due to incremental inputs from D23F itself, which has been assigned to zone 4. However, this implies that the water use from the tributary has been miss-represented. It is also possible that the relatively high FT parameter is not appropriate for this catchment and that it should fall into zone 5. The same conclusion could be reached about D23G, but this does not affect the evaluations of the model at D23F. Figure 4.26 illustrates the final results after these changes were made.

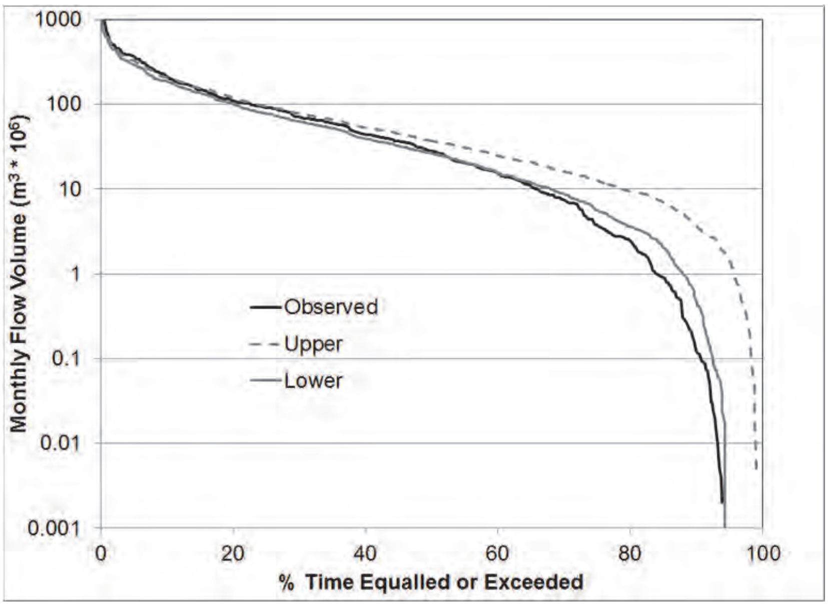


Figure 4.26 Revised present day uncertainty bounds for D23F compared with observed data at D2H001.

Figure 4.27 illustrates the full frequency distributions of simulated mean monthly flow as well as the simulated values for the 10th, 50th (median) and 90th percentiles of the flow duration curves. Arrows are included to illustrate the same values using the observed flow data. The diagrams indicate that high and consequently mean monthly flow tend to be over-simulated by the majority of the ensembles, while moderate to low flows are the opposite and there is a tendency to under-simulation. These results have to be seen in the context of different record lengths and some remaining uncertainties about the quality and accuracy of the observed flow data (particularly at high flows). In many respects, the simulations of present day conditions appear to be reasonable, but there remain concerns about whether the ‘real’ uncertainty has been represented by the model. This applies to both the natural simulations, as well as the simulations of present day conditions. The main problem is that there simply is not enough information, either to quantify the water use or to assess the simulations.

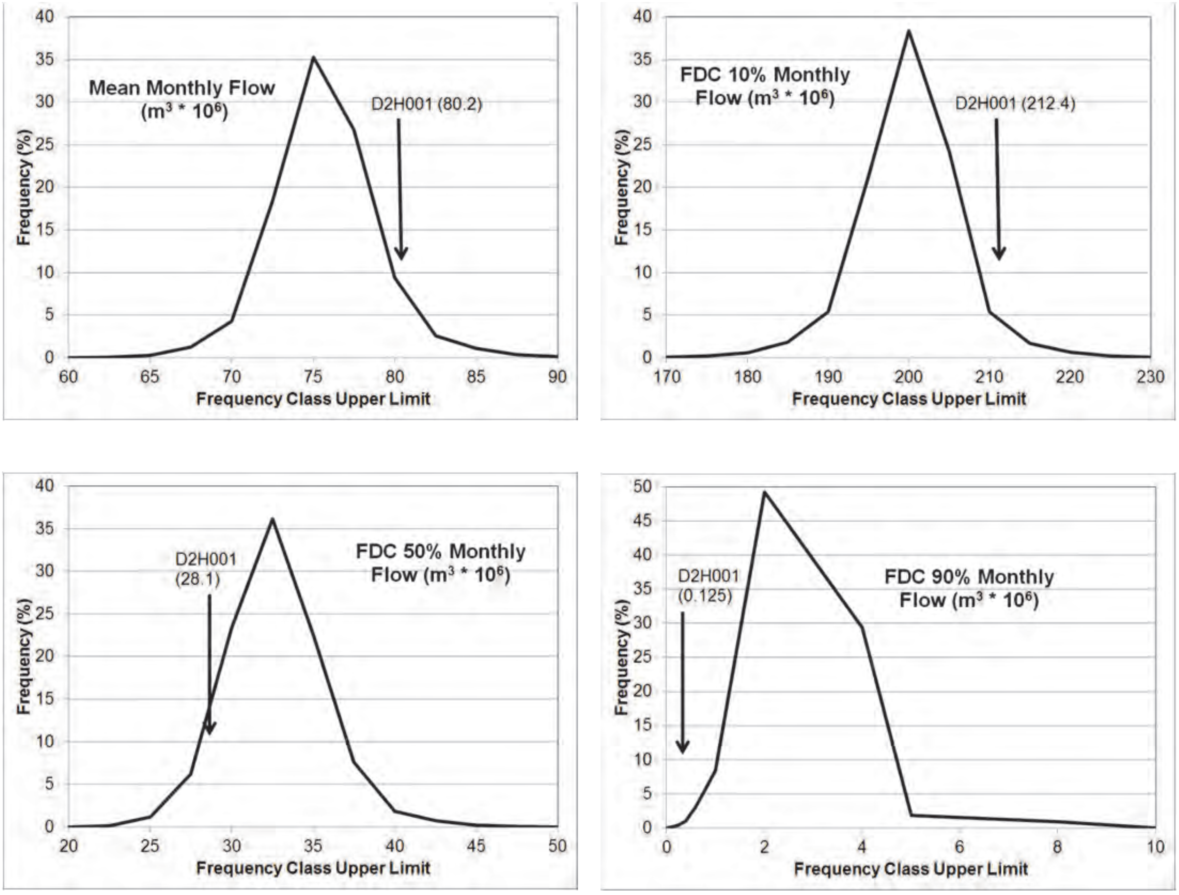


Figure 4.27 Frequency distributions for simulated mean monthly flow and the 10th, 50th and 90th FDC percentiles for the present day uncertainty model runs. (equivalent values for observed data at D2H001 are included).

4.6.4 Results – Natural and present day simulations (climate change data)

The details of the climate change data preparation for the Caledon River basin are identical to those applied in the Buffalo River. Therefore, the process of bias correction is not repeated in this report, but the results (Figure 4.28) are very similar to those found for the Amatole system. The main result for natural flow conditions is that the band of uncertainty is increased when all of the uncertainties across all of the nine GCMs are considered together. These uncertainties are further illustrated in Table 4.11 which lists the range of simulated mean annual runoff for the historical conditions as well as the nine downscaled GCMs and which includes the factor by which the GCM results differ from the historical for the lower and upper uncertainty bounds. Table 4.11 suggests that this can vary from 0.75-1.24 for the lower bound and 0.7-1.22 for the upper bound. The overall conclusion is that the uncertainty in water resources availability for the future is increased by a large amount and that the GCM projections do not agree on the direction of change. Figure 4.28 does, however, indicate that the lower bound of the GCM projections is further below the historical lower uncertainty bound than the equivalent differences between the upper bounds. There is, therefore, some suggestion of a drying tendency in the Caledon basin. A final point is that there is no pattern in the differences in the projections between the GCMs that can be considered generally skillful and those that are less skillful for this region.

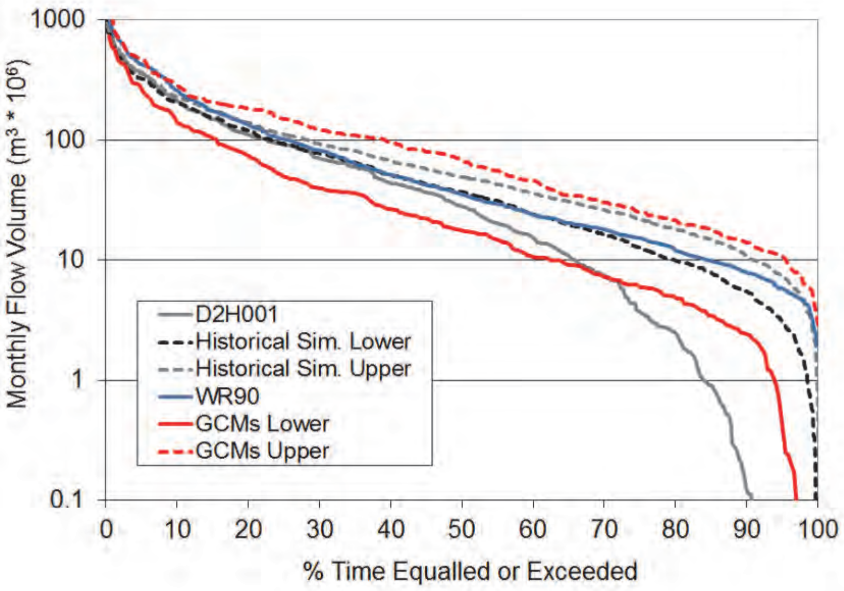


Figure 4.28 Uncertainty bounds for D2H001 (D23F) under natural conditions (historical data) and for future climate change projections (using the same model parameters).

Table 4.11 Comparisons of uncertainty bounds for simulated mean annual runoff using historical climate inputs (based on WR2005 data) and using nine downscaled, near future scenario projections.

Climate Model	**Generally skillful×**	**Simulated mean annual runoff ($10^6 \times m^3$)**	
		Lower	**Upper**
GFDL		734 (0.75)	808 (0.70)
GISS		761 (0.78)	918 (0.80)
CSIRO		849 (0.87)	1 020 (0.88)
MPI	Yes	903 (0.93)	1 061 (0.92)
CCCMA	No	943 (0.97)	1 112 (0.96)
CNRM	Yes	963 (0.99)	1 149 (1.00)
MRI	No	964 (0.99	1 137 (0.99)
Historical		971 (1.00)	1 152 (1.00)
IPSL	Yes	1 126 (1.16)	1 317 (1.14)
MIUB	No	1 209 (1.24)	1 410 (1.22)

Figure 4.29 shows the range of changes in mean monthly rainfall across quaternary catchments in several regions including the Caledon. There are clearly quite substantial variations (from extremes of about -10% to over +30%) between the climate change models, but more of them suggest increases in rainfall. An analysis of the skill of the climate change models by comparing the baseline rainfall simulations with the historical data (2005) does not help to reduce the variability in predicted impacts. In fact, the two models with the highest skill scores are GISS and IPSL, and these represent almost the full range of predicted changes in rainfall shown in Figure 4.29. The result illustrated in Figure 4.28 therefore demonstrates a substantial impact of increased temperature and therefore, evaporative losses. The range of temperature changes suggested by the climate change models is much lower and they all have increases of between 15-25%, with winter increases tending to be higher than summer increases.

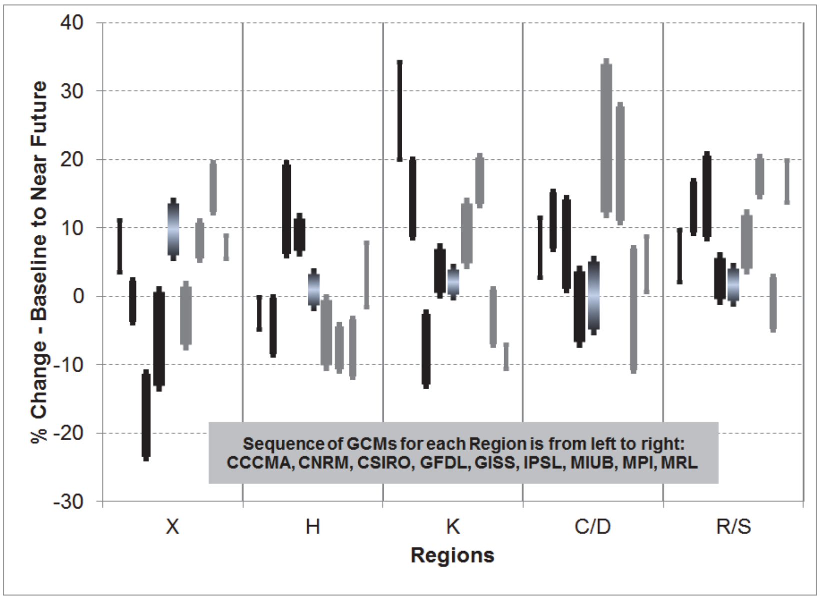


Figure 4.29 Range of changes in mean monthly rainfall between baseline (1961-2000) conditions and near future (2046-2065) for the nine downscaled climate change scenarios.

This section of the report deals with an investigation of the potential climate change impacts on the present day uncertainty model results using the same analysis approaches used for the natural conditions. It is important to emphasise that the parameter sets and input uncertainty bounds have not been changed for the model runs based on climate change inputs. Figure 4.30 shows the results of the uncertainty model runs (at D23F) in terms of the frequency distributions of mean annual flow volume for all of the nine downscaled climate models compared to the historical results, while similar information is presented in Figure 4.31 for the 12 month minimum flows. The latter is an approximate representation of the expected yield from a relatively small dam (e.g. Welbedacht Dam). These are all based on sub-catchment D23F and all the frequency distributions are based on 10 000 ensemble outputs. The enormous increase in uncertainty across all of the climate models is immediately apparent.

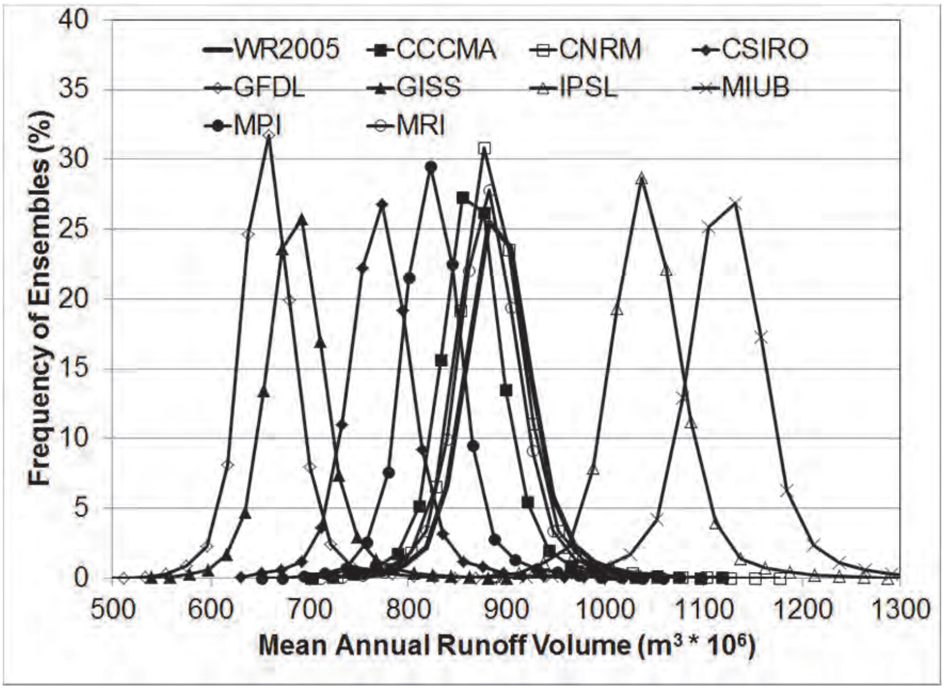


Figure 4.30 Frequency distributions of mean annual runoff volumes at D23F for the ordinary uncertainty (parameter uncertainty only – 10 000 ensembles) version based on historical climate inputs and inputs from nine downscaled GCMs.

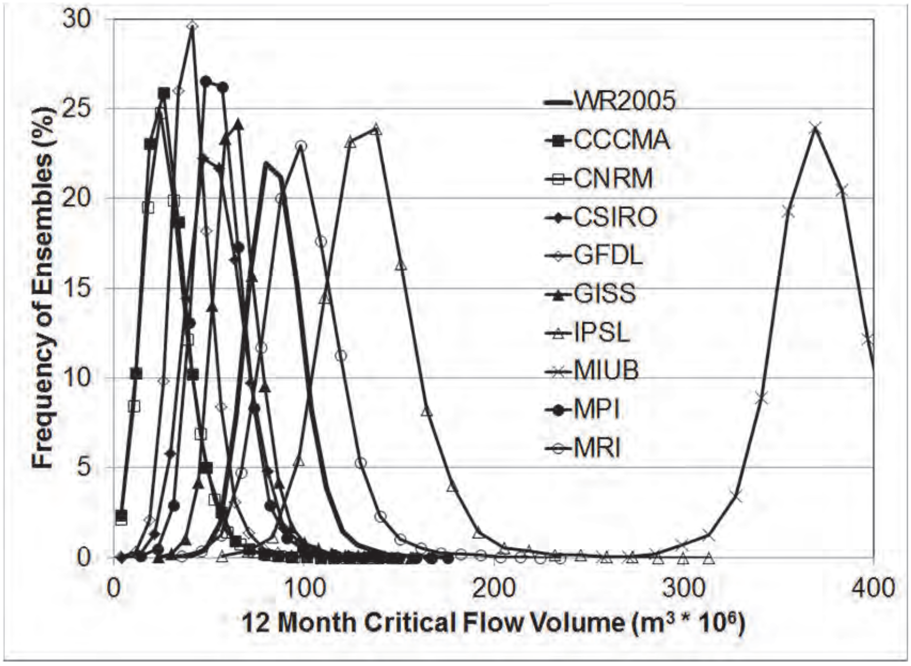


Figure 4.31 Frequency distributions of 12 month critical period minimum flow at D23F for the ordinary uncertainty (parameter uncertainty only – 10 000 ensembles) version based on historical climate inputs and inputs from nine downscaled GCMs.

An alternative approach to assessing the climate change uncertainties is to assume that all of the climate model outputs are equally likely and therefore, combine them into a single frequency distribution (i.e. an ensemble of 90 000 simulation results). This approach is consistent with the normal assumptions about the equal likelihood of different climate model projections as well as the skill tests carried out. The results of this analysis for both the mean annual runoff estimates and for the 12 month critical minimum flow are presented in Figure 4.32 and 4.33 and the equivalent natural flow simulations using WR2005 climate inputs have been included.

Figures 4.32 and 4.33 are based on cumulative frequency distributions because the number of class intervals is greater in the GCM output frequency data. These results reflect the large differences between the individual GCM outputs. The majority of the frequency distributions based on the total GCM outputs suggest a reduction in available water resources. Figures 4.32 and 4.33 also include the cumulative frequency distributions of the uncertainty simulations based on natural conditions and WR2005 rainfall (‘Natural WR2005’). Perhaps the most interesting observations are that the upper bounds of all of the simulations (with the exception of the extreme MIUB GCM) are similar, while the lower bounds of the natural mean annual runoff (MAR) simulations are over 200 × 10^6 m^3 greater than the lower bounds of the present day simulations based on WR2005 climate data and even higher relative to the total GCM ensemble and the stochastic rainfall ensemble. There is also an approximately 200 × 10^6 m^3 difference between the MAR medians based on natural and present day conditions.

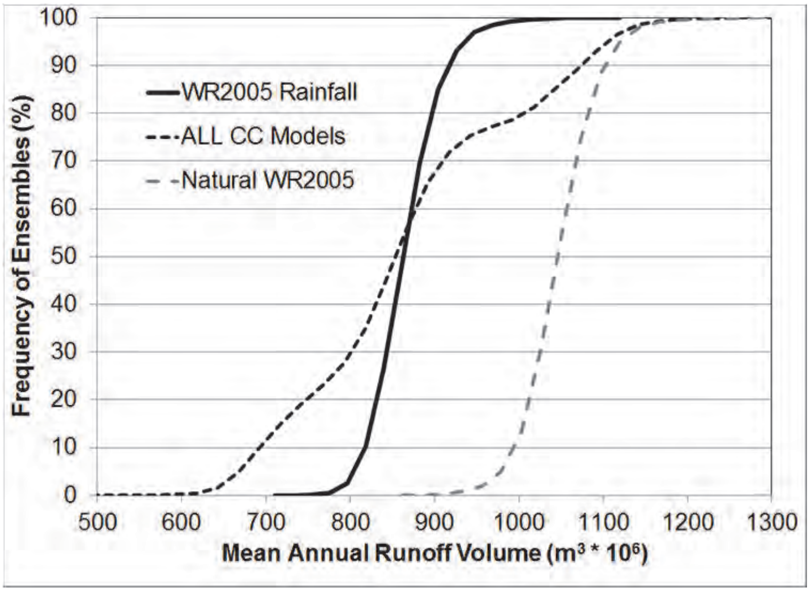


Figure 4.32 Cumulative frequency distributions of mean annual runoff volumes for the ordinary uncertainty (parameter uncertainty only – 10 000 ensembles) version based on historical climate inputs and the combined outputs from the nine downscaled GCMs (90 000 ensembles).

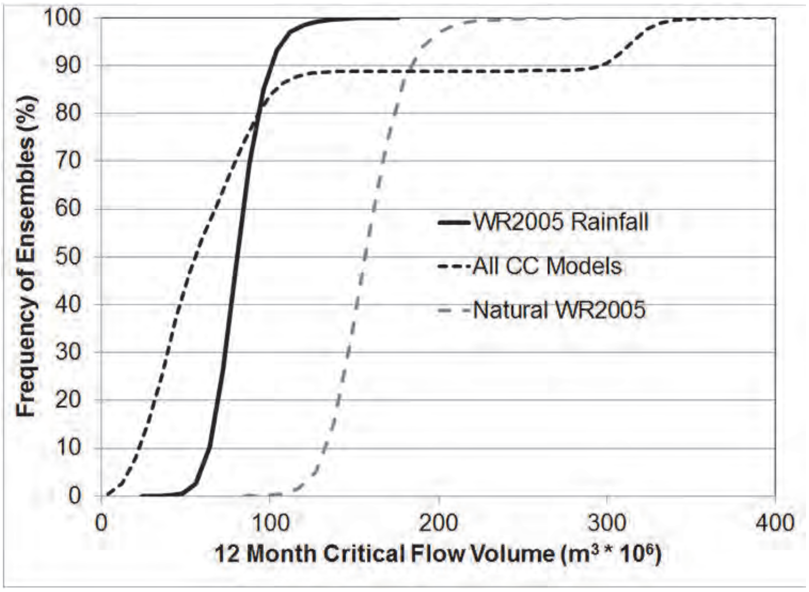


Figure 4.33 Cumulative frequency distributions of 12 month critical period minimum flow for the ordinary uncertainty (parameter uncertainty only – 10 000 ensembles) version based on historical climate inputs and the combined outputs from the nine downscaled GCMs (90 000 ensembles).

4.6.5 Conclusions

Throughout the climate change and water resources modelling studies undertaken for this project, monthly time series of rainfall data have been used. However, these data sets have the potential to mask other possible changes in future climates that occur at sub-monthly time scales. Results of the daily rainfall uncertainty analysis conducted by PhD candidate Thabiso Mohobane are presented in Appendix B.

The Caledon River basin is generally representative of the situation in many parts of South Africa, where the observed stream flow data associated with gauging stations are of limited value for calibrating hydrological models to simulate natural conditions. However, as this study suggests, at least some of the observed data can be useful for assessing uncertainty ensemble outputs from models.

As with the climate model results for the Amatole basin, the range of uncertainty is increased. However, there is a tendency for the lower flows in most of the climate model projections. A large part of this effect is associated with assumed higher evaporation rates superimposed on relatively small changes in rainfall amounts. The effects are somewhat exacerbated in the simulations of present day water use conditions relative to the climate change projections of natural water resources availability.

CHAPTER 5. APPLICATION OF WEAP FOR WATER AVAILABILITY AND USE MODELLING

by

Sukhmani K. Mantel

WEAP is a system level forecasting tool for simulating flows and water quality for surface and groundwater resources. The model uses rainfall data to simulate natural hydrology and has the capacity to estimate future availability of water depending on the demand, storage and pollution sources, along with climate data such as air temperature, humidity, etc. (Sieber and Purkey, 2007). For this reason, it has been used in combination with the Pitman hydrological model.

5.1 Current Scenario: Set-up and calibration

The infrastructure and the water transfer schemes of the Amatole system that this project focused on are shown in Figure 5.1. Figures 5.2a and 5.2b show schematics of the model setup in WEAP for the Amatole system.

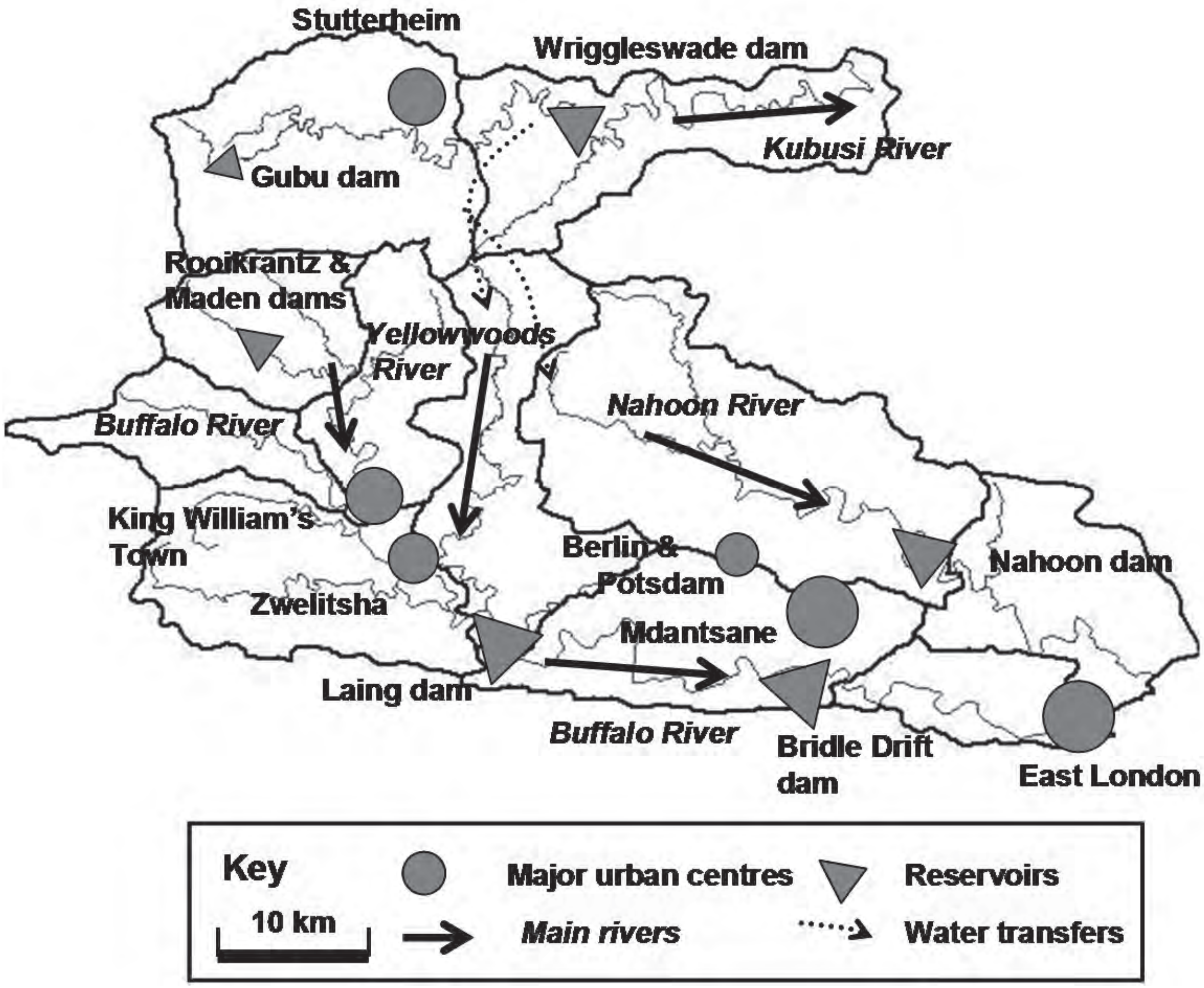


Figure 5.6 Map of the Amatole catchments in the Eastern Cape.

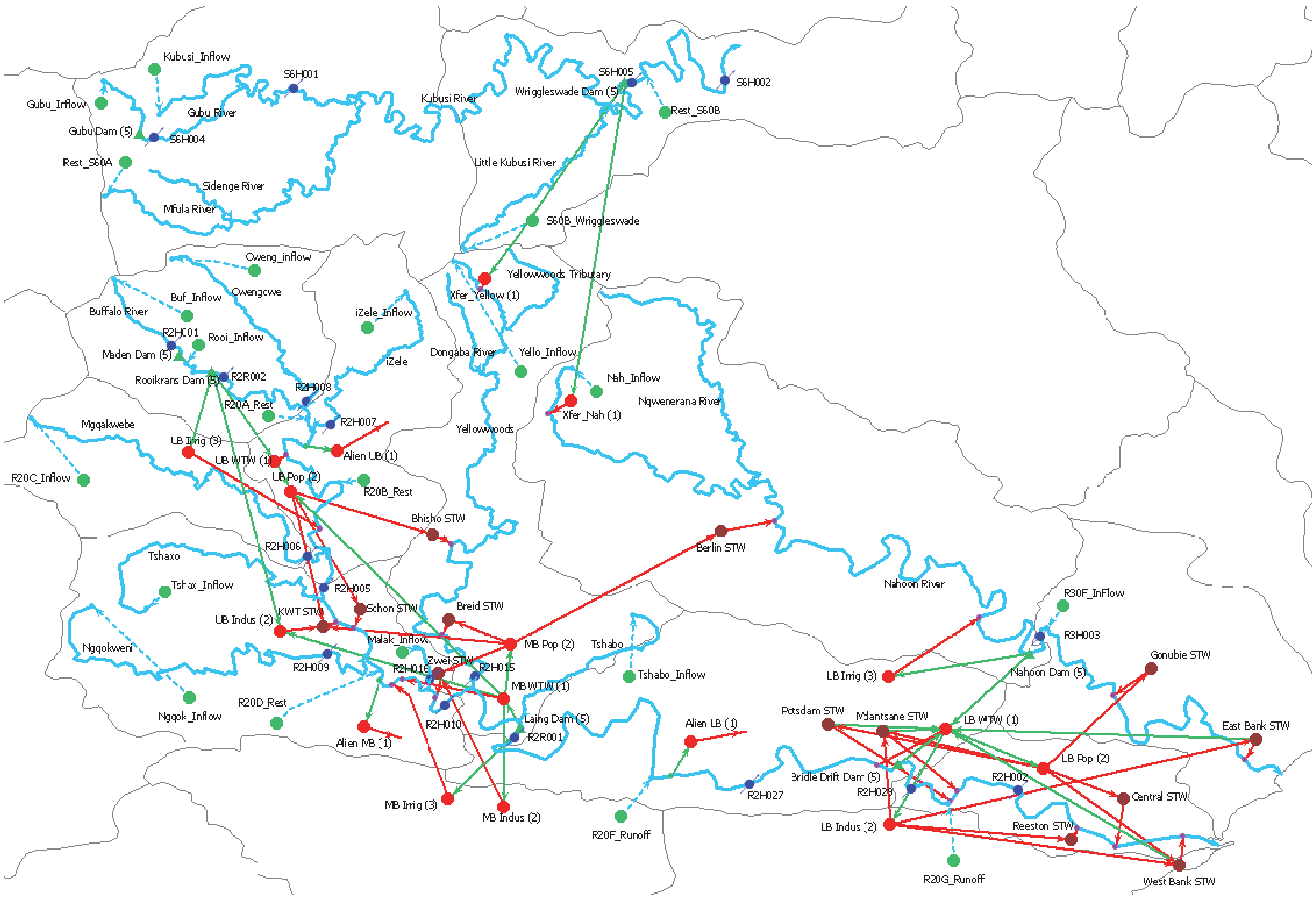


Figure 5.7a Screen capture of the Amatole system in WEAP.

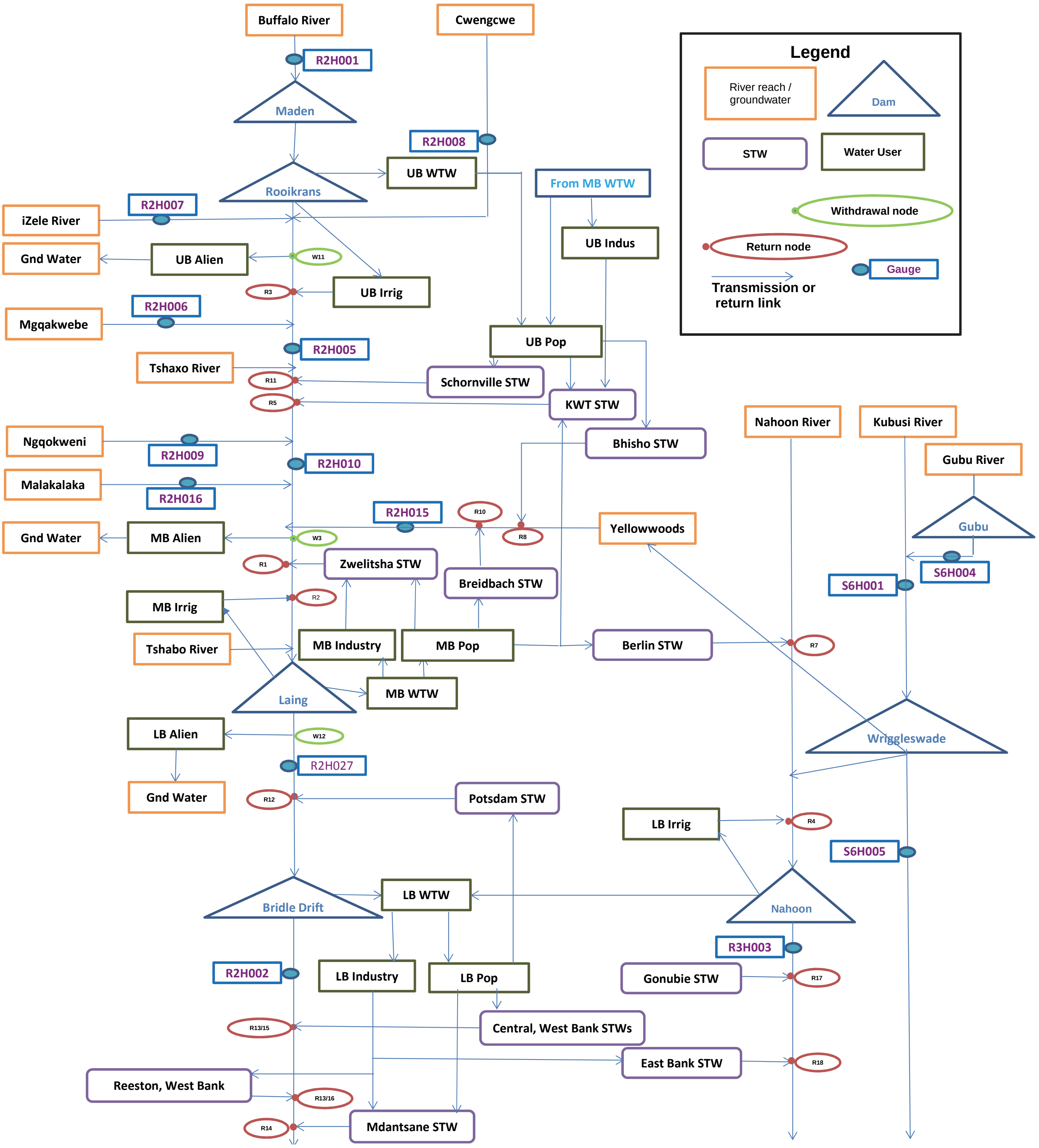


Figure 5.2b A schematic showing details of the Amatole system that were entered into the WEAP model. UB is Upper Buffalo; MB is Middle Buffalo; LB is Lower Buffalo.

5.1.1 Input hydrology for river tributaries

The input hydrology of the Amatole system tributaries was estimated using the FAO rainfall-runoff option in the WEAP model. Rainfall data estimated for individual quaternaries from the WR2005 database (Middleton and Bailey, 2008) were entered for each tributary. Further details of the other data entered into WEAP (including catchment area, effective precipitation and monthly evapotranspiration) are presented in detail in Appendix E and some of the important aspects are summarised here.

5.1.2 Reservoir data

The locations of the reservoirs on the Amatole system are shown in Figure 5.3. Reservoirs are considered to be demand sites in terms of water storage.

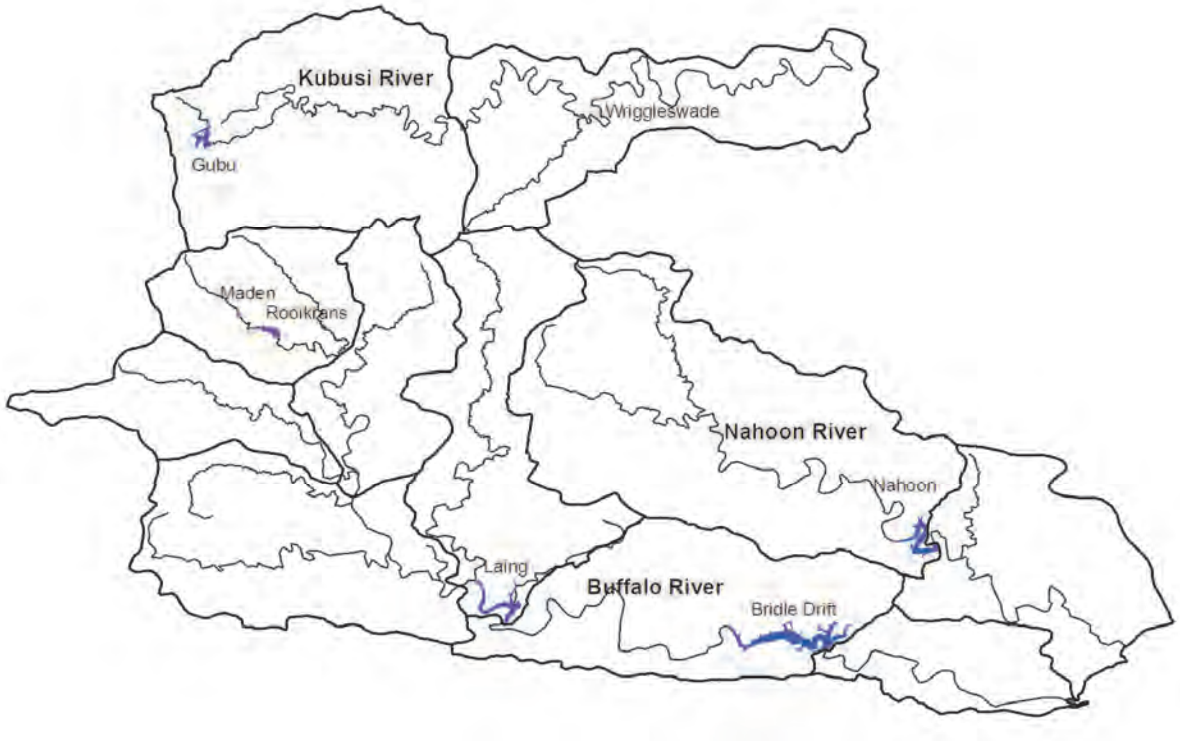


Figure 5.3 Locations of the six reservoirs in the Amatole system that were entered into the WEAP model.

5.1.3 Water demand sites: Population, agriculture, industry

The primary water demand categories are human settlements, industry, agricultural sites and alien vegetation (in some parts of the catchment). For simplification, the Amatole system has been divided into three demand areas – Upper, Middle and Lower Amatole following DWAF (2008). The water requirements of the water users have been entered into the WEAP model as a stationary demand over the years. This was done in order to assess the effects of the varying hydrology in isolation instead of hydrological variation in combination with variation in water demand over the modelled years. The current water requirements that have been used are those for the year 2005 listed in DWAF (2008: Table 4.13) and details of the demand sites are provided in Appendix E.

5.1.4 Water demand sites: Invasive aliens

WR2005 (Middleton and Bailey, 2008) provides data for the area covered by invasive aliens for each quaternary. Water lost to invasive aliens was estimated from DWAF (2004b) to be approximately 3 × 10^6 m^3 y^{-1} which was divided into the three demand areas of Upper, Middle and Lower Amatole (DWAF, 2008). It was assumed that 96% of the flow would be consumed by the alien vegetation. Further details are provided in Appendix E.

5.1.5 Water treatment works capacity

Feedback from Dr Nikite Muller of Amatola Water provided the data in Table 5.1 on water treatment works capacity.

Table 5.3 Current production of Water Treatment Works in the Amatole system. Data source: DWAF (2008), AWB (2010a), AWB (2010b), BCM (2012).

Water Treatment Work	**Present Production Mℓ d^{-1} (10^6 m^3 y^{-1})**
Rooikrantz WTW	1.2 (0.44)
King William's Town WTW	13.0 (4.75)
Laing Dam WTW	33 (12.05)
Nahoon WTW	33.7 (12.30)
Umzonyana WTW	120.0 (43.80)

5.1.6 Water Losses in the system

DWAF (2008) provides estimates of losses in the water provision system, as shown in Table 5.2, which were incorporated into the WEAP model. The losses in the WEAP model include evaporative, leakage and consumption losses and thus, those reported in Table 5.2 are higher than those listed in DWAF (2008).

Table 5.4 Water losses (as evaporative/leakage/consumption) in the Amatole system.

Loss/water consumption	Upper Amatole	Middle Amatole	Lower Amatole	Source of data
Dams to Water treatment works (WTW) and through WTW	10%	4%	9%	DWAF (2008)
Demand site (population or industry)	20%	20%	20%	Estimated, including consumption and conveyance losses (DWAF, 2008)
Wastewater treatment works (WWTW)	5%	5%	5%	DWAF (2008)
Return flow loss from demand site to WWTW	10%	10%	10%	Estimated from reticulation losses (DWAF, 2008)
Return flow loss from WWTW to river	10%	10%	10%	Estimated from reticulation losses (DWAF, 2008)
Total loss / consumption	44.6%	40.9%	44.0%	----

5.1.7 Stream flow data for calibration

Daily stream flow data (from October 1960-September 2000) for selected gauging stations in the Amatole catchment (Table 5.3 and Figure 5.4) were downloaded from the DWA website. Some stations had missing periods of data that were patched through application of the Patching Flow Data module in SPATSIM (Hughes et al*.,* 2000). Patching for a specific gauging station used data from nearby gauging stations that had data available for the periods of missing data. Three gauge stations (R2H002, R2H027 and S6H005) that are located near dams had missing data, but because of their location below or near dams, their data could not be patched using the above technique.

Table 5.3 Selected stream flow gauging stations for model input. Data source: http://www.dwa.gov.za/Hydrology.

Station No.	Data available	Latitude (S); Longitude (E)	River
R2H001	1946-10-01 to 2010-07-20	32°43’55.0”; 27°17’37.0”	Buffalo River
R2H002	1947-10-01 to 2010-07-20	32°59’47.6”; 27°47’46.8”	Buffalo River
R2H005	1947-10-01 to 2010-07-20	32°52’31.4”; 27°22’58.3”	Buffalo River
R2H006	1948-07-05 to 2010-07-20	32°51’30.3”; 27°22”14.6”	Mgqakwebe River
R2H007	1947-11-01 to 1981-12-30	32°46’45.6”; 27°23’06.8”	iZele River
R2H008	1947-06-01 to 2010-07-20	32°46’04.6”; 27°22’22.7”	Qwengcwe River
R2H009	1947-06-01 to 2010-07-19	32°54’55.6”; 27°23’10.8”	Ngqokweni River
R2H010	1950-07-01 to 2010-07-19	32°56’25.9”; 27°27’38.3”	Buffalo River
R2H015	1988-03-21 to 2010-07-20	32°55’54.1”; 27°28’21.2”	Yellowwoods
R2H016	1988-03-22 to 2010-07-19	32°56’06.5”; 27°26’45.2”	Malakalaka River
R2H027	1994-02-24 to 2010-07-22	32°59’29.9”; 27°38’24.1”	Buffalo River
R3H003	1965-01-15 to 2010-07-22	32°54’18.6”; 27°48’33.8”	Nahoon River
S6H001	1947-04-12 to 2010-07-21	32°34’45.7”; 27°21’57.3”	Kubusi River
S6H002	1947-06-01 to 1995-08-21	32°34’32.7”; 27°37’21.8”	Kubusi River
S6H004	1971-09-22 to 2010-07-21	32°36’30.0”; 27°16’59.9”	Gubu River

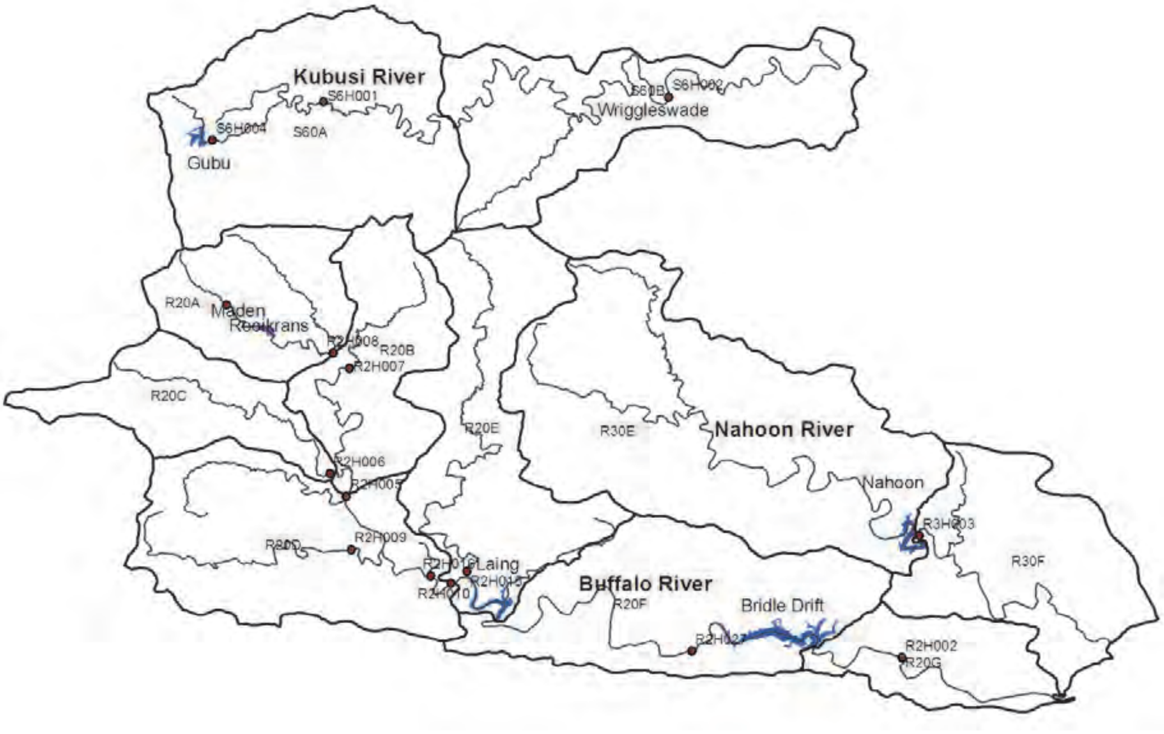


Figure 5.4 Stream flow gauging stations located on the Buffalo, Nahoon and Kubusi rivers that were used in the study.

5.1.8 Calibration results: Stream gauges (1980-2005)

WEAP results for the simulation of hydrology from rainfall data were matched against recorded data by stream gauges to assess how accurately the model was simulating water quantity. The stream gauges whose data were compared with WEAP simulated reach data are shown in Table 5.4. The results for simulated and observed data for yearly flows and flow duration curves (FDC) are presented in Appendix F for the reaches near the upstream gauges on the Buffalo River (R2H001, R2H006, R2H007, R2H008, R2H009, R2H015, R2H027).

Simulated data for the Nahoon River could not be calibrated against measured flow data because the stream gauge R3H003 is located below the Nahoon Dam. Overall, the model simulation matches the gauge data when comparing yearly and monthly flow figures. The simulated data match the pattern of variation although they are slightly higher than the recorded flows at the gauges. The reasons for the difference between simulated and recorded flows could be due to uncertainty arising from various sources. These include uncertainty in the model structure, that in the observed flow data and uncertainty in the water user demands. The difference may also arise from variation in the actual water user demands that vary over time, whereas stationary demands were entered into the WEAP model.

Table 5.4 Gauge data used for calibrating the input hydrology for the Buffalo River tributaries using the rainfall-runoff model under WEAP.

Tributary name	Gauge on the tributary
Buffalo (upstream R20A)	R2H001
Qwengcwe (R20A)	R2H008
iZele (R20B)	R2H007
Mgqakwebe (R20C)	R2H006
Ngqokweni (R20D)	R2H009
Yellowwoods (R20E)	R2H015
Buffalo (midstream R20D)	R2H005
Buffalo (midstream R20D)	R2H010
Buffalo (downstream R20F)	R2H027

5.2 Current Scenario: Model results

5.2.1 Current Scenario: Reservoir storage

The WEAP simulated reservoir storage (estimated from reservoir storage + spill below dam) was compared to the actual data (estimated from reservoir storage + uncontrolled spill + river releases) provided by Mr Cobus Ferreira of the DWA in East London to assess how good the WEAP simulations are. Figures 5.5-7 show the results and indicate that overall, the simulation matches the pattern of change, although it simulates higher storage values in some cases.

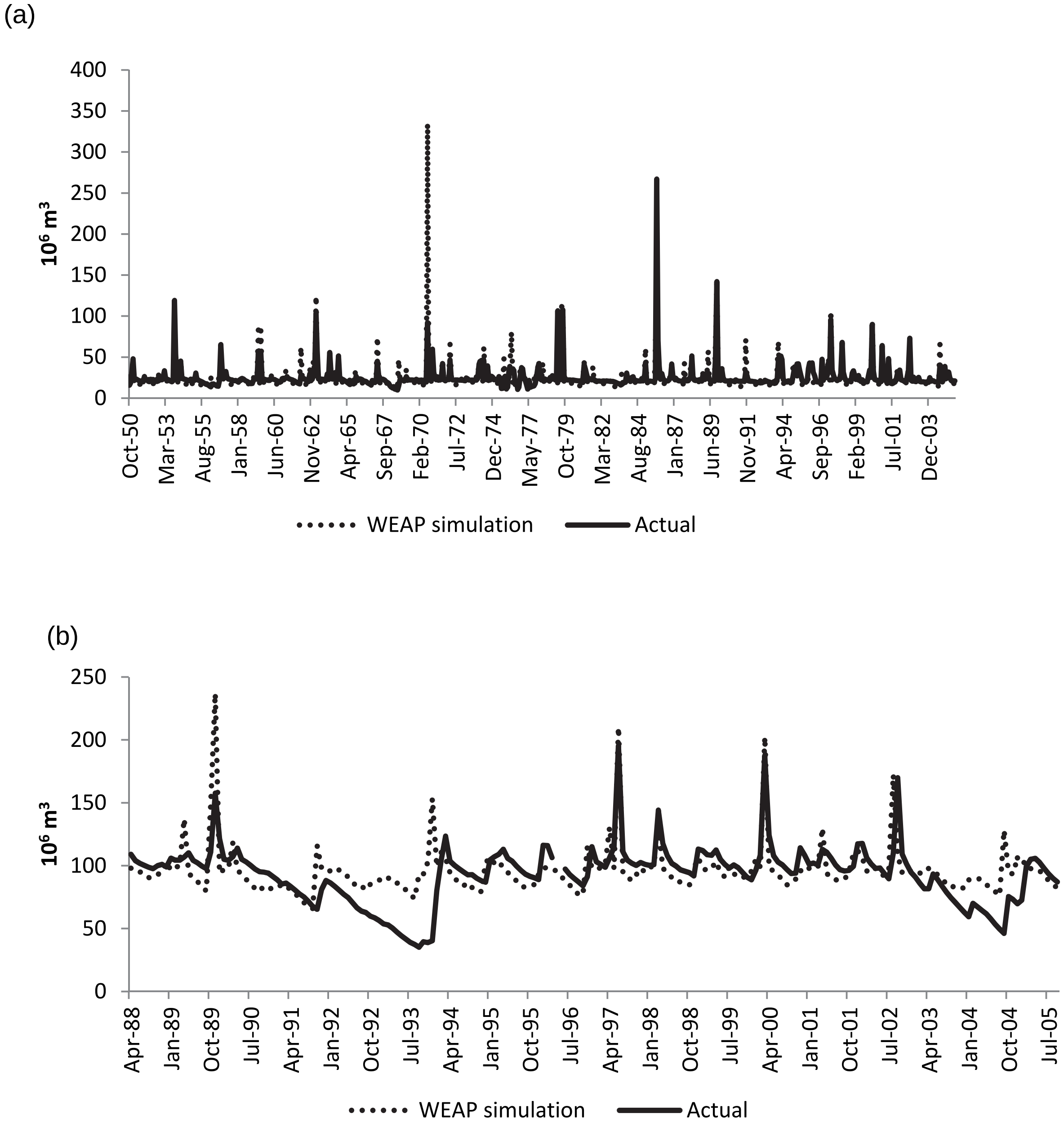


Figure 5.5 Reservoir storage simulated by WEAP relative to actual values for the (a) Laing and (b) Bridle Drift dams.

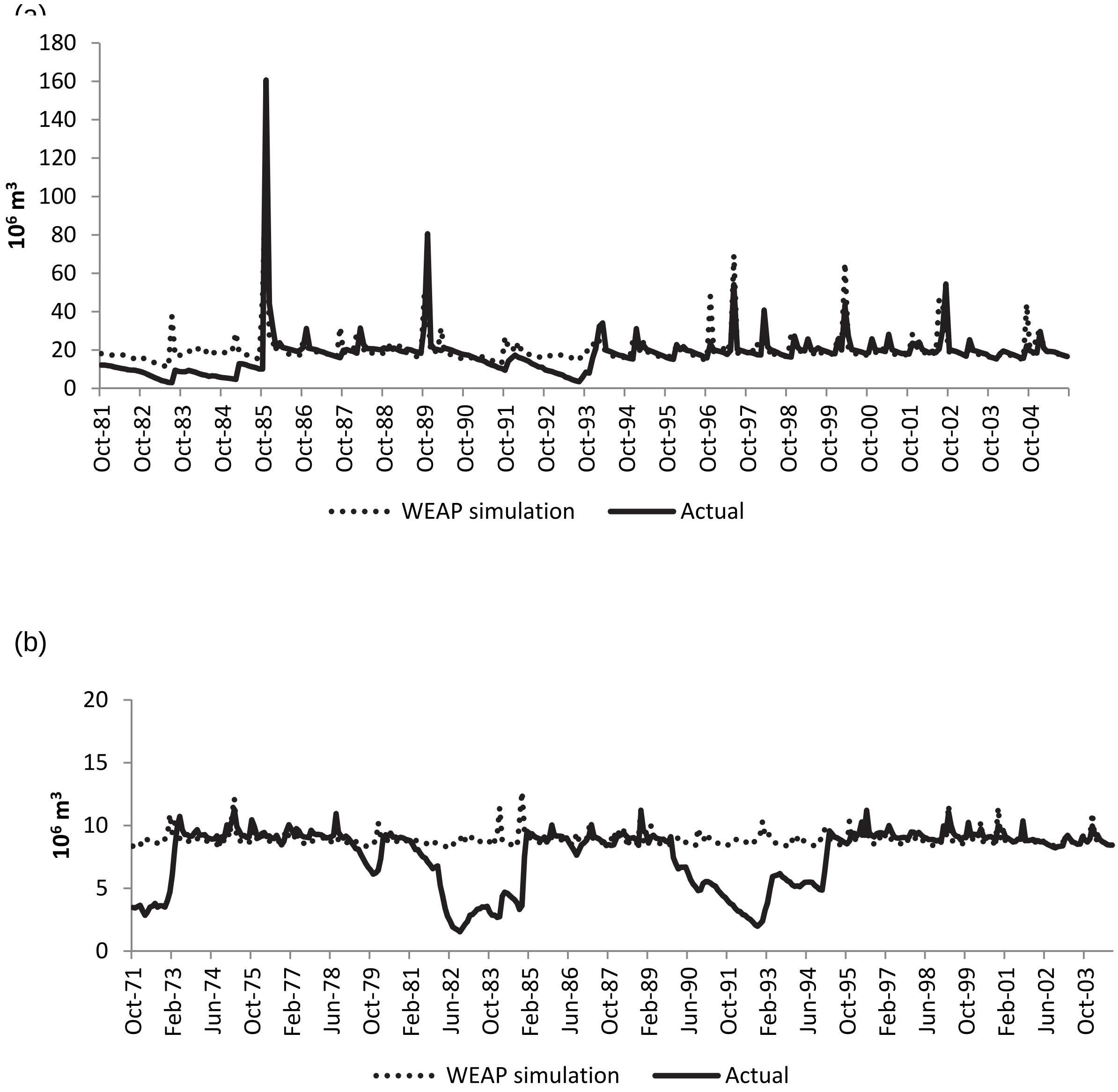


Figure 5.6 Reservoir storage simulated by WEAP relative to actual values for the (a) Nahoon and (b) Gubu dams.

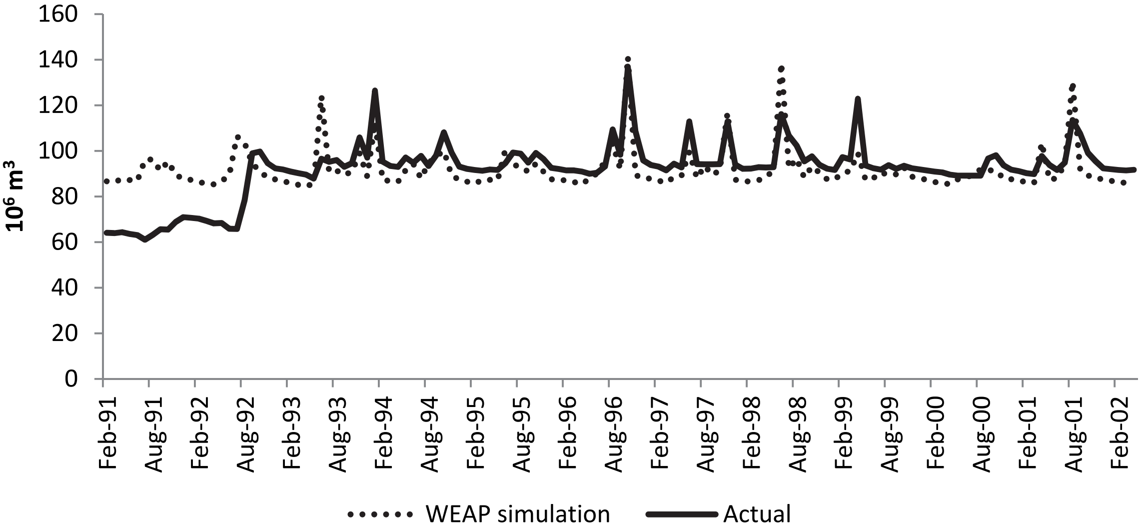


Figure 5.7 Reservoir storage simulated by WEAP relative to actual values for the Wriggleswade Dam.

5.2.2 Current Development Scenario: Supply requirements and water user deficit

To determine if the current water requirements can be met with the available infrastructure, the WEAP model was run for the full historical rainfall record for the years 1921-2005. *The simulation was run over the 85 years as the full historical dataset represents the present extremes in hydrological conditions for the Amatole system.*

Table 5.5 shows the supply requirements (including water lost in reticulation) for the various user groups under the Current Development Scenario. The results of the WEAP model run indicate that the water user requirements were met 100% of the time for all users under the Current Development Scenario, i.e. there is no deficit in meeting the demands at present.

Table 5.5 Supply requirement (10^6 m^3; including water loss in reticulation system) of the three demand areas for population, industry, alien vegetation, and irrigation sectors for the Amatole system for the years 1921-2005 (***Current Development Scenario***).

	Oct	Nov	Dec	Jan	Feb	Mar	Apr	May	Jun	Jul	Aug	Sep	Sum
Upper Amatole													
Pop.	0.42	0.41	0.42	0.42	0.38	0.42	0.41	0.42	0.41	0.42	0.42	0.41	4.96
Indus.	0.21	0.20	0.21	0.21	0.19	0.21	0.20	0.21	0.20	0.21	0.21	0.20	2.48
Alien.	0.14	0.13	0.14	0.14	0.12	0.14	0.13	0.14	0.13	0.14	0.14	0.13	1.59
Irrig.	0.12	0.12	0.10	0.07	0.07	0.06	0.06	0.10	0.12	0.12	0.14	0.14	1.24
Middle Amatole													
Pop.	0.67	0.65	0.67	0.67	0.61	0.67	0.65	0.67	0.65	0.67	0.67	0.65	7.94
Indus.	0.10	0.10	0.10	0.10	0.09	0.10	0.10	0.10	0.10	0.10	0.10	0.10	1.23
Alien.	0.07	0.06	0.07	0.07	0.06	0.07	0.06	0.07	0.06	0.07	0.07	0.06	0.79
Irrig.	0.19	0.19	0.15	0.11	0.11	0.10	0.10	0.15	0.19	0.19	0.21	0.21	1.90
Lower Amatole													
Pop.	2.77	2.68	2.77	2.77	2.50	2.77	2.68	2.77	2.68	2.77	2.77	2.68	32.65
Indus.	0.90	0.87	0.90	0.90	0.81	0.90	0.87	0.90	0.87	0.90	0.90	0.87	10.61
Alien.	0.05	0.05	0.05	0.05	0.05	0.05	0.05	0.05	0.05	0.05	0.05	0.05	0.62
Irrig.	0.13	0.13	0.10	0.08	0.08	0.06	0.06	0.10	0.13	0.13	0.14	0.14	1.26

5.3 Future development scenarios: Model setup for near future water requirement scenarios under current climate variability

The near future (2046-2065) water requirements were calculated from the expected increase in water demands from the years 2005-2030 that were extrapolated to the middle of the near future period (i.e. water requirements for the year 2056). Water requirements of the users have been entered into the WEAP model as a stationary demand for the near future years using the values for the year 2056. For the population water requirements, the document DWAF (2008) defines three scenarios:

- **Lower Development Scenario** No change is predicted in the mix of level of service.
- **Intermediate Development Scenario** A gradual increase in the level of service is predicted for the population of informal settlements with the unit consumption of 25 ℓ/c/d increasing to 120 ℓ/c/d by 2025.
- **Upper Development Scenario** An additional increase in the level of service of the population currently served at 120 ℓ/c/d to 200 ℓ/c/d by 2025 in addition to an increase for the population of the informal settlements.

These scenarios have been tested using the current climate variability (i.e. no climate change effects) in order to look at the effects of changes in water requirements in isolation. This is why this section is labelled "*Model setup for near future requirements scenarios under current climate variability*". The WEAP model scenarios for the near future development were therefore run over the full hydrological recorded period from 1921-2005.

5.3.1 Near future water requirements: Intermediate Development Scenario

The water requirements for the Intermediate Development Scenario of near future development are listed in Table 5.6a and Figures 5.8a-c. Note that the water requirement figures for the current situation and the year 2030 are obtained from the main report by DWAF (2008: Table 4.13). These have been extrapolated to the middle of the near future period (i.e. the year 2056).

The following changes in water requirements are expected in the near future under the Intermediate Development Scenario relative to the Current Scenario water requirements:

- Domestic/population water requirements increase in the Upper and Lower Amatole and decrease in the Middle Amatole.
- Industrial water requirements for the Upper and Middle Amatole remain unchanged, and they increase in the Lower Amatole.
- Irrigation water requirements remain unchanged.

Table 5.6b shows the population growth figures obtained from the Planning Team in DWAF (2008) for the year 2030 that were extrapolated to the year 2056. The expected population annual water use rates were then calculated (Table 5.6c) to match the water requirements in Table 5.6a. The population water requirements for the near future were thus entered into the WEAP model as population figures for the year 2056 and the annual water use rates.

Table 5.6a Water requirements (10^6 m^3 y^{-1}) for population, industry and agriculture for the current and the near future (2046-2065) under the Intermediate Development Scenario obtained from DWAF (2008) for the year 2030. The figures for the near future year 2056 have been obtained by extrapolating the growth rate from 2030 to 2056.

Scenario (Year)	**Upper Amatole**	**Middle Amatole**	**Lower Amatole**	**Total**
Domestic / population water requirement				
Current (2005)	4.96	7.94	32.65	45.55
Predicted (2030)	7.25	6.86	37.79	51.90
Near future (2056)	10.76	5.90	44.01	60.67
Industrial water requirement				
Current (2005)	2.48	1.23	10.61	14.32
Predicted (2030)	2.48	1.23	13.34	17.05
Near future (2056)	2.48	1.23	16.93	20.64
Agriculture irrigation water requirement				
Current (2005)	1.24	1.9	1.26	4.4
Predicted (2030)	1.24	1.9	1.26	4.4
Near future (2056)	1.24	1.9	1.26	4.4

Table 5.6b Population growth scenario for the year 2030 according to the Planning Team in DWAF (2008: Appendix 1). The figures for the near future year 2056 have been obtained by extrapolating the population growth rate from the year 2030 to 2056. These figures were used for all three development scenarios.

Scenario (Year)	**Upper Amatole**	**Middle Amatole**	**Lower Amatole**	**Total**
Current (2005)	90 465	122 196	478 017	690 678
Predicted (2030)	109 939	110 932	489 734	710 603
Near future (2056)	134 651	100 317	502 222	737 190

Table 5.6c Annual water use rates (m^3/person) used in the WEAP model in order to match figures for population water requirements in Table 5.6a for the near future under the Intermediate Development Scenario obtained from DWAF (2008).

Scenario (Year)	**Upper Amatole**	**Middle Amatole**	**Lower Amatole**
Current (2005)	54.83	64.98	68.30
Predicted (2030)	65.95	61.84	77.16
Near future (2056)	79.91	58.81	87.63

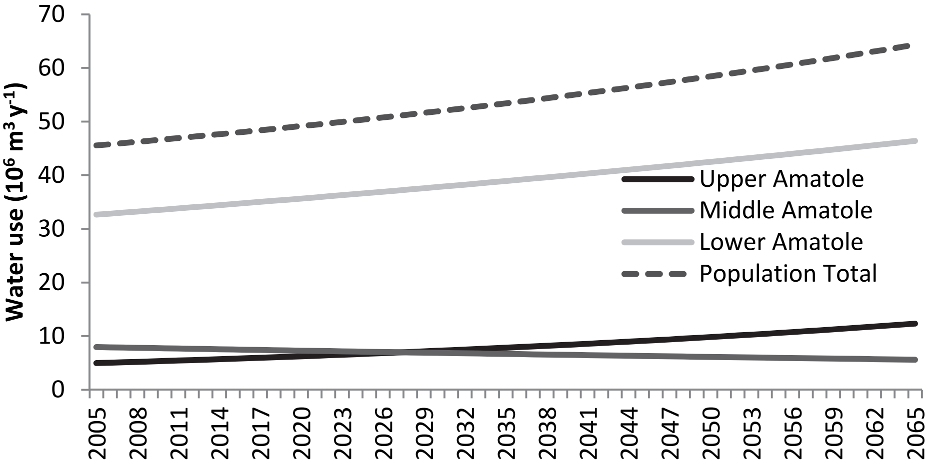


Figure 5.8a Expected population water requirements for the three water demand areas under the Intermediate Development Scenario in the near future up to the year 2065. The WEAP model setup used the values for the year 2056 as stationary water requirements.

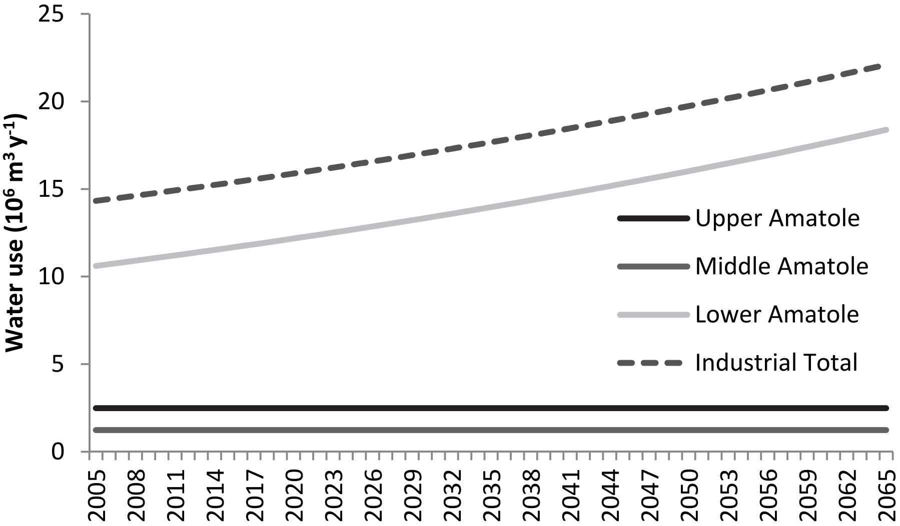


Figure 5.8b Expected industrial water requirements for the three water demand areas under the Intermediate Development Scenario in the near future up to the year 2065. The WEAP model setup used the values for the year 2056 as stationary water requirements.

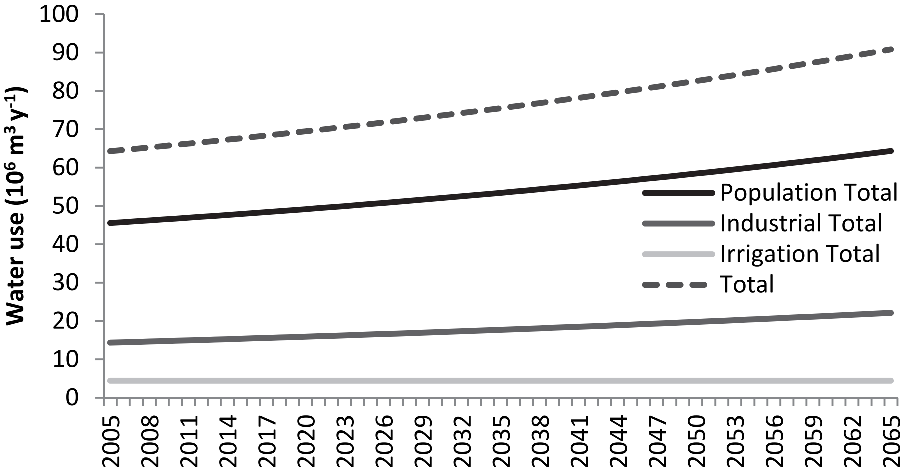


Figure 5.8c Expected total water requirements for the Amatole system under the Intermediate Development Scenario in the near future up to the year 2065. The WEAP model setup used the values for the year 2056 as stationary water requirements.

5.3.2 Near future water requirements: Lower Development Scenario

The water requirements for the Lower Development Scenario are listed in Table 5.7a. The population annual water use rates are shown in Table 5.7b to match the population water requirements in Table 5.7a. The population growth figures for the year 2056 were kept the same as in Table 5.6b for the Intermediate Development Scenario.

The following changes in water requirements are expected in the near future under the Lower Development Scenario relative to Current Scenario water requirements:

- Domestic / population water requirements increase in the Upper Amatole and decrease in the Middle and Lower Amatole relative to the current water requirements.
- Industrial water requirements for the Upper and Middle Amatole remain unchanged, and they increase in the Lower Amatole but to a lesser extent than under the Intermediate Development Scenario.
- Irrigation water requirements are reduced to zero.

Table 5.7a Water requirements (10^6 m^3 y^{-1}) for the population, industry and agriculture sectors for the current and near future (2046-2065) under the Lower Development Scenario obtained from DWAF (2008) for the year 2030. The figures for the near future year 2056 have been obtained by extrapolating the growth rate from 2030 to 2056.

Scenario (Year)	**Upper Amatole**	**Middle Amatole**	**Lower Amatole**	**Total**
Domestic /population water requirement				
Current (2005)	4.96	7.94	32.65	45.55
Predicted (2030)	5.31	7.51	32.13	44.95
Near future (2056)	5.70	7.10	31.60	44.40
Industrial water requirement				
Current (2005)	2.48	1.23	10.61	14.32
Predicted (2030)	2.48	1.23	11.52	15.23
Near future (2056)	2.48	1.23	12.55	16.26
Agriculture irrigation water requirement				
Current (2005)	1.24	1.90	1.26	4.40
Predicted (2030)	0	0	0	0
Near future (2056)	0	0	0	0

Table 5.7b Annual water use rates (m^3/person) used in the WEAP model in order to match figures for population water requirements in Table 5.7a for the near future (2046-2065) Lower Development Scenario.

Scenario (Year)	Upper Amatole	Middle Amatole	Lower Amatole
Current (2005)	54.83	64.98	68.30
Predicted (2030)	48.30	67.70	65.61
Near future (2056)	42.33	70.78	62.92

5.3.3 Near future water requirements: Upper Development Scenario

The water requirements for the Upper Development Scenario are listed in Table 5.8a. The population annual water use rates are shown in Table 5.8b to match the population water requirements in Table 5.8a. Note that the population growth figures for the year 2056 were kept the same as Table 5.6b.

The following changes in water requirements are expected in the near future under the Upper Development Scenario relative to the Current Scenario water requirements:

- Domestic/population water requirements increase in the Upper and Lower Amatole and decrease in the Middle Amatole as under the Intermediate Development Scenario, but the increases are to a much higher extent, and the decreases are to a lower extent as compared to the Intermediate Development Scenario.
- Industrial water requirements for the Upper and Middle Amatole remain unchanged, and they increase for the Lower Amatole as under the Intermediate Development Scenario but to a higher extent.
- Irrigation water requirements increase in the Middle and Lower Amatole.

The uncertainty in the population water requirements for the Amatole system is shown in Figure 5.9 projected up to the year 2065 from the values available for the years 2005 and 2030. The majority of the uncertainty arises from the water requirements in the Lower Amatole area. Since water requirements of the water users have been entered into the WEAP model as stationary demands, the values for the year 2056 (i.e. the middle of the near future period) were used in the WEAP model for the near future development scenarios. ***The population water requirements are the major contributor to the uncertainty in the total water requirements for the Buffalo area*** (shown in Figure 5.10 projected up to the year 2065 from the values available for the years 2005 and 2030).

Table 5.8a Water requirements (10^6 m^3 y^{-1}) for population, industry and agriculture for current and near future (2046-2065) under the Upper Development Scenario obtained from DWAF (2008) for the year 2030. The figures for the near future year 2056 have been obtained by extrapolating the growth rate from 2030 to 2056.

Scenario (Year)	**Upper Amatole**	**Middle Amatole**	**Lower Amatole**	**Total**
Domestic / population water requirement				
Current (2005)	4.96	7.94	32.65	45.55
Predicted (2030)	8.12	7.88	47.17	63.17
Near future (2056)	13.55	7.82	69.17	90.54
Industrial water requirement				
Current (2005)	2.48	1.23	10.61	14.32
Predicted (2030)	2.48	1.23	15.16	18.87
Near future (2056)	2.48	1.23	21.97	25.68
Agriculture irrigation water requirement				
Current (2005)	1.24	1.90	1.26	4.40
Predicted (2030)	1.24	3.43	2.54	7.21
Near future (2056)	1.24	6.34	5.26	12.84

Table 5.8b Annual water use rates (m^3/person) used in WEAP model in order to match figures for population water requirements in Table 5.8a for the near future (2046-2065) Upper Development Scenario.

Scenario (Year)	**Upper Amatole**	**Middle Amatole**	**Lower Amatole**
Current (2005)	54.83	64.98	68.30
Predicted (2030)	73.86	71.03	96.32
Near future (2056)	100.63	77.95	137.73

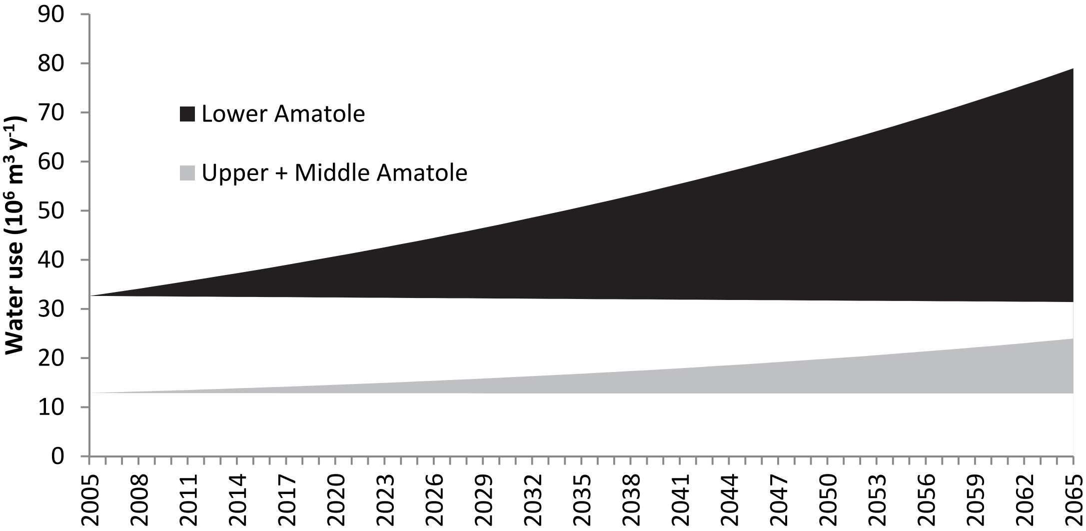


Figure 5.9 Projected uncertainty in the population water requirements for the Amatole system in the near future (2046-2065). The uncertainty in the Upper and Middle Amatole water requirements are shown together as they overlap and would not appear clearly if shown individually relative to the large uncertainty in the Lower Amatole. The values have been extrapolated up to the year 2065 from the values available for the years 2005 and 2030.

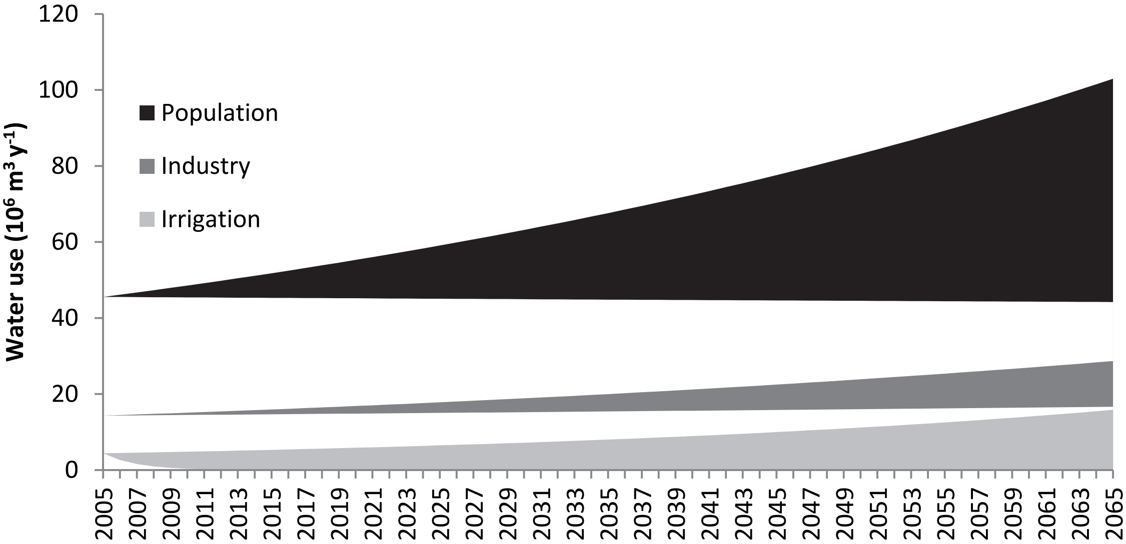


Figure 5.10 Projected uncertainty in the water requirements originating from the population, industrial and irrigation sectors for the Amatole system in the near future (2046-2065). The values have been extrapolated up to the year 2065 from the values available for the years 2005 and 2030.

5.4 Future development scenarios: Model results for near future water requirement scenarios under current climate variability

5.4.1 Comparison of Current and Intermediate Development scenario results

In order to look at the impacts of an increase or a decrease in water requirements due to development alone in the near future (i.e. without considering the effects of climate change), it was assumed that the rainfall extremes in future climate are similar to the historical rainfall extremes. Thus, the WEAP model was re-run for the full historical rainfall period (1921-2005) using the expected water requirements for Intermediate Development in the near future. Section 5.6 presents the results for the near future development scenarios under future climate variability (using the 2046-2065 near future climate scenarios).

The results for the Current Development Scenario and those from the Intermediate Development Scenario, that were run using the current climate variability data for the years 1921-2005, were compared. The comparison did not find significant differences in the simulated stream flows in the Buffalo and Nahoon rivers. This is because the near future development scenarios in general require much greater volumes of water than is available in the system. Thus, the WEAP model calculates a reduction in the demand side coverage or an increase in the water deficit. Table 5.6a shows the comparative water requirements for the various user groups under the Intermediate Development Scenarios for the near future. Under this scenario, there is a large increase in the population water requirements for the Upper and Lower Amatole areas (also see Figure 5.8a), and a decrease in the water demand for this sector in the Middle Amatole area in the near future relative to the current situation. Industrial water requirements are expected to increase in the Lower Amatole area only in the near future under the Intermediate Development Scenario, while the other demands are expected to remain unchanged.

Assuming there are no changes in the infrastructure and the system operation in the near future, the results for demand side percentage deficit under the Intermediate Development Scenario in the near future (Table 5.9) are significantly increased for population and industrial water users relative to the current situation where all demands were met all the time. The model results for the Intermediate Development Scenario show that overall, the system provides lower average demand side coverage relative to the Current Development Scenario i.e. greater percentage water deficit particularly for the Lower Amatole system.

Table 5.9 Statistics representing percentage water deficits for the three demand areas along the Amatole system for the Intermediate Development Scenario in the near future. The model was run for rainfall variability in the historical record from 1921-2005.

	Min. deficit	**Median deficit**	**Max. deficit**	**percentage months with >50% deficit**	**percentage months with >25% deficit**
Upper Amatole					
Population	8	8	8	0.0%	0.0%
Industry	0	0	0	0.0%	0.0%
Alien Veg.	0	0	0	0.0%	0.0%
Irrigation	0	0	0	0.0%	0.0%
Middle Amatole					
Population	8	8	8	0.0%	0.0%
Industry	7	7	8	0.0%	0.0%
Alien Veg.	0	0	0	0.0%	0.0%
Irrigation	0	0	0	0.0%	0.0%
Lower Amatole					
Population	16	16	16	0.0%	0.0%
Industry	16	16	16	0.0%	0.0%
Alien Veg.	0	0	0	0.0%	0.0%
Irrigation	0	0	0	0.0%	0.0%

5.4.2 Uncertainty under future development scenarios: Stream flow

As with the Intermediate Development Scenario, the WEAP model was run for the full 85 years of the historical rainfall record with the water requirements set for the Lower and Upper Development scenarios as defined in sections 5.3.2 and 5.3.3. Figures 5.11-12 show the uncertainty due to the three development scenarios for the lower reaches near the stream gauges and at the estuary. There is a comparatively larger band of uncertainty at low flows for the reach near R2H027 compared to the other locations. Note that the estuarine flows for the Buffalo and Nahoon rivers are low for a majority of the time because of the upstream dams resulting in a thin FDC envelope.

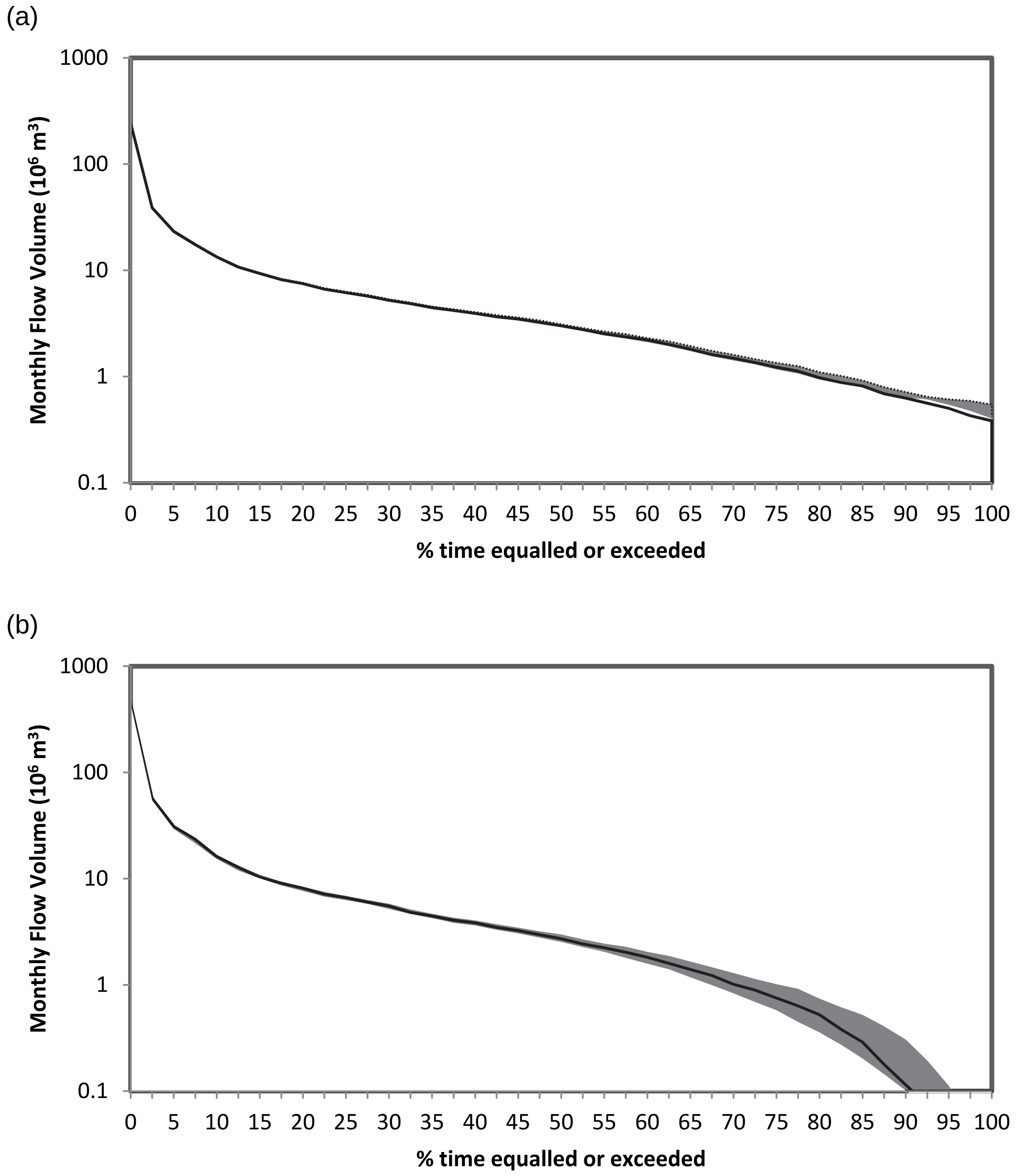
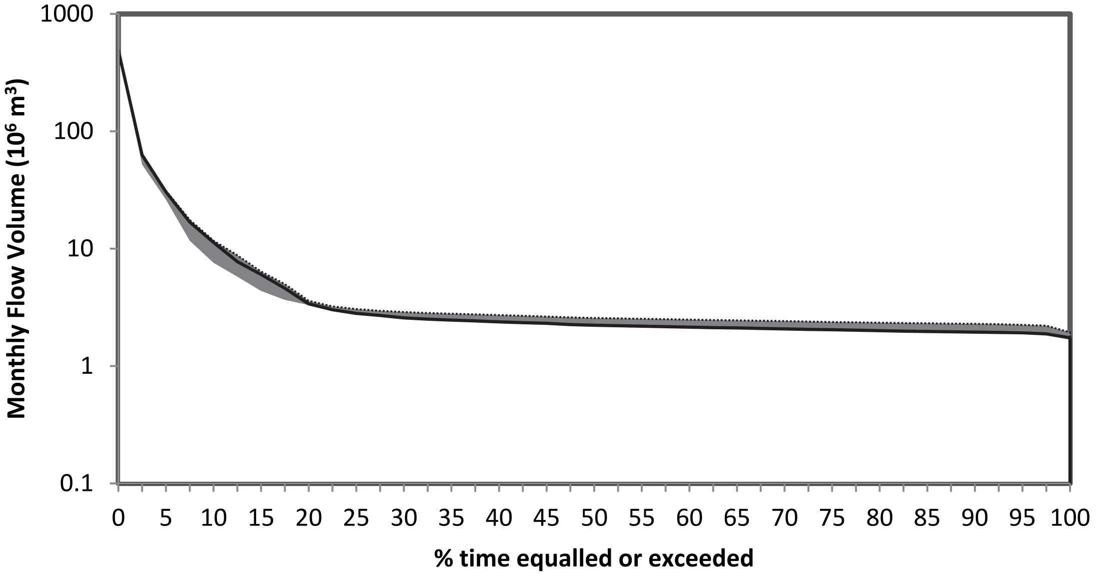


Figure 5.11 Results of the WEAP model for the mid-stream reaches near the gauges (a) R2H010 and (b) R2H027 along the Buffalo River for the current (solid black line) and the uncertainty band (grey band) generated from the results for the socio-economic development scenarios in the near future.

(a)



(b)

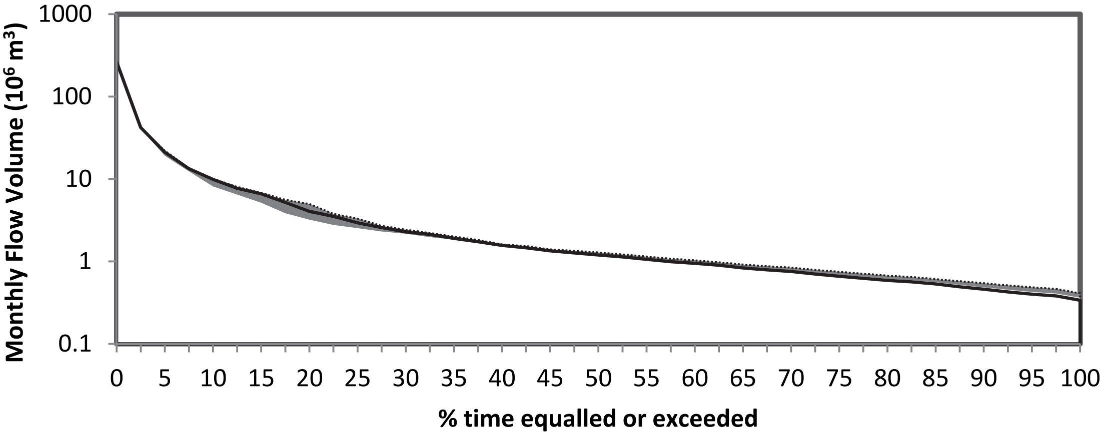


Figure 5.12 Results of the WEAP model for the lower-stream reaches at (a) the Buffalo River estuary, and (b) Nahoon River estuary for the current (solid black line) and the uncertainty band (grey band) generated from the results for the socio-economic development scenarios in the near future.

5.4.3 Uncertainty under future development scenarios: Water deficits

The supply requirements for the Lower and Upper Development scenarios are given in Tables 5.7a and 5.8a. The percentage water deficit for the Lower and Upper Development scenarios varied greatly, particularly for the population and industrial water requirements in all three areas of the Amatole system. Under the Lower Development Scenario, the water supply requirements for the population, industry and irrigation sectors is projected to be lower (60.65×10^6 m^3 y^{-1}) relative to the current situation (64.27×10^6 m^3 y^{-1}) and thus, the results showed that there is expected to be no water deficit under the Lower Development Scenario in the near future, similar to the current situation. Under the Upper Development Scenario, the percentage water deficit is 27-44% for population and industry with higher percentage deficit in the Lower Amatole area (Table 5.10). The range of uncertainty in water deficits under the development scenarios (Lower-Upper) is given in Table 5.10.

Table 5.10 Range of percentage water deficits for the three demand areas along the Amatole system for the Lower to Upper Development scenarios for the near future. The model was run for rainfall variability in the historical record from 1921-2005.

	Oct.	**Nov.**	**Dec.**	**Jan.**	**Feb.**	**Mar.**	**Apr.**	**May**	**Jun.**	**Jul.**	**Aug.**	**Sep.**
Upper Amatole												
Pop.	0-27	0-27	0-27	0-27	0-27	0-27	0-27	0-27	0-27	0-27	0-27	0-27
Indus.	0	0	0	0	0	0	0	0	0	0	0	0
Alien	0	0	0	0	0	0	0	0	0	0	0	0
Irrig.	0	0	0	0	0	0	0	0	0	0	0	0
Middle Amatole												
Pop.	0-27	0-27	0-27	0-27	0-27	0-27	0-27	0-27	0-27	0-27	0-27	0-27
Indus.	0-27	0-27	0-27	0-27	0-27	0-27	0-27	0-27	0-27	0-27	0-27	0-27
Alien	0	0	0	0	0	0	0	0	0	0	0	0
Irrig.	0	0	0	0	0	0	0	0	0	0	0	0
Lower Amatole												
Pop.	0-44	0-44	0-44	0-44	0-44	0-44	0-44	0-44	0-44	0-44	0-44	0-44
Indus.	0-44	0-44	0-44	0-44	0-44	0-44	0-44	0-44	0-44	0-44	0-44	0-44
Alien	0	0	0	0	0	0	0	0	0	0	0	0
Irrig.	0	0	0	0	0	0	0	0	0	0	0	0

5.4.4 Uncertainty under future development scenarios: Reservoir storage

To obtain an indication of variation in the minimum reservoir storage under future development scenarios relative to the present rainfall variation (for the years 1921-2005), the average simulated monthly storage for the four major reservoirs on Buffalo and Nahoon rivers are portrayed in the Figures 5.13a-16a. The development scenarios were run for the full 85 years of the historical rainfall record with the water requirements set for the Lower and Upper Development scenarios. For the purposes of management of water supply, the minimum simulated monthly storage under future development scenarios relative to present rainfall variation (1921-2005) is presented in the Figures 5.13b-16b. Under the Upper Development Scenario, the minimum dam storage can be reduced by as much as 50% in some cases relative to the current situation (Figures 5.13b-16b). Note that under these model runs, there are no water transfers from the Wriggleswade Dam on Kubusi River, which is expected to occur in future. The scenarios with water transfers were conducted separately, and their results are discussed later in the chapter (Section 5.7).

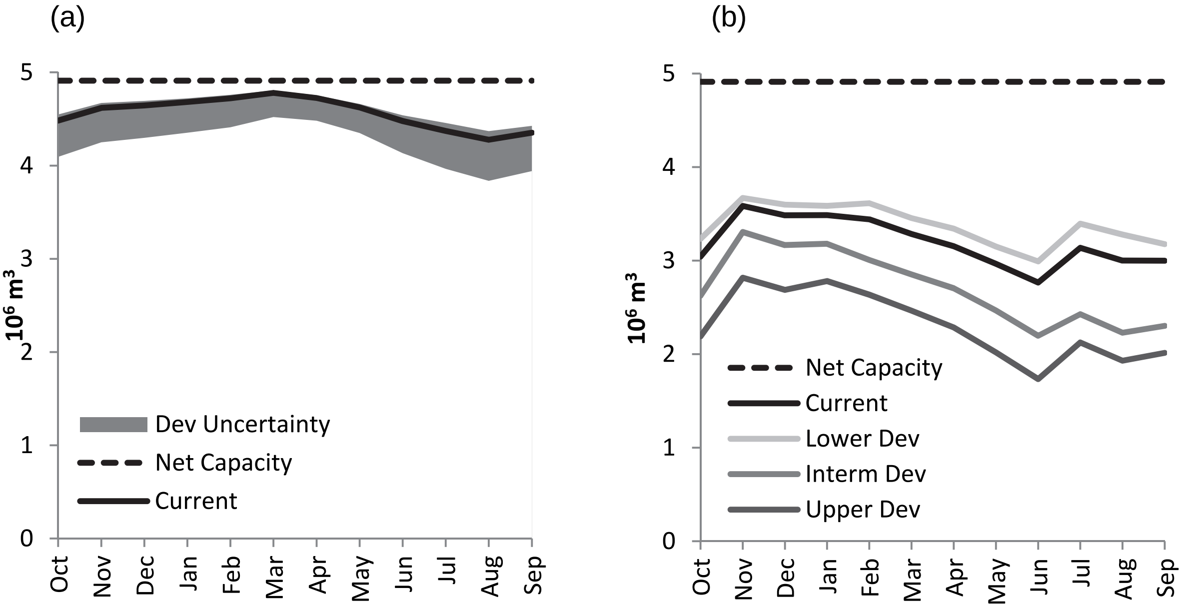


Figure 5.13 (a) Average simulated monthly reservoir storage and (b) minimum simulated monthly reservoir storage for the Rooikrantz Dam under present climate conditions (1921-2005; black line) and under the near future development scenarios run with present day climate conditions.

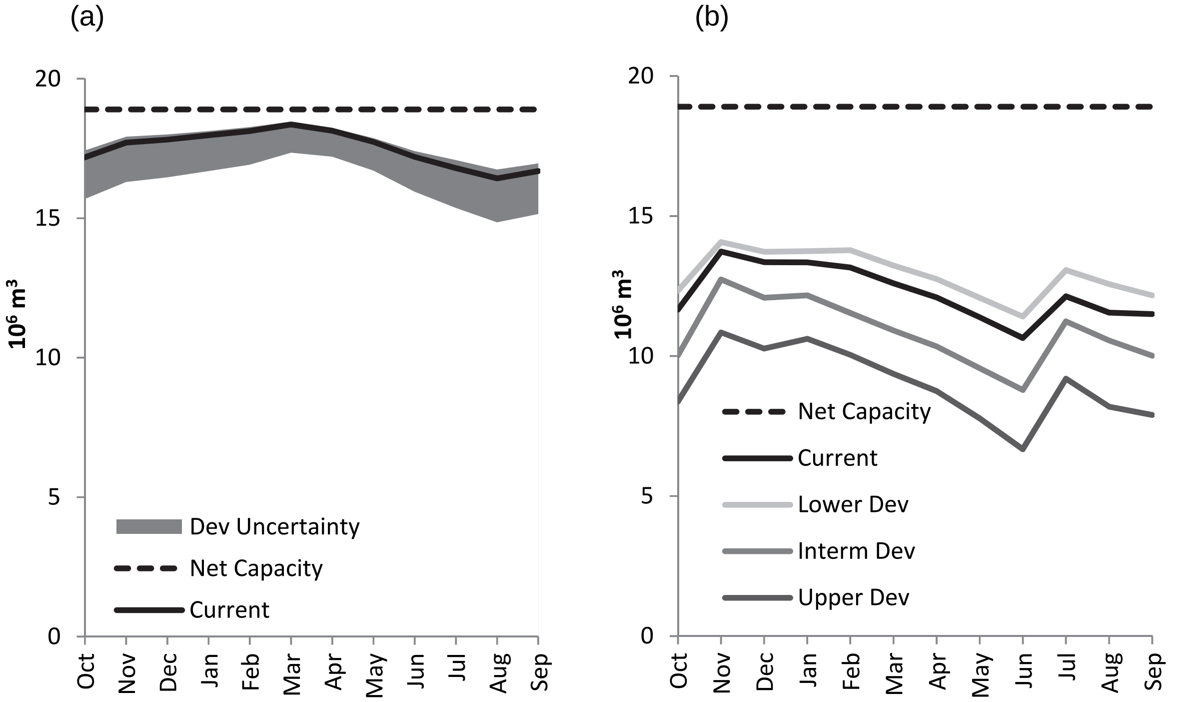


Figure 5.14 (a) Average simulated monthly reservoir storage and (b) minimum simulated monthly reservoir storage for the Laing Dam under present climate conditions (1921-2005; black line) and under the near future development scenarios run with present day climate conditions.

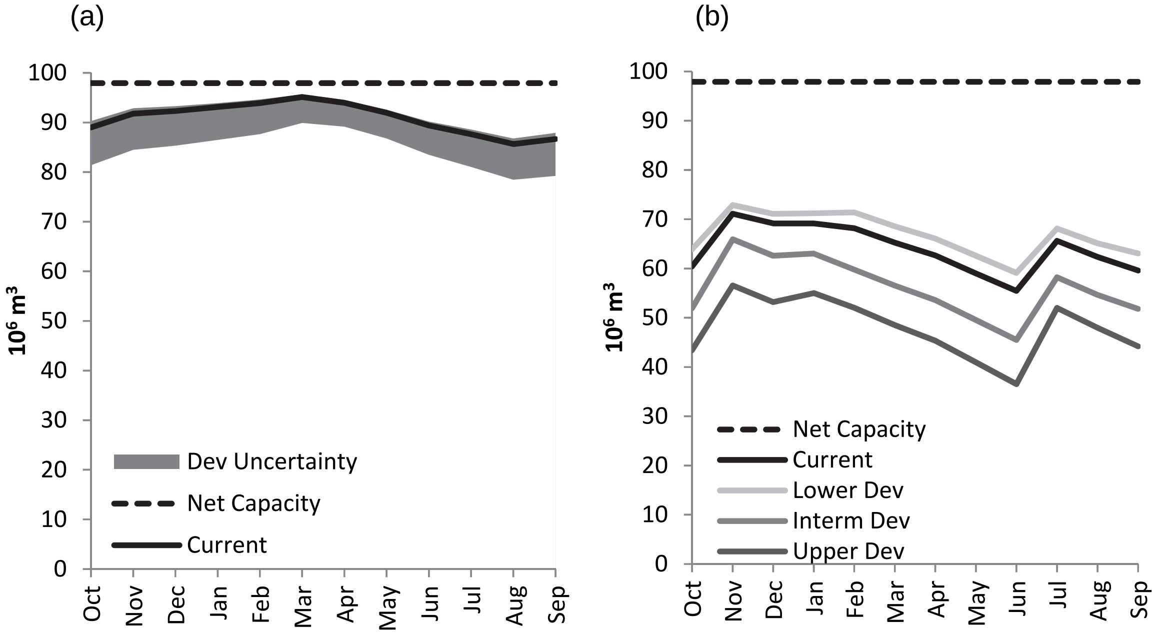


Figure 5.15 (a) Average simulated monthly reservoir storage and (b) minimum simulated monthly reservoir storage for the Bridle Drift Dam under present climate conditions

(1921-2005; black line) and under the near future development scenarios run with present day climate conditions.

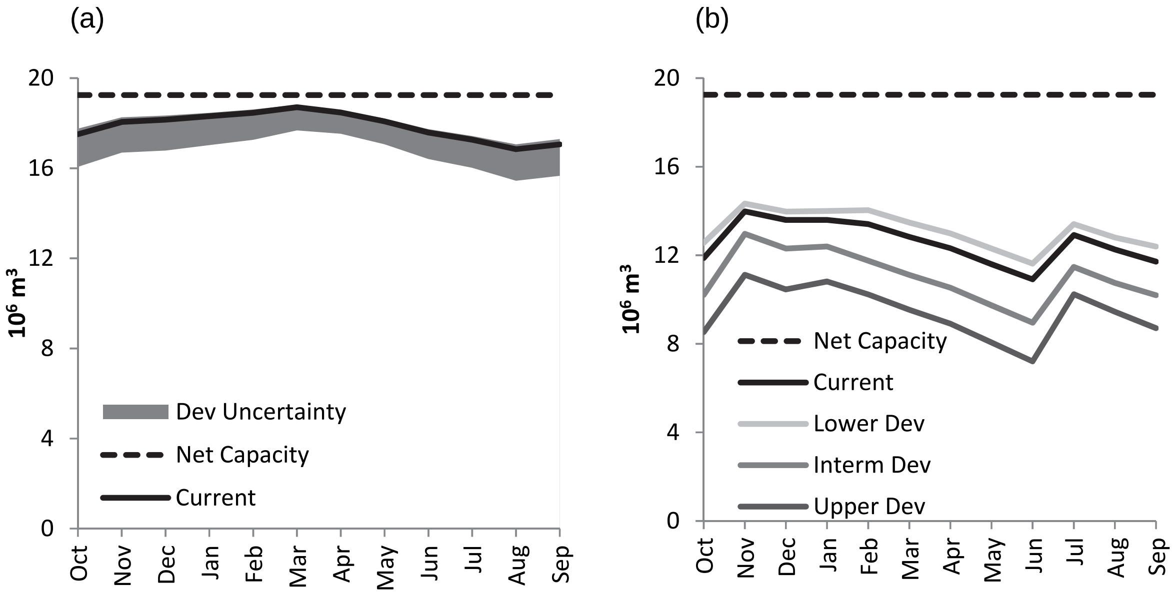


Figure 5.16 (a) Average simulated monthly reservoir storage and (b) minimum simulated monthly reservoir storage for the Nahoon Dam under present climate conditions (1921-2005; black line) and under the near future development scenarios run with present day climate conditions.

5.5 Future climate scenarios: Model results for near future climate change scenarios (2046-2065)

5.5.1 Uncertainty under future climate scenarios: Stream flow

All nine climate change scenarios (listed in Chapter 4) were entered into the WEAP model as near future climate predictions with their rainfall and evapotranspiration data for quaternaries. Figures 5.17-22 present the results at various reaches near stream gauges and the estuaries for present day simulation (shown as a solid black line) and the minimum and maximum uncertainty (grey band) for flow generated using the nine near future climate change scenarios. Note that below dams, flows to the estuary are low for majority of the time, with the exception of the Buffalo estuary where waste water treatment works discharge.

An increase in flow is predicted for the near future scenarios, as generally, the lower limit of the uncertainty band overlaps with the present day situation. Additionally, in general, there is greater uncertainty, particularly at medium to high flows under climate change scenarios.

For each of the stream reaches, the median flow volume value predicted for the nine climate change scenarios were read off from the flow duration curve at an x-axis value of 10-20% and 80-90% of the months exceeded or equalled. These were compared with equivalent values for the current day scenario. The results for FDC values at 10-20% time (i.e. high flows) indicated an increase of 36-63% relative to present day simulation for the stream reaches and a 97-176% increase in median flows for the estuarine reaches. Similar comparison of FDC values at 80-90% time (i.e. low flows) found an increase of 18-90% relative to present day simulation for the stream reaches but only a 0-1% increase for the estuarine flows. Note that the comparatively reduced uncertainty bands (Figures 5.17-22) generated by the WEAP model relative to the Pitman model results (Figure 4.22) are due the exclusion of parameter uncertainty when running the WEAP model.

Note that for the results presented in this section, the water demands of the users for the climate change scenarios were kept constant at the level for the year 2005 in order to look at the effects of climate change scenarios in isolation (see Table 5.6). The results of the WEAP model run indicated that the water user requirements were met at 100% demand level under the nine climate change scenarios, same as under the Current Scenario.

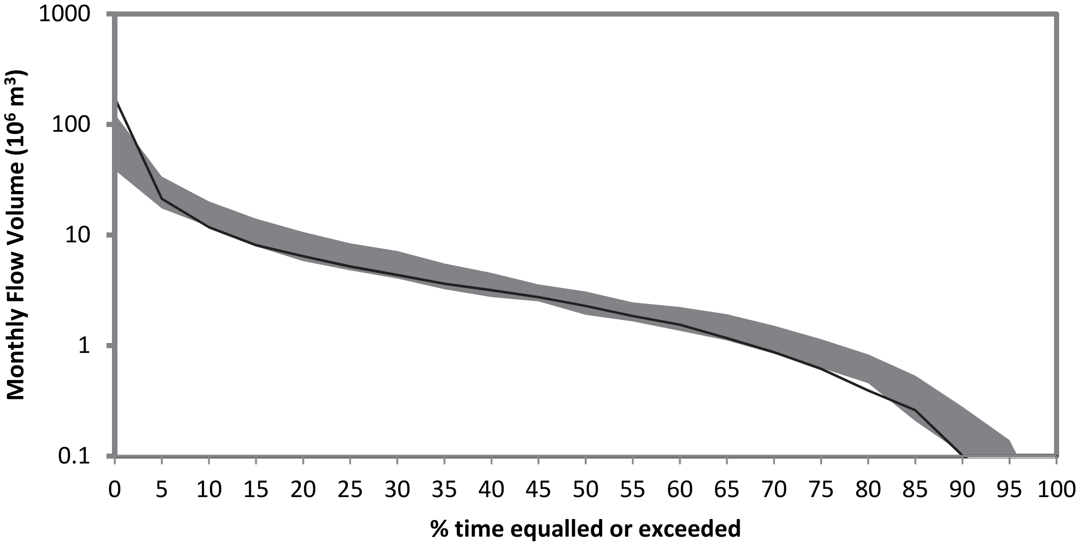


Figure 5.17 Flow duration curve at a reach near R2H005 under present climate conditions (solid line; 1921-2005) and under the near future climate scenarios (2046-2065) shown as a band of uncertainty (minimum and maximum values). Results are shown for all nine climate change scenarios.

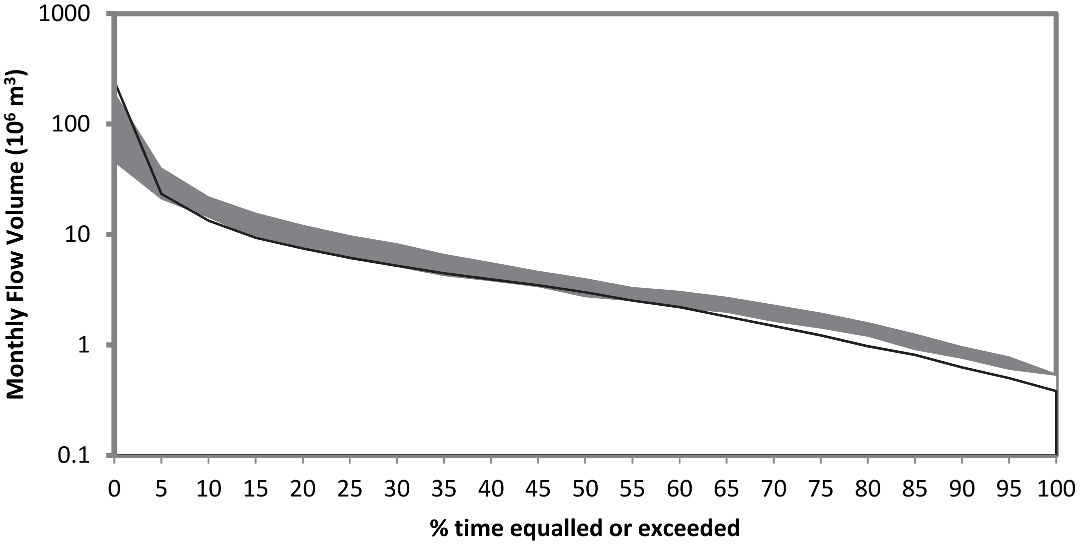


Figure 5.18 Flow duration curve at a reach near R2H010 under present climate conditions (solid line; 1921-2005) and under the near future climate scenarios (2046-2065) shown as a band of uncertainty (minimum and maximum values). Results are shown for all nine climate change scenarios.

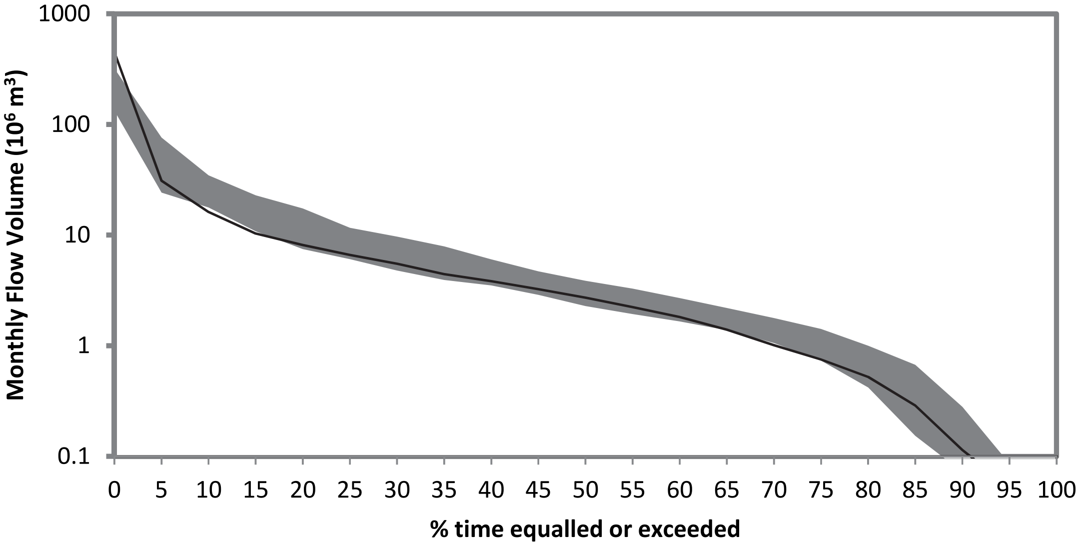


Figure 5.19 Flow duration curve at a reach near R2H027 under present climate conditions (solid line; 1921-2005) and under the near future climate scenarios (2046-2065) shown as a band of uncertainty (minimum and maximum values). Results are shown for all nine climate change scenarios.

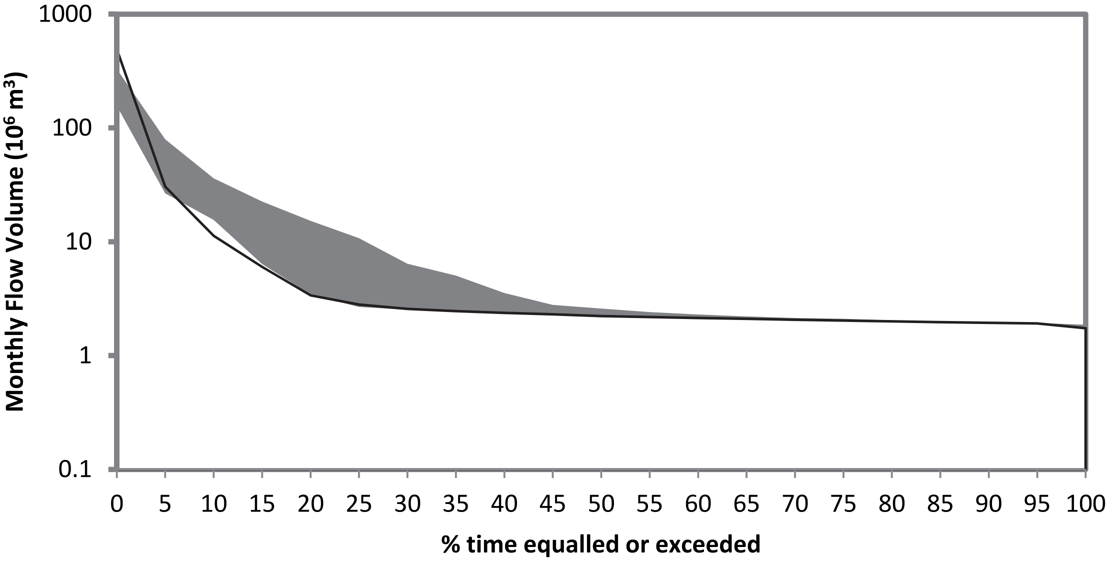


Figure 5.20 Flow duration curve at the Buffalo River estuary under present climate conditions (solid line; 1921-2005) and under the near future climate scenarios (2046-2065) shown as a band of uncertainty (minimum and maximum values). Results are shown for all nine climate change scenarios.

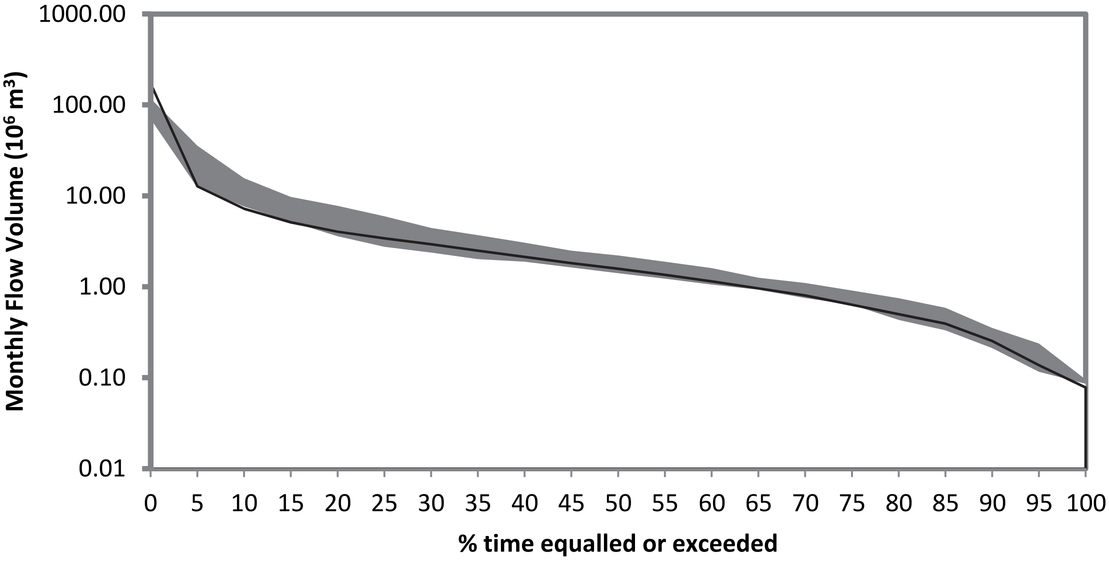


Figure 5.21 Flow duration curve at a reach above the Nahoon Dam under present climate conditions (solid line; 1921-2005) and under the near future climate scenarios (2046-2065) shown as a band of uncertainty (minimum and maximum values). Results are shown for all nine climate change scenarios.

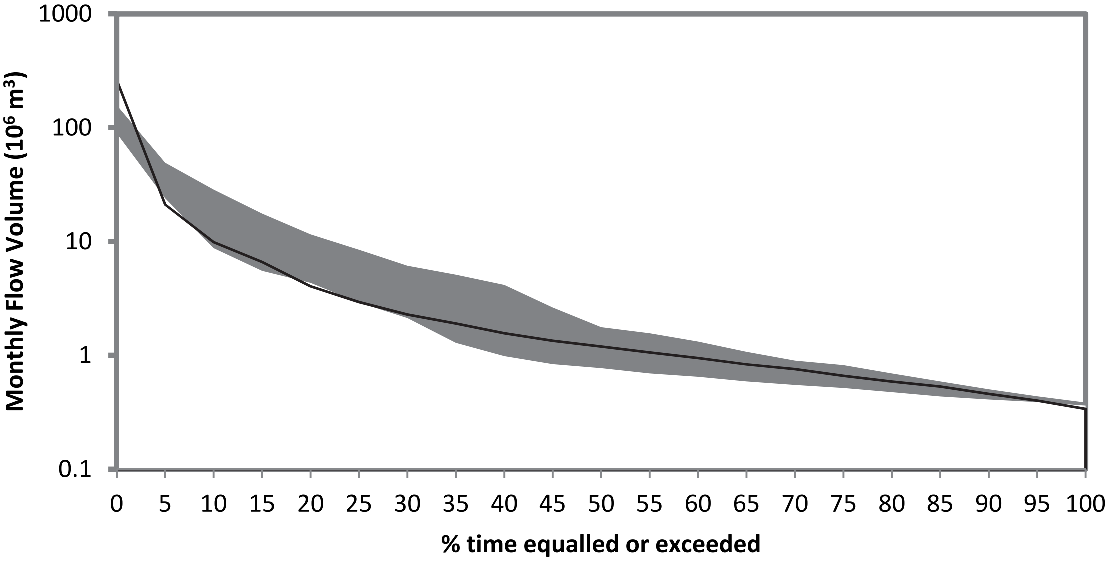


Figure 5.22 Flow duration curve at the Nahoon River estuary under present climate conditions (solid line; 1921-2005) and under the near future climate scenarios (2046-2065) shown as a band of uncertainty (minimum and maximum values). Results are shown for all nine climate change scenarios.

5.5.2 Uncertainty under future climate scenarios: Seasonality of stream flows

To obtain an indication of the variation in the seasonality of stream flow relative to the present day situation, monthly average simulated flows for the present day (solid line) and near future climate scenarios (band of uncertainty obtained from minimum and maximum values for the nine climate change scenarios) are presented in Figures 5.23-25. The present day simulated flows generated by the WEAP model show a large uncertainty band in the monthly flows for the near future climate scenarios. An area of concern is the possible reduction in low monthly flows in the streams for the months of April-June. If one compares the median values, the seasonality is somewhat similar to the present day situation. However, the near future seasonality could be more dramatic with greater difference between the high flow months and the low flow periods compared to the present day situation if the upper extreme of the uncertainty bands in Figures 5.23-25 becomes reality.

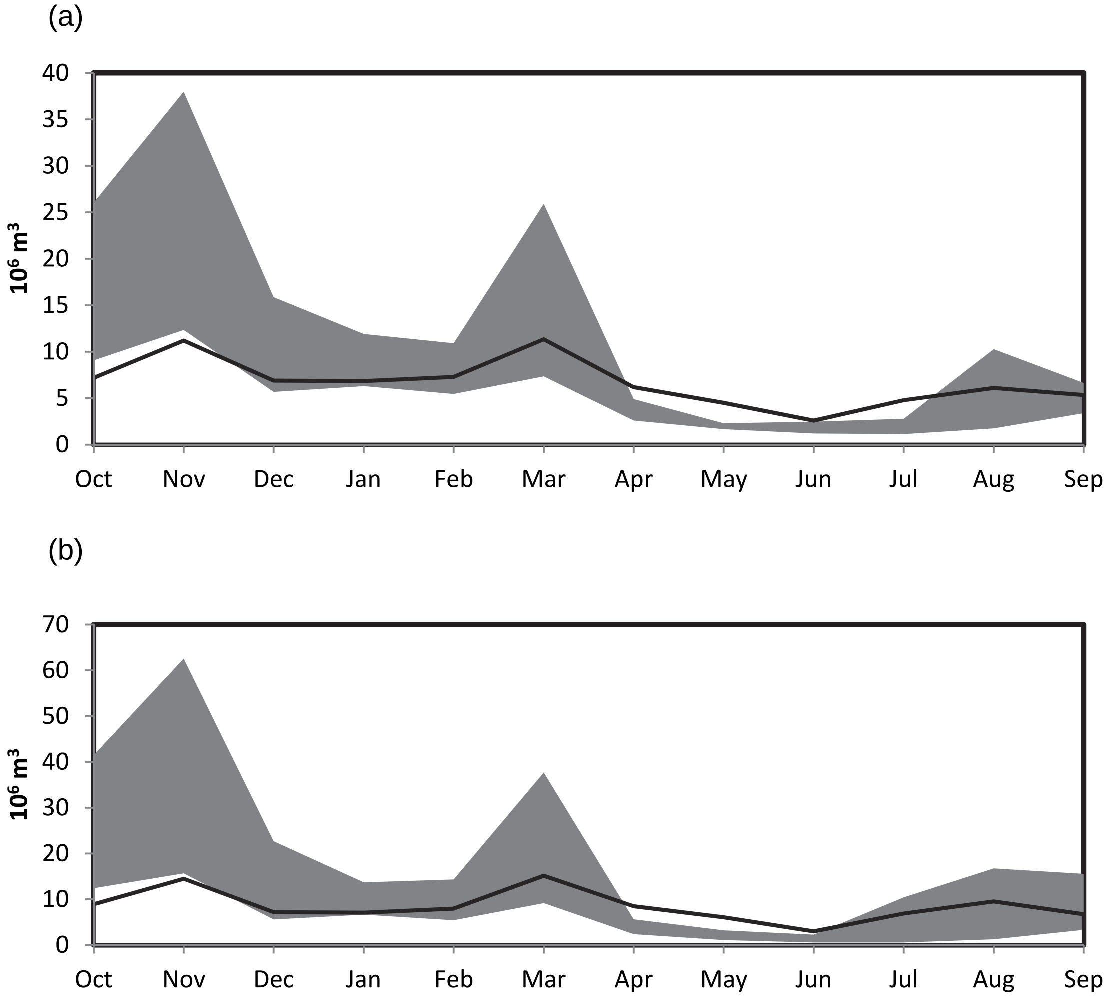


Figure 5.23 Average simulated monthly flow at a reach near (a) R2H010 and (b) R2H027 on the Buffalo River under present climate conditions (1921-2005; solid line) and under the near future climate scenarios (2046-2065) shown as a band of uncertainty (minimum and maximum values).

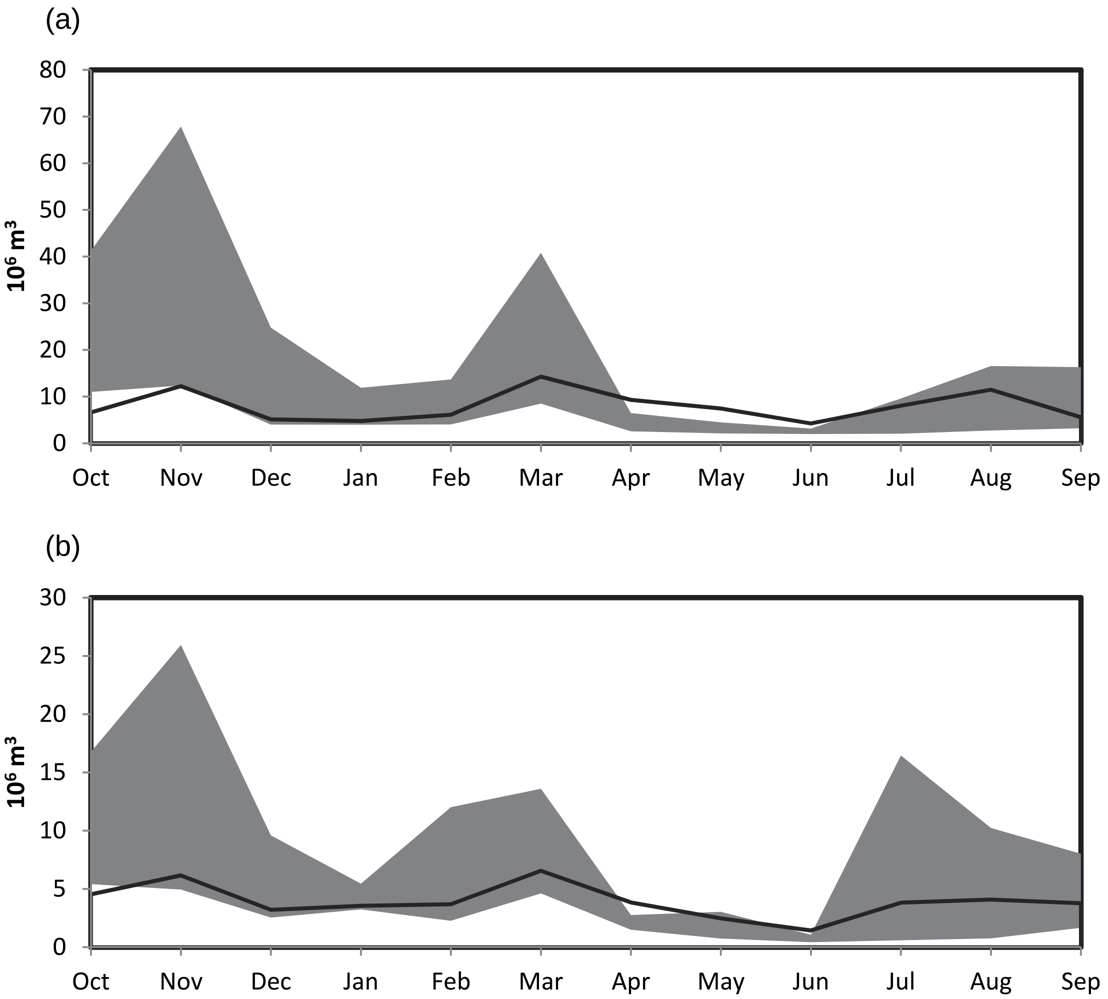


Figure 5.24 Average simulated monthly flow (a) at the Buffalo River estuary and (b) above the Nahoon Dam under present climate conditions (1921-2005; solid line) and under the near future climate scenarios (2046-2065) shown as a band of uncertainty (minimum and maximum values).

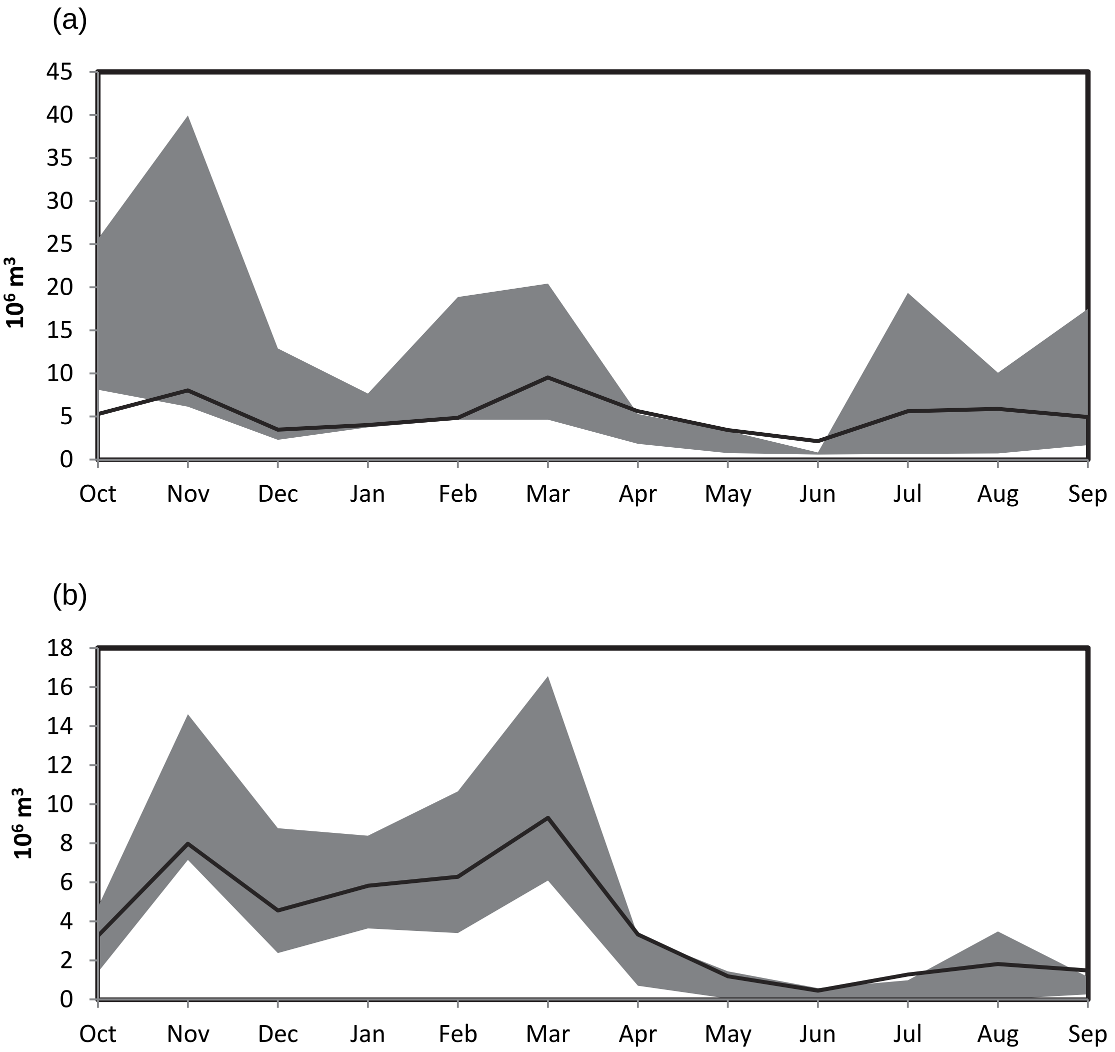


Figure 5.25 Average simulated monthly flow (a) at the Nahoon River estuary and (b) below the Wriggleswade Dam under present climate conditions (1921-2005; solid line) and under the near future climate scenarios (2046-2065) shown as a band of uncertainty (minimum and maximum values).

5.5.3 Uncertainty under future climate scenarios: Reservoir storage

To obtain an indication of the variation in the average reservoir storage under the near future climate scenarios (2046-2065) relative to the present day situation (i.e. the rainfall variation for the historical periods 1921-2005), Figures 5.26-28 present the results for the average storage for the seven reservoirs on the Buffalo, Nahoon and Kubusi rivers relative to present day average storage. Overall, the uncertainty bands for the near future climate straddle the present day reservoir storage. For management purposes, it can be noted that the minimum monthly storage expected under the near future climate scenarios for these reservoirs is higher than with that simulated for the current day climate situations. This is due to an increase in expected rainfall under the near future climate scenarios for the Amatole area.

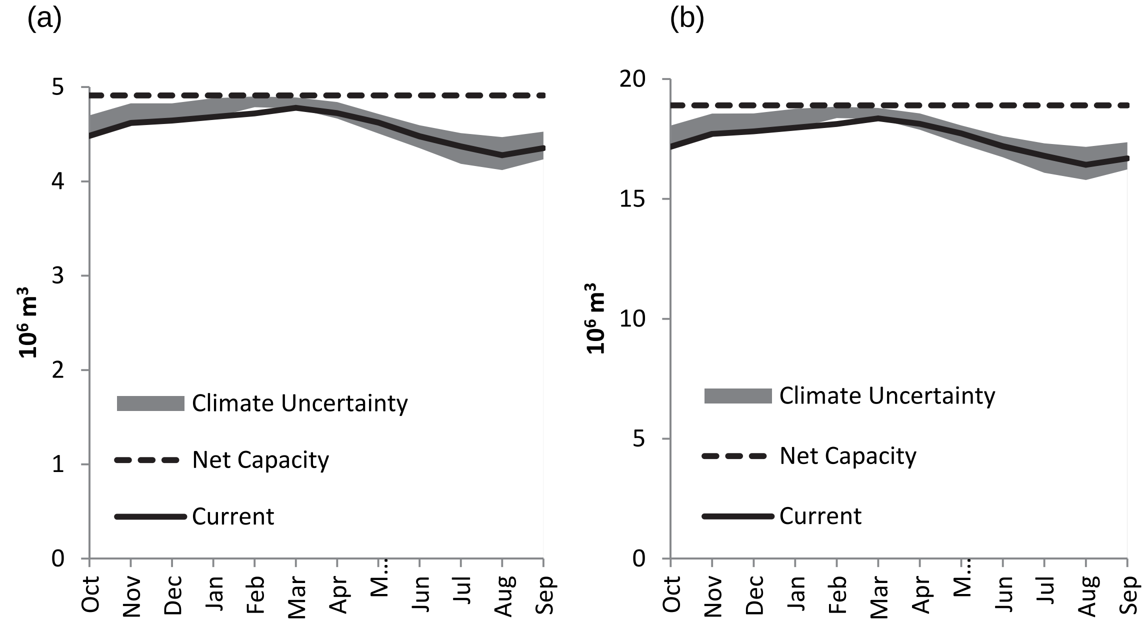


Figure 5.26 Average simulated monthly reservoir storage for (a) the Rooikrantz Dam and (b) the Laing Dam under present climate conditions (1921-2005; black line) and under the near future climate scenarios (2046-2065).

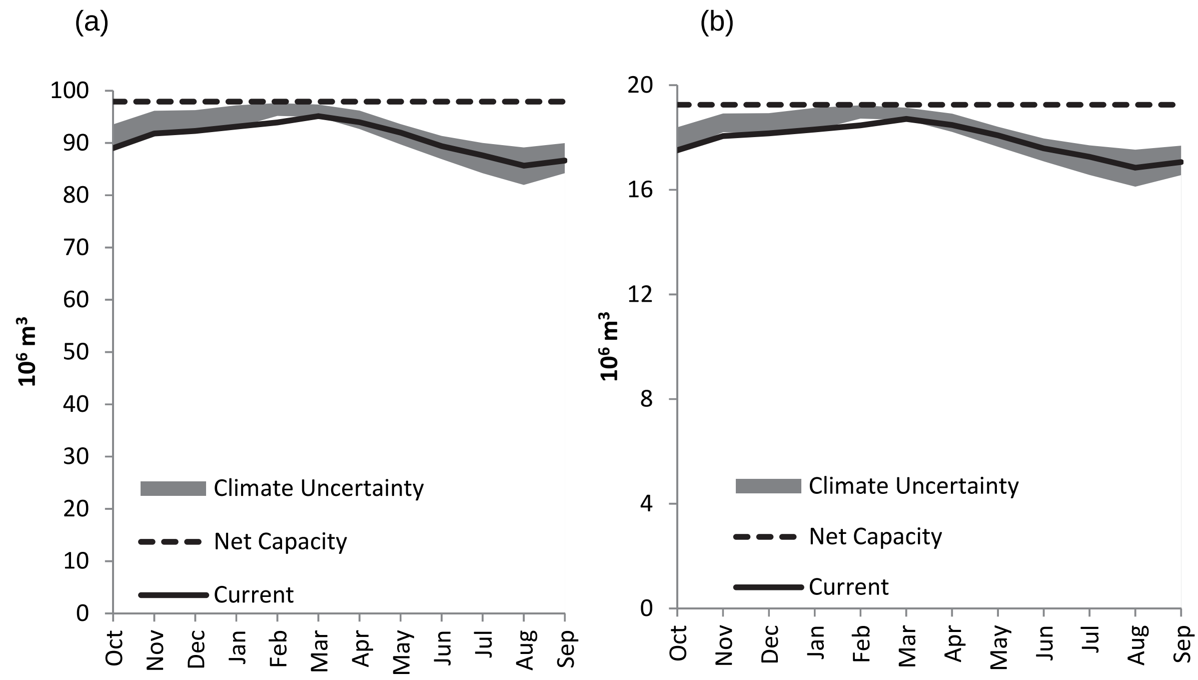


Figure 5.27 Average simulated monthly reservoir storage for the (a) Bridle Drift and (b) Nahoon dams under present climate conditions (1921-2005; black line) and under the near future climate scenarios (2046-2065).

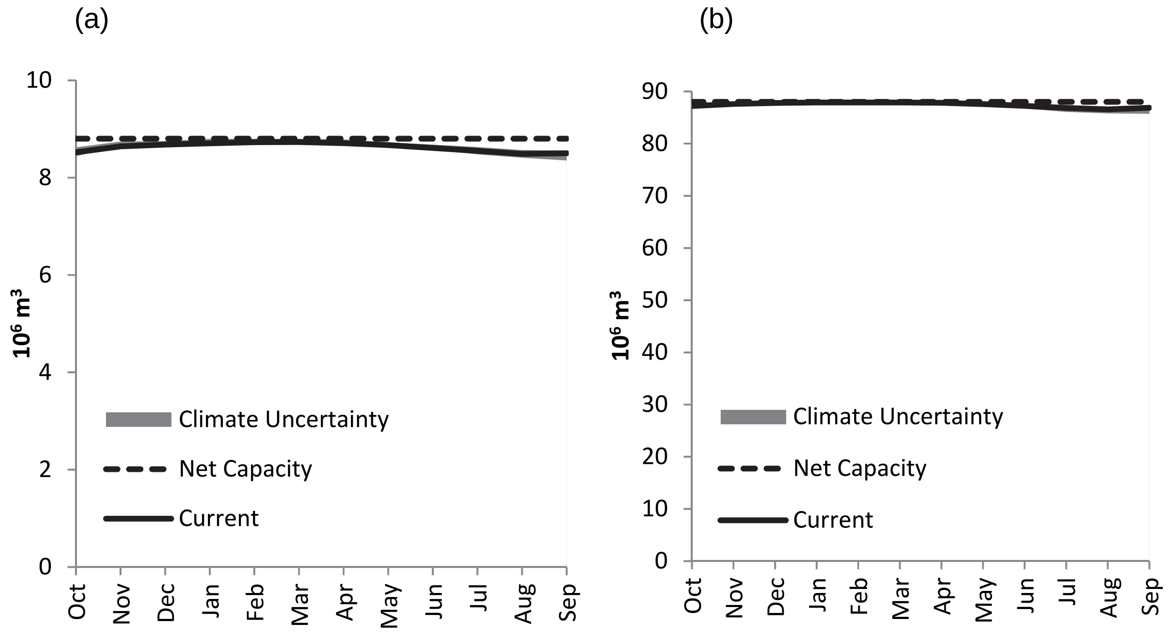


Figure 5.28 Average simulated monthly reservoir storage for the (a) Gubu and (b) Wriggleswade dams under present climate conditions (1921-2005; black line) and under the near future climate scenarios (2046-2065).

5.6 Future development and future climate scenarios: Model results for near future development scenarios under near future climate variability

In Section 5.4, WEAP model simulations were conducted for the near future development scenarios under current climate variability (i.e. using the historical rainfall data for the years 1921-2005) in order to look at the impacts of development on the water resources in isolation. Section 5.5 presented the results for climate change scenarios for the near future (for the years 2046-2065) in isolation while keeping the water requirements fixed to those for the year 2005. In this section, the results for the near future development scenarios under the near future climate conditions (i.e. the predicted rainfall for the years 2046-2065 under the nine climate change scenarios) are presented and compared with the results in sections 5.4 and 5.5. A total of 27 model runs (nine climate change scenarios, each in combination with three different socio-economic development scenarios) were conducted.

The results for stream flows under the near future climate for the three development scenarios show greater uncertainty, primarily at the low flows relative to the results for climate change scenarios in isolation (see Figures 5.29a and 5.29b). The uncertainty for the reach located near the stream gauge R2H027 at low and medium flows is greater than for the other simulated reaches (Figure 5.30a compared to Figures 5.29a, 5.29b, 5.30b). The greater uncertainty at low flows follows from the results presented in Sections 5.4 and 5.5 that in isolation, the socio-economic development and the climate change scenarios resulted in greater uncertainty at low flows.

The supply requirements for this section are the same as in Tables 5.6a, 5.7a and 5.8a for the near future socio-economic development scenarios. Under the Lower Development Scenario with near future climate predictions, there is no percentage deficit as with the Current Scenario. The results for percentage deficit for the water users for the Intermediate and Upper Development scenarios are shown as a range in Table 5.11. The results for the Intermediate Development Scenario under near future climate scenarios is a percentage deficit of 8-16% for the population and industrial users, while that under the Upper Development Scenario and under future climate predictions is 27-44% for these water users (Table 5.12).

Comparison of the storage volume under the Intermediate versus the Upper Development scenarios combined with the nine climate change scenarios show a larger uncertainty band under the Upper Development Scenario relative to the Intermediate Development Scenario (Figures 5.31-34). The storage capacity under these scenarios overlaps with the current simulated storage due to an increase in rainfall under the near future climate scenarios (which generally results in an increase in water volume stored in the reservoir) and increased water demand under the Intermediate and Upper Development scenarios (which leads to a reduction in stored amounts in the reservoirs).

Note that the results presented so far have not considered any upgrades in infrastructure from the present day, nor do they include water transfers from Wriggleswade Dam. These infrastructure changes are considered in the next section.

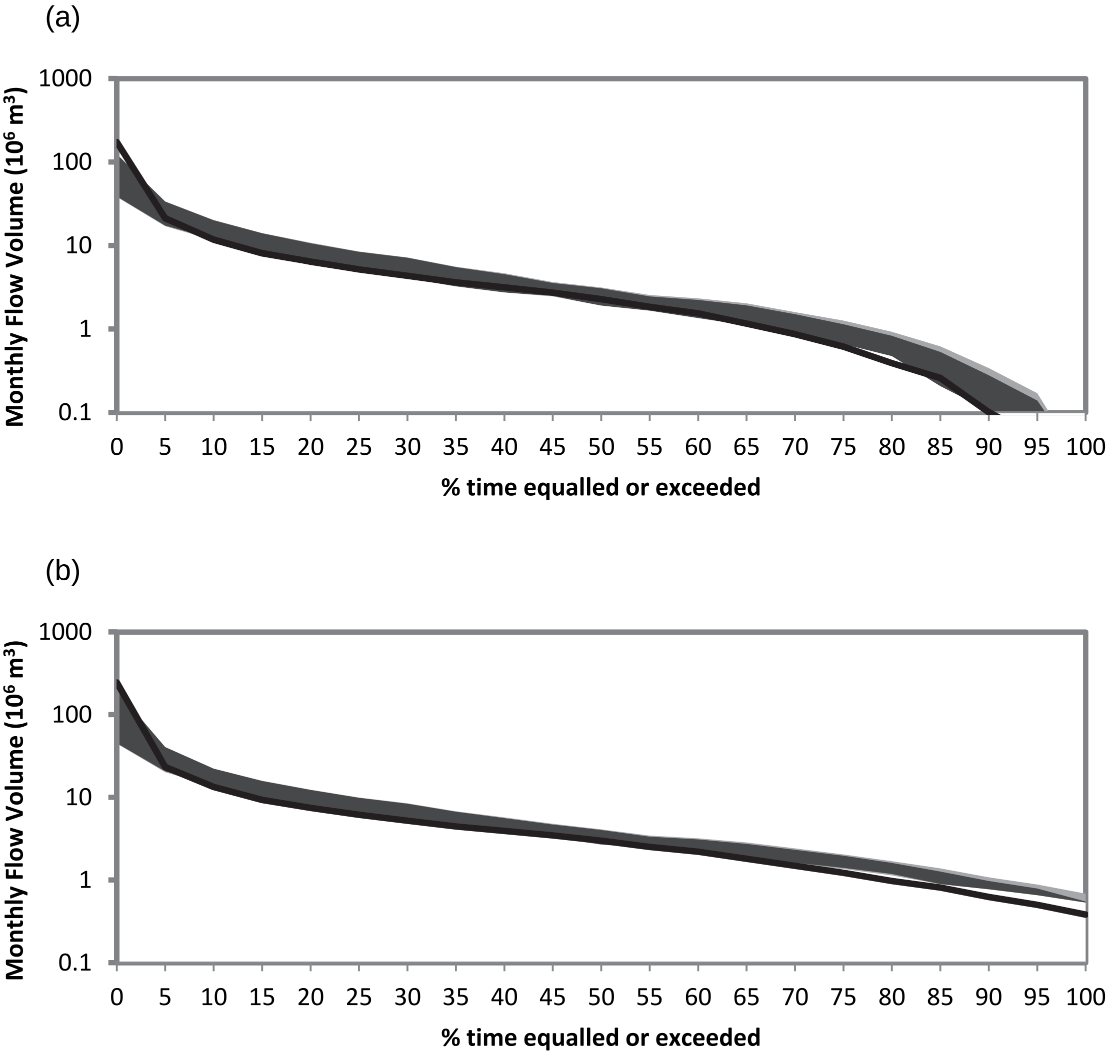


Figure 5.29 Flow duration curve at a reach near (a) R2H005 and (b) R2H010 under present climate conditions (solid line; 1921-2005), under the near future climate scenarios (2046-2065) with present day water requirements (dark grey band of uncertainty using minimum and maximum values) and under the near future climate scenarios with near future development water requirements (light grey band of uncertainty).

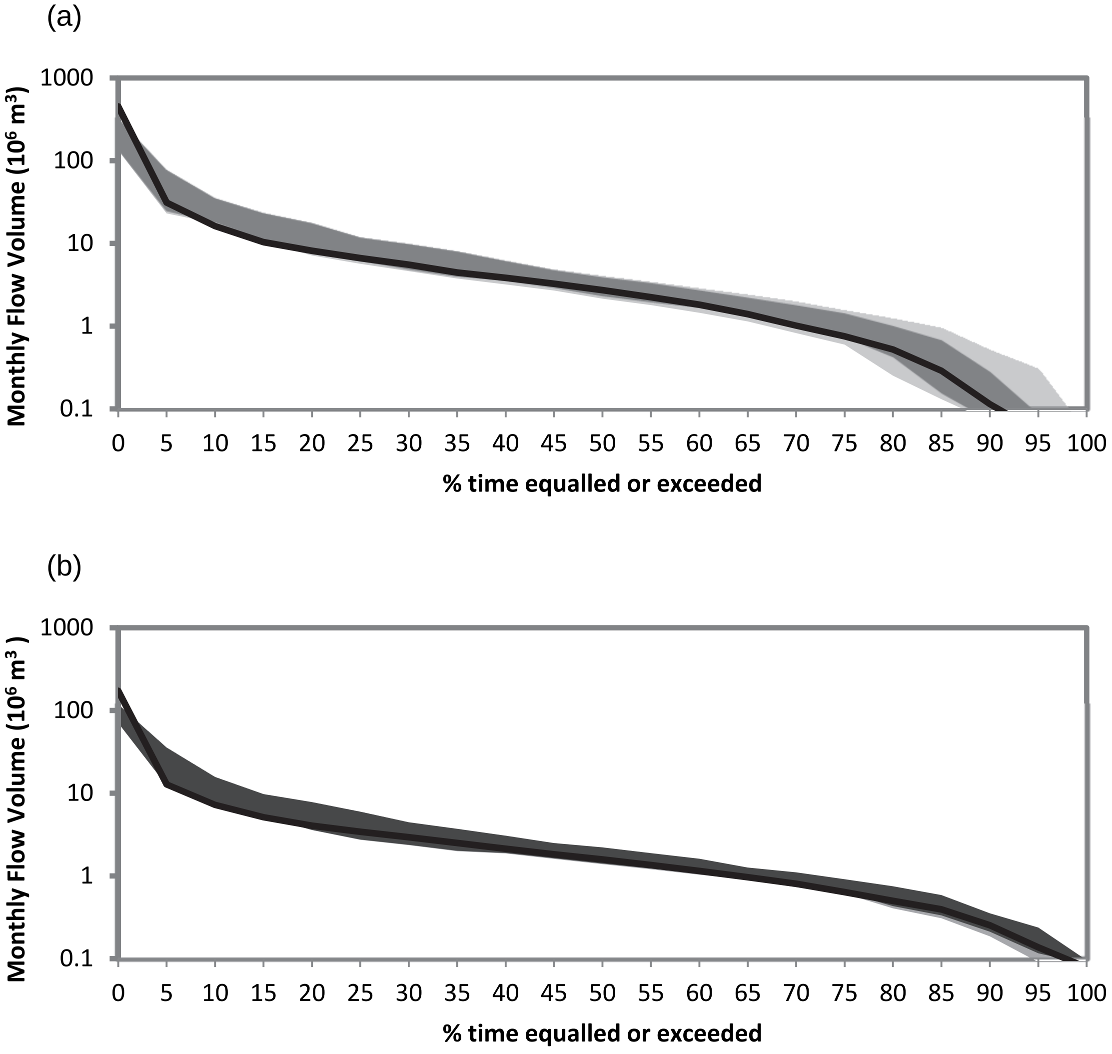


Figure 5.30 Flow duration curve at a reach (a) near R2H027 and (b) below the Nahoon Dam under present climate conditions (solid line; 1921-2005), under the near future climate scenarios (2046-2065) with present day water requirements (dark grey band of uncertainty using minimum and maximum values) and under the near future climate scenarios with near future development water requirements (light grey band of uncertainty).

Table 5.11 Range of statistics calculated for the percentage water deficits for population, industry, alien vegetation and irrigation sectors along the Amatole system for the nine climate change scenarios for the years 2046-2065 using the water requirements for the Intermediate (lower number in the range) and Upper (upper number in the range) Development scenarios.

	Min deficit	**Median deficit**	**Max deficit**	**Percentage months with >50% deficit**	**Percentage months with >25% deficit**
Upper Amatole					
Population	8-27	8-27	8-27	0	0-99
Industry	0	0	0	0	0
Alien Veg.	0	0	0	0	0
Irrigation	0	0	0	0	0
Middle Amatole					
Population	8-27	8-27	8-27	0	0-99
Industry	8-27	8-27	8-27	0	0-99
Alien Veg.	0	0	0	0	0
Irrigation	0	0	0	0	0
Lower Amatole					
Population	16-44	16-44	16-44	0	0-99
Industry	16-44	16-44	16-44	0	0-99
Alien Veg.	0	0	0	0	0
Irrigation	0	0	0	0	0

Table 5.12 Median water deficits (in 10^6 m^3 y^{-1}) along the Amatole system for the nine climate change scenarios for the years 2046-2065 using the water requirements for the Intermediate (lower number in the range) and Upper (upper number in the range) Development scenarios.

	Intermediate Development	**Upper Development**
Upper Amatole		
Population	1.57	6.94
Industry	0.00	0.00
Middle Amatole		
Population	0.86	4.01
Industry	0.18	0.63
Lower Amatole		
Population	13.60	57.95
Industry	5.24	18.41

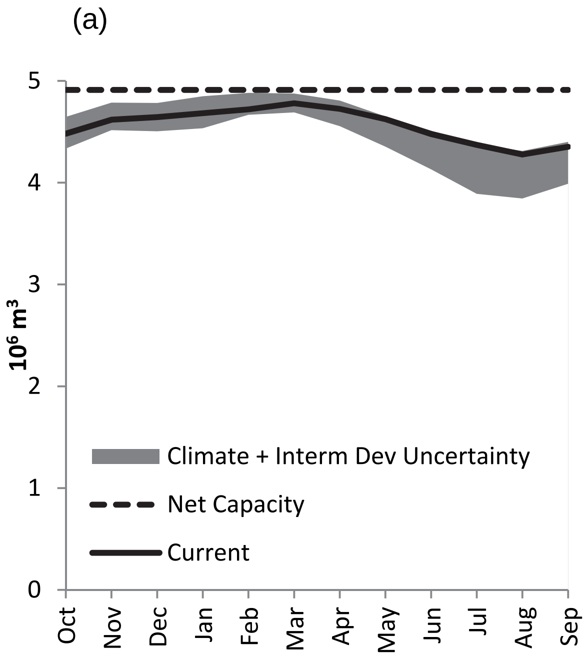


Figure 5.31 Average simulated monthly reservoir storage for the Rooikrantz Dam under the (a) Intermediate and (b) Upper Development scenarios with nine near future climate conditions (2046-2065). The current simulated reservoir storage (for the years 1921-2005; black line) and the net capacity (dashed line) are shown for reference.

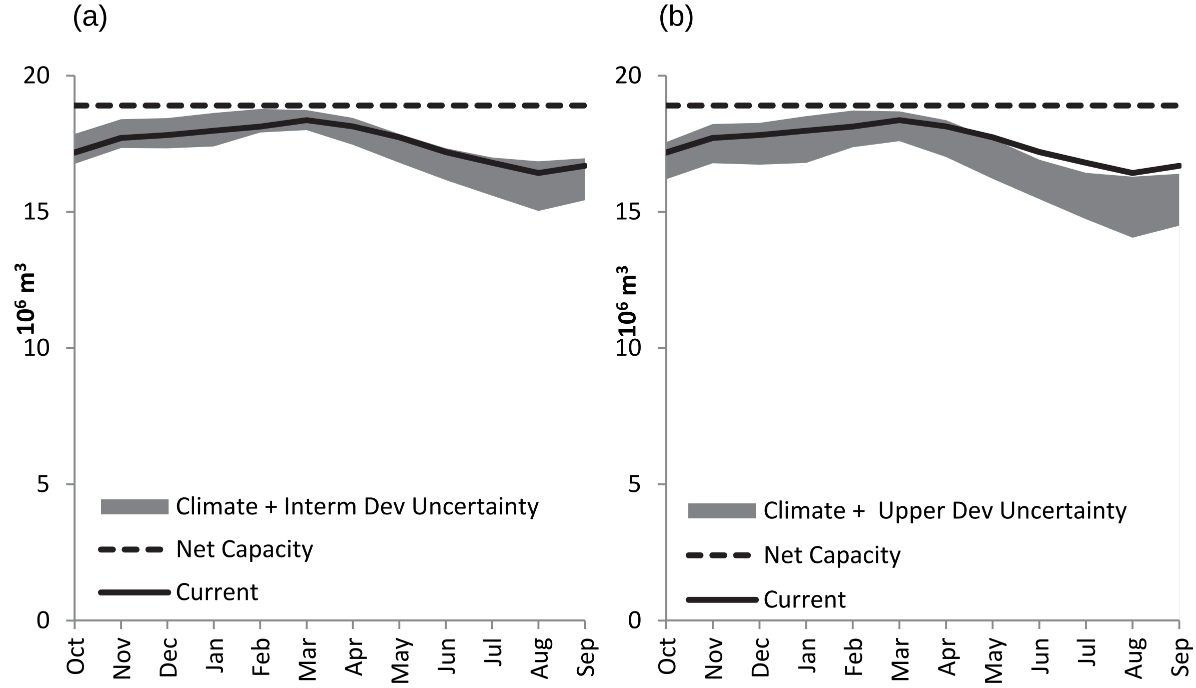


Figure 5.32 Average simulated monthly reservoir storage for the Laing Dam under the (a) Intermediate and (b) Upper Development scenarios with nine near future climate conditions (2046-2065). The current simulated reservoir storage (for the years 1921-2005; black line) and the net capacity (dashed line) are shown for reference.

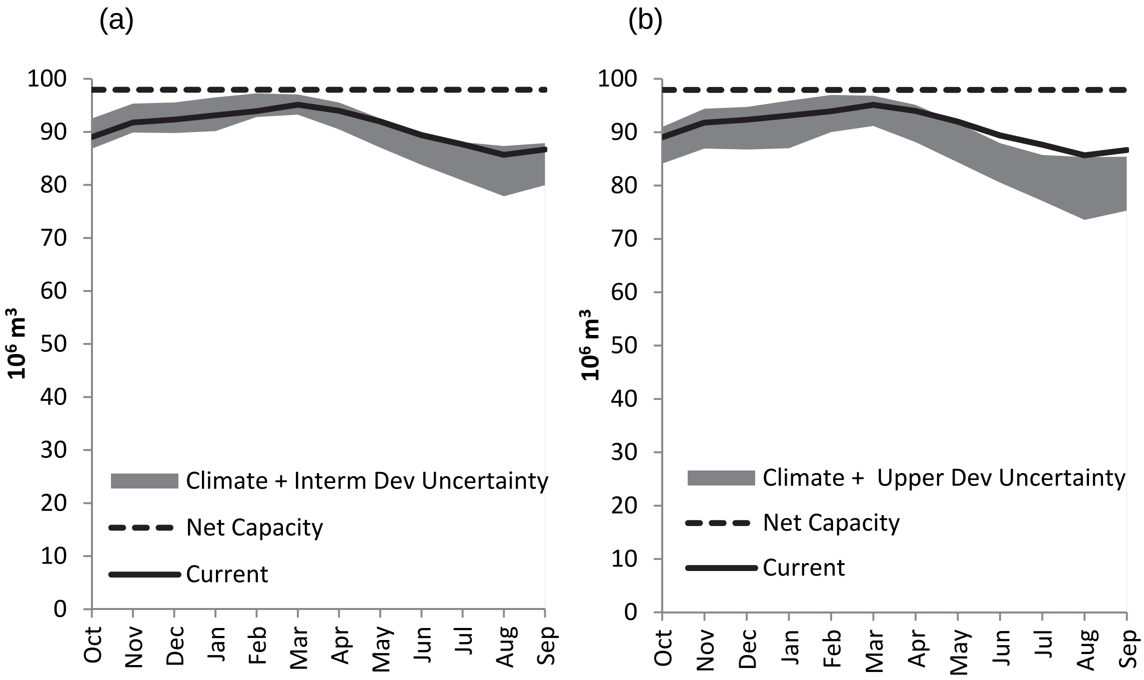


Figure 5.33 Average simulated monthly reservoir storage for the Bridle Drift Dam under the (a) Intermediate and (b) Upper Development scenarios with nine near future climate conditions (2046-2065). The current simulated reservoir storage (for the years 1921-2005; black line) and the net capacity (dashed line) are shown for reference.

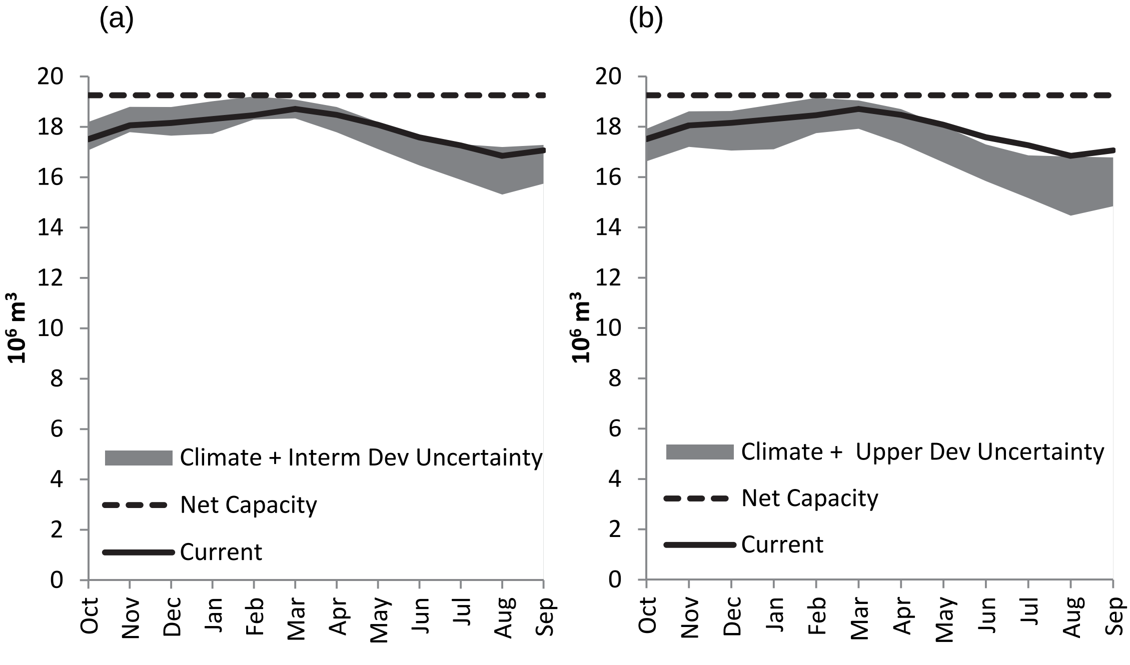


Figure 5.34 Average simulated monthly reservoir storage for the Nahoon Dam under the (a) Intermediate and (b) Upper Development scenarios with nine near future climate conditions (2046-2065). The current simulated reservoir storage (for the years 1921-2005; black line) and the net capacity (dashed line) are shown for reference.

5.7 Effects of expected upgrades to infrastructure and water transfers

The WEAP model was initially setup with no change in infrastructure in terms of water treatment in the future. As the results in the previous sections indicate, the present infrastructure will not meet the demands under the Intermediate and Upper Development scenarios. Thus, a WEAP scenario with three planned infrastructure upgrades was run for each of the near future climate change and Intermediate or Upper Development scenarios in order to assess the effects on available water and water quality issues. The water quantity results are presented here and the water quality issues are presented in Chapter 6. The three planned infrastructure upgrades are as follows:

- The WTW production capacity to treat water is expected to increase as shown in Table 5.13. There is a possibility that the Nahoon WTW capacity might also increase in future, but this is presently under discussions (Dr Nikite Muller, *pers. comm.*)
- According to Amatola Water and UWP (2012a), some the WWTWs are to be decommissioned in addition to building a large WWTW in future. The WWTWs that are planned for decommissioning are Bhisho, Breidbach and King Williams Town WWTWs and the upgrade planned is for Zweilitsha WWTW whose capacity is planned to go up to 35 × 10^6 ℓ day^{-1}. This will have primary effect on the water quality of the rivers, along with some effect on the water quantity because of change in discharge from the WWTWs.
- Finally, water is available through transfers from the Wriggleswade Scheme to supplement the Amatole Water Supply System by a value of 18 × 10^6 m^3 y^{-1} (DWAF, 2004b). Historically, there have only been a few transfers. The trial transfer was performed during the 1990s. In 2010, there have been two transfers, one to the Nahoon Dam and the other to the Laing and Bridle Drift dams. The cost of these water transfers are known to be high (ECPSDP, 2010).

Table 5.13 Current and future production of Water Treatment Works in the Amatole system. Data source: DWAF (2008), AWB (2010a) and AWB (2010b), Dr Nikite Muller (*pers. comm.*).

Water Treatment Work	**Present Production Mℓ d^{-1} (10^6 m^3 y^{-1})**	**Future Predicted Production Mℓ d^{-1} (10^6 m^3 y^{-1})**
Rooikrantz WTW	1.2 (0.44)	1.2 (0.44)
King William's Town WTW	13.0 (4.75)	13.0 (4.75)
Laing Dam WTW	33 (12.05)	33 (12.05)
Nahoon WTW	33.7 (12.30)	33.7 (12.30)
Umzonyana WTW	120.0 (43.80)	150.0 (54.75)

Using these three future infrastructure changes, the WEAP model was rerun for the Intermediate and the Upper Development scenarios in combination with the nine near future climate change models. Table 5.14 shows the results for predicted water deficits under these scenarios of increased water availability in the future. Comparing Table 5.14 with Table 5.11 (i.e. results with present day infrastructure) shows that the infrastructure upgrades will provide sufficient water under the Intermediate Development Scenario (i.e. no water deficits in the near future) and the water deficits will be greatly reduced (water deficits reduced from 27-44% for population and industrial users to 16-25%) by these upgrades and water transfers. Water deficit amount for the system under the Upper Development Scenario with water transfers and upgrades is a total of 50.18 × 10^6 m^3 y^{-1}.

5.8 Discussion: Results and use of WEAP model

This study has used the ‘off-the-shelf’ well-tested WEAP model (Water Evaluation and Planning Model) developed by the Stockholm Environment Institute (SEI) (Sieber and Purkey, 2007). The rainfall-runoff model included in WEAP was used to simulate the river hydrology and the calibration involved comparison of the simulated present day water discharge against the observed stream gauge data for the period 1980-2005. The calibration provided acceptable results and the difference observed between the simulated and the actual recorded flows is believed to be due to the uncertainty arising from various sources including uncertainty in the model structure, that in the observed flow data, uncertainty in the water user demand amounts, in addition to the variation in these user demands over time (stationary, instead of variable, demands were entered into the WEAP model). Simulation results for the full hydrological variability from 1921-2005 indicated that the current water requirements can be met for 100% user demands and this has been confirmed by Amatola Water Board as reality on the ground.

5.8.1 WEAP as a system level model

As discussed in Chapter 3, the WEAP model is a widely used model, particularly for water quantity / availability modelling. However, the project team’s experience of this model found it lacking in some aspects related to modelling of water treatment works and reservoir water quality. The WEAP water use and availability results in this report have been presented in three major sections above. The model was first run using socio-economic development (Lower, Intermediate and Upper) predictions for the near future (2046-2065 extrapolated from data available up to 2030) with hydrological variability for present climate (1921-2005). This was followed by a model run using the near future climate predictions (2046-2065) for rainfall and evapotranspiration using nine downscaled GCMs and present day water requirements (for the year 2005). This allowed analysis of the Amatole system’s ability to meet the present day water demands under the nine climate change scenarios in isolation without incorporating the predicted changes in water demands. Finally, the near future water requirements were combined with near future climate change scenarios and the combined uncertainty was assessed and compared. The results are discussed below.

5.8.2 Near future water requirement scenarios (development predictions) under current climate variability

The near future development requirements were incorporated in the WEAP model as Lower, Intermediate and Upper water requirement scenarios based on the reconciliation strategy (DWAF, 2008). The actual current population numbers on which these predictions were based would have changed as the reconciliation strategy used population numbers from the 2001 census; this difference should be considered as part of the uncertainty in the predictions. These scenarios included changes in population water requirements relative to current water requirements (increases for the Upper Amatole, decreases for the Middle Amatole and increases or decreases for the Lower Amatole depending on the specific scenario), industrial water requirements (increases in the Lower Amatole), and irrigation water requirements (ranging from no agricultural demand to increases in the Middle and Lower Amatole areas) under the different development scenarios.

Table 5.14 Range of statistics calculated for the percentage water deficits for population, industry, alien vegetation and irrigation sectors along the Amatole system for the nine climate change scenarios for the years 2046-2065 using the water requirements for the Intermediate (lower number in the range) and Upper (upper number in the range) Development scenarios, with upgrades to infrastructure and transfers from the Wriggleswade Dam (see text for details).

	Min. deficit	**Median deficit**	**Max. deficit**	**Percentage months with >50% deficit**	**Percentage months with >25% deficit**
Upper Amatole					
Population	0-16	0-16	0-16	0	0
Industry	0	0	0	0	0
Alien Veg.	0	0	0	0	0
Irrigation	0	0	0	0	0
Middle Amatole					
Population	0-16	0-16	0-16	0	0
Industry	0-16	0-16	0-16	0	0
Alien Veg.	0	0	0	0	0
Irrigation	0	0	0	0	0
Lower Amatole					
Population	0-25	0-25	0-25	0	0
Industry	0-25	0-25	0-25	0	0
Alien Veg.	0	0	0	0	0
Irrigation	0	0	0	0	0

Table 5.15 Median water deficits (in 10^6 m^3 y^{-1}) along the Amatole system for the nine climate change scenarios for the years 2046-2065 using the water requirements for the Intermediate (lower number in the range) and Upper (upper number in the range) Development scenarios, with upgrades to infrastructure and transfers from Wriggleswade Dam.

	Intermediate Development	**Upper Development**
Upper Amatole		
Population	0.00	4.15
Industry	0.00	0.00
Middle Amatole		
Population	0.00	2.39
Industry	0.00	0.37
Lower Amatole		
Population	0.00	32.84
Industry	0.00	10.44

Initially, no changes in infrastructural or system operation have been incorporated under the future development scenarios relative to the current situation in order to look at the effects of the future development water requirements in isolation without improvements in infrastructure. Additional scenarios with updates to the infrastructure were then added as additional scenarios (Section 5.7). The models were run over the full hydrological recorded period from 1921-2005. The expected percentage increase in the total water requirements under the future development scenarios ranges from -5.6% (i.e. decrease under the Lower Development Scenario) to 99.6% (increase under the Upper Development Scenario) with an expected 33.0% increase in the total water requirements under the Intermediate Development Scenario (Table 5.16).

The Amatola Water Infrastructure Master Plan provides data for present and projected total water requirements for population and industry that are supplied by the WTWs (see Figure 5.35). These water requirements are within the band of uncertainty input into the WEAP model (Figure 5.10) although the requirements in Figure 5.35 indicate a levelling off of water demands by the year 2022.

Table 5.16 Total water requirements (10^6 m^3 y^{-1}) for the three sectors (not including alien vegetation demands) under the current and the future development scenarios (Lower, Intermediate and Upper) for the years 2046-2065.

	Current	**Lower Dev.**	**Intermediate Dev.**	**Upper Dev.**
Population	45.55	44.41	60.49	90.01
Industry	14.32	16.24	20.57	25.55
Irrigation	4.40	0.00	4.40	12.74
Total	64.27	60.65	85.46	128.30
% increase	---	-5.6%	33.0%	99.6%

The results for the demand side deficit under the Lower Development Scenario (with water demands lower than current day requirements; Table 5.7a) show no deficit in demand side provision of water, same as for the present day situation. It must be noted, however, that ***environmental flow requirements have not been included in these model runs and thus, the results for water deficit are conservative***. This is since only the preliminary environmental flow requirements have been calculated and the DWA is aiming to re-evaluate these in the near future. Additionally, alien vegetation demands (total of 3 × 10^6 m^3 y^{-1}) could either increase or decrease in future depending on management programmes implemented.

Under the Intermediate and Upper Development scenarios, the population and industrial demands are not met (particularly in the Lower Amatole area) if the infrastructure is kept the same as at present. The percentage water deficit for the population and industry users in the Lower Amatole area is between 16% (Intermediate Development Scenario) and 44% (Upper Development Scenario), while the Middle Amatole could experience shortages of 8-27% for these same water users in the near future (Tables 5.9 and 5.10). Additionally, under these Intermediate and Upper Development scenarios, the minimum dam storage simulated by WEAP shows a reduction relative to the present day situation.

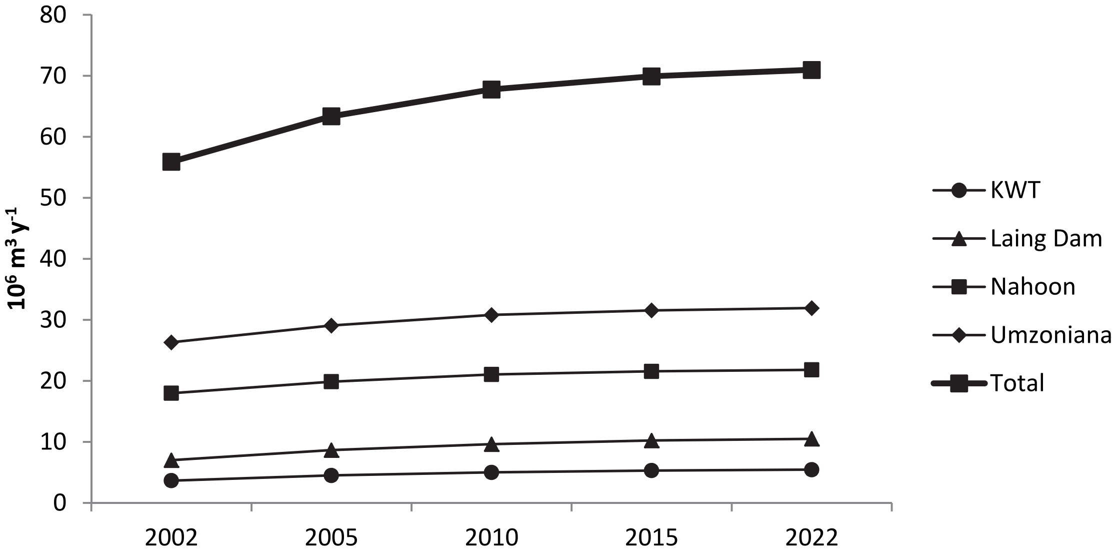


Figure 5.35 Future water requirements for industry and population for the Buffalo City Municipality derived from the Amatola Water Infrastructure Master Plan using the BCM population growth rates applied to recorded water requirements in 2005 (AWB 2010a: Table 4-16).

5.8.3 Near future climate change scenarios with current water user demands

The most direct influence of climate change will be on water temperature through effects on air temperature. Water temperature not only influences the chemical and biological processes in rivers, but also influences the river organisms through indirect effects on available habitat as well as direct effects on their growth and development (Dallas & Day, 2004; Dallas, 2008, 2009; Rivers-Moore et al., 2008).

Under this project, nine climate change scenarios downscaled by CSAG were entered into the WEAP model as near future climate predictions. An increase in flow in the Buffalo and Nahoon rivers is predicted by the WEAP model for the near future climate scenarios. A median increase of 36-63% relative to the present day simulation for high flows and an increase of 18-90% for low flows were determined for the Buffalo and Nahoon rivers. These results are in agreement with projections of increased flows presented in DEA (2011: p. 81) for the Eastern Cape for both the 1-in-10 year low flows and 1-in-10 year high flows.

Due to increased flows under near future climate scenarios, it is expected that there should be no demand deficit for the water users if the demands remain the same as those for the present day. Additionally, an increase in expected rainfall under the near future climate scenarios translate into higher minimum monthly storage under future climate than that for the present day situation.

With regards to the seasonality of flows, the near future climate scenarios show similar seasonality relative to the present day simulated flows generated by WEAP. However, the upper extreme of the uncertainty bands indicate that the seasonality could be more dramatic in difference with a large magnitude difference in flow volumes between seasons.

5.8.4 Near future climate change scenarios with near future water user demands

The final section on water availability and use in this chapter combined the predictions for near future climate change and development changes in the WEAP model. The results for climate change plus development scenarios show greater uncertainty, primarily at low flows relative to the climate change scenarios in isolation. ***This stresses the need for future planning incorporating both climate and development impacts together instead of in isolation, particularly as increased uncertainty exists at the low flows. The increased uncertainty at the low flows would impact the meeting of the environmental flow requirements, and has implications for the frequency of water transfers needed and stricter management of reservoir storage for both water quantity and quality.***

5.8.5 Effects of improved infrastructure on meeting near future development demands

The above results confirm that water transfers from the Wriggleswade Dam (in addition to other water conservation measures) will be necessary to top up the Laing Dam at a higher frequency than at present, particularly if the Intermediate or Upper Development scenarios become reality. Section 5.7 investigated the effect of water transfers from the Wriggleswade Dam to Yellowwoods and Nahoon rivers, in addition to upgrades in WTW capacity for treating water to meet the higher user demand. The results found that these measures will provide sufficient water to meet the demands under the Intermediate Development Scenario, but there will be some deficit (of up to 50.18×10^6 m^3 y^{-1}) under the Upper Development Scenario. As noted above, ***these results have not incorporated environmental flow requirements and thus, represent conservative water deficit results***.

A final note to consider is that *since the predicted demands might level off (as shown in Figure 5.35 which shows predictions until the year 2022) instead of increasing as has been modelled in WEAP (using extrapolations of projections until 2030 in DWAF, 2008), the demands under the Upper Development Scenario might be different than those used in the WEAP model*. ***This confirms and stresses the need for continued monitoring of population changes and industrial growth in order to plan and manage the Amatole system effectively and efficiently under increased uncertainty in predictions for the future. This needs to be combined with monitoring of the catchment in terms of stream discharge, river and reservoir water quality, and reservoir storage in order to reduce the uncertainty in the predicted scenarios for climate change and socio-economic development.***

CHAPTER 6. APPLICATION OF WEAP MODEL FOR WATER QUALITY

by

Andrew Slaughter

It was decided that the water quality variables to be simulated by WEAP would be EC, NO_3-N + NO_2-N and PO_4-P. These choices are justified: 1) the Amatole system is naturally saline, and higher salinities due to human impacts increase costs of water treatment; 2) the Buffalo River is impacted by human induced eutrophic conditions, and the nutrients NO_3-N + NO_2-N and PO_4-P contribute greatly to this problem and; 3) the chosen water quality variables are relatively well represented within the Department of Water Affairs historical monitoring data.

6.1 Set-up/calibration

A brief summary of the calibration results will be given here. The model simulation for EC was fairly good for the Upper Amatole, with some isolated unrealistic spikes in EC that are most likely due to the irrigation return flow simulation by the model. The model consistently under-simulated EC for the Middle and Lower Amatole, which is due to the model over-simulating flow for these regions.

The simulation for PO_4-P across the entire system clearly demonstrated a shortcoming of the water quality simulation method of WEAP. The nutrient PO_4-P was added as a non-conservative water quality variable to the model (a variable that is subject to in-stream alterations of concentration due to factors other than dilution such as uptake by fauna and chemical speciation). Within WEAP, a single, spatially global degradation coefficient can be added for non-conservative water quality variables that encompass the various factors influencing in-stream concentrations of a particular non-conservative variable into one coefficient. For PO_4-P, it was evident that phosphate is removed from the Middle and Lower Amatole system faster than it is in the Upper Amatole, therefore, the application of a global degradation coefficient in WEAP will not obtain good calibration results for the entire system. This was evident in the results of the calibration, where the calibration results were relatively good for the Middle and Lower Amatole system, but were relatively inaccurate for the Upper Amatole. It is known that the Buffalo River system is phosphate limited, meaning that phosphate concentrations are likely to reduce more rapidly than that of nitrogen species. In addition, from the observed data, PO_4-P concentrations below the Laing Dam appear to be relatively low compared to upstream with little variation. It is theorised that Laing Dam has an ameliorating and regulating effect on downstream PO_4-P concentrations.

Generally good simulations for NO_3-N + NO_2-N for the Upper, Middle and Lower Buffalo River within the calibration were obtained.

The table of water quality parameters and signatures used in the WEAP model to achieve calibration to historical observed data is placed here (Table 6.1), as it is of relevance to the modelling of development and climate change scenarios.

Table 6.1 Water quality parameters and signatures used in the WEAP model to achieve calibration to historical observed data.

Water quality variable	**Parameter/signature**	**Value**
EC	Population outflow concentration	100 mS m^{-1}
PO_4-P	Population outflow concentration	6 mg ℓ^{-1}
NO_3-N + NO_2-N	Population outflow concentration	24 mg ℓ^{-1}
EC	Industry outflow concentration	350 mS m^{-1}
PO_4-P	Industry outflow concentration	1.24 mg ℓ^{-1}
NO_3-N + NO_2-N	Industry outflow concentration	24 mg ℓ^{-1}
EC	Irrigation return flow concentration*	100 mS m^{-1}
PO_4-P	Irrigation return flow concentration*	0.05 mg ℓ^{-1}
NO_3-N + NO_2-N	Irrigation return flow concentration*	0.05 mg ℓ^{-1}
EC	Tributary signatures generated from patching historical monitoring data from representative gauging stations.	Time series
PO_4-P	Tributary signatures generated from patching historical monitoring data from representative gauging stations.	Time series
NO_3-N + NO_2-N	Tributary signatures generated from patching historical monitoring data from representative gauging stations.	Time series
EC	Reservoir signatures generated by taking monthly averages over all years from historical monitoring data.	Seasonal series
PO_4-P	Reservoir signatures generated by taking monthly averages over all years from historical monitoring data.	Seasonal series
NO_3-N + NO_2-N	Reservoir signatures generated by taking monthly averages over all years from historical monitoring data.	Seasonal series
EC	WWTWs signatures generated using historical monitoring data and an interpolation function within WEAP	Interpolated series

* parameters adjusted during the calibration process

Table 6.1 continued

Water quality variable	**Parameter/signature**	**Value**
PO_4-P	WWTWs signatures generated using historical monitoring data and an interpolation function within WEAP	Interpolated series
NO_3-N + NO_2-N	WWTWs signatures generated using historical monitoring data and an interpolation function within WEAP	Interpolated series
PO_4-P	First – order decay rate*	0.7
NO_3-N + NO_2-N	First – order decay rate*	0.1

*parameters adjusted during the calibration process

6.2 Water quality results for climate change and development

6.2.1 Setup of water quality signatures and parameters for simulation of climate change as well as development scenarios.

Within the calibration process, the water quality signatures of tributary inflows were determined from historical monitoring data from representative gauging stations. Because of large temporal gaps in the data, patching techniques, or data in-filling techniques were developed. These methods depended on finding a relationship between particular water quality variables and flow, as flow was the independent variable that was available on a daily time scale.

These relationships for the various tributaries have been established during the calibration stage from the historical monitoring data. However, the question of water quality signatures for inflowing tributaries for future climate change and development scenarios poses a problem. One can obtain the future simulated flow from the WEAP model's rainfall-runoff hydrological module, using the climate change predicted rainfall. However, the model is a monthly time step model, and will give simulated flow results at a monthly resolution, while the data in-filling techniques require daily flow. A method was used that disaggregates monthly simulated flow into daily simulated flows, using the daily simulated rainfall data. This method is incorporated into the Water Quality Systems Assessment Model and is described in Section 7.3. The method allowed the availability of daily simulated flow, from which water quality signatures for the various tributary inflows could be determined.

All other water quality signatures and parameters were kept the same as determined during the calibration process. Because an interpolation technique applied to observed data was used within WEAP to determine the WWTWs return flow water quality within the calibration process, the average values of observed data were used to specify water quality concentrations from WWTWs in the future scenarios. Salinity changes due to climate change and development for the Upper Buffalo River seem negligible compared to the current situation (see Figure 6.1a). The model simulated various spikes in EC which is reflected in Figure 6.1a, but these are most likely an artefact of the shortcomings in calibration.

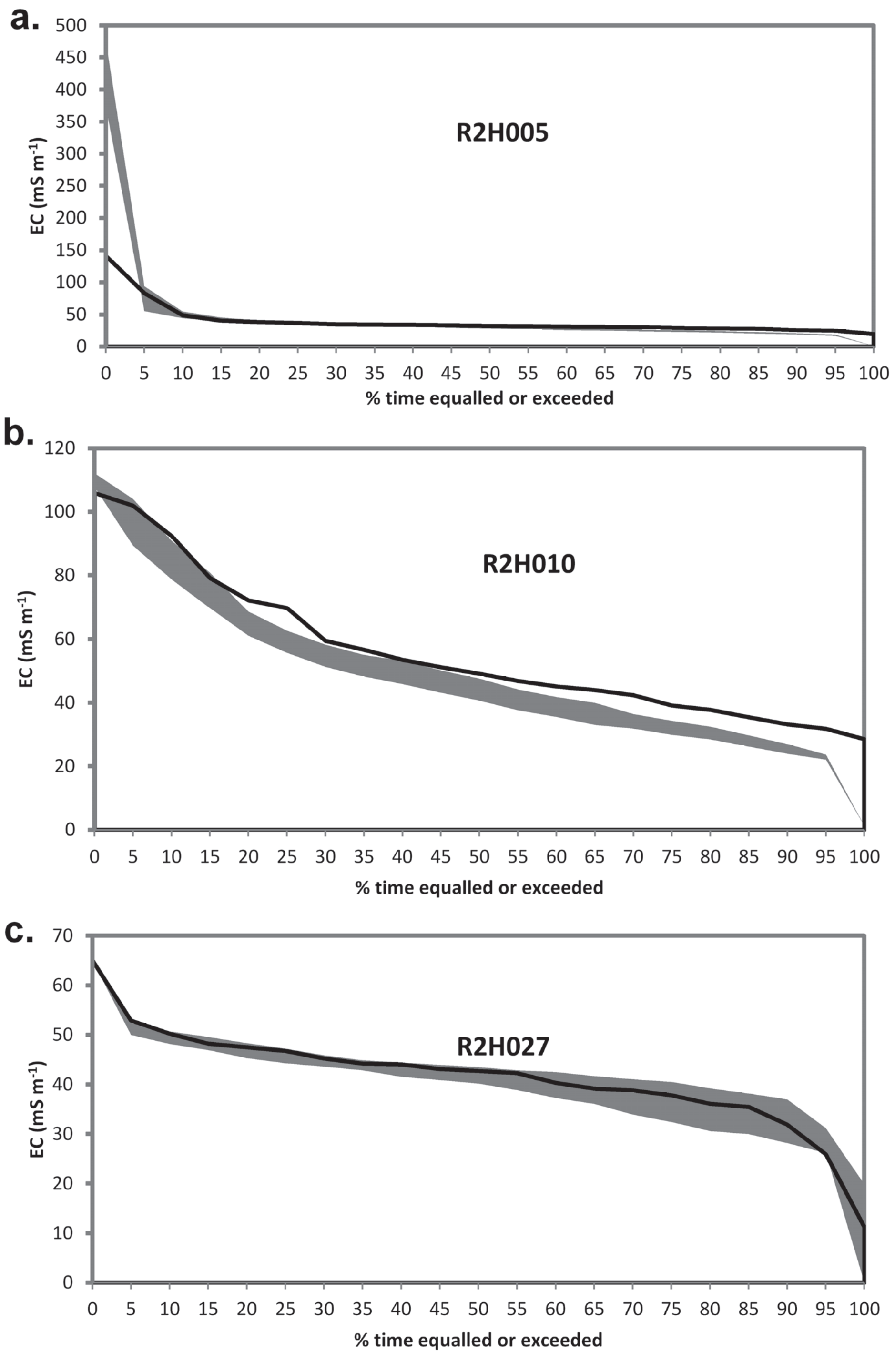


Figure 6.1 Electrical Conductivity duration curves for the Buffalo River under present conditions (solid line; 1999-2005) and under near future climate scenarios (2046-65) with intermediate future development water requirements (grey band of uncertainty using minimum and maximum values): a. Upper Buffalo; b. Middle Buffalo; c. Lower Buffalo

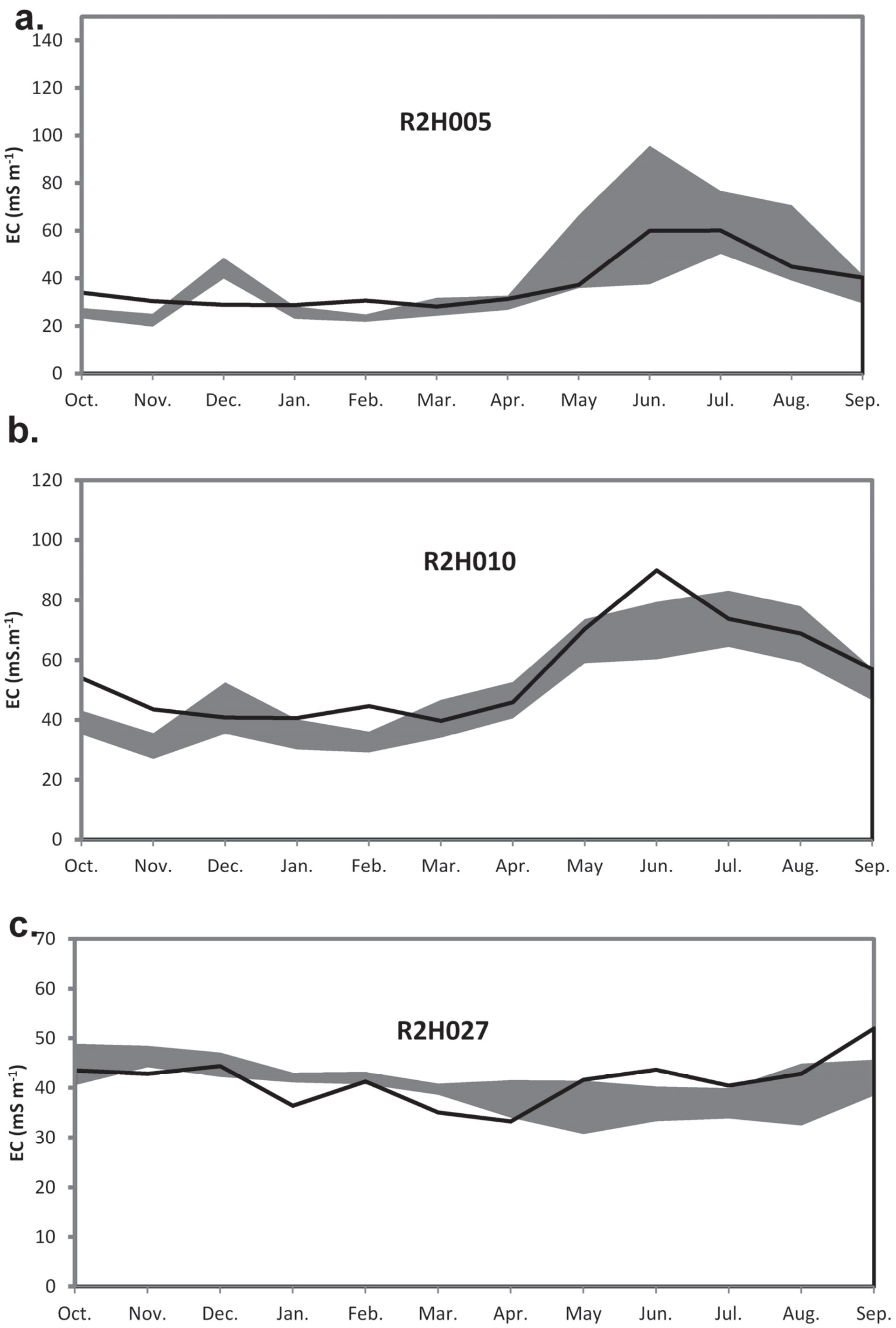


Figure 6.2 Monthly averaged simulated Electrical Conductivity for the Buffalo River under present conditions (1999-2005; solid line) and under near future climate scenarios (2046-65) as well as future Intermediate Development Scenario water requirements shown as a band of uncertainty (minimum and maximum values): a. Upper Buffalo; b. Middle Buffalo; c. Lower Buffalo.

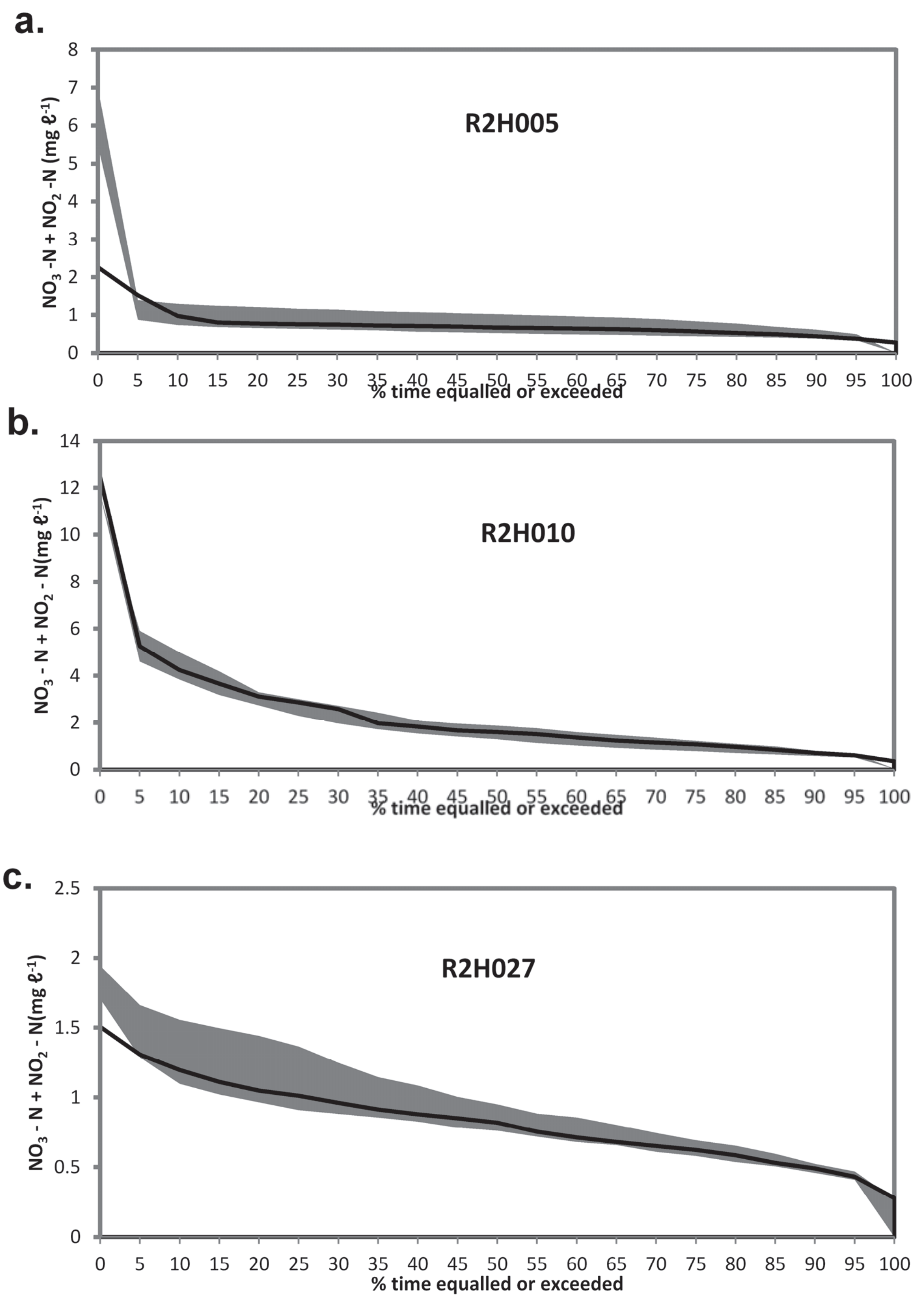


Figure 6.3 NO_3-N + NO_2-N duration curve for the Buffalo River under present conditions (solid line; 1999-2005) and under near future climate scenarios (2046-65) with future Intermediate Development Scenario water requirements (grey band of uncertainty using minimum and maximum values: a. Upper Buffalo; b. Middle Buffalo; c. Lower Buffalo.

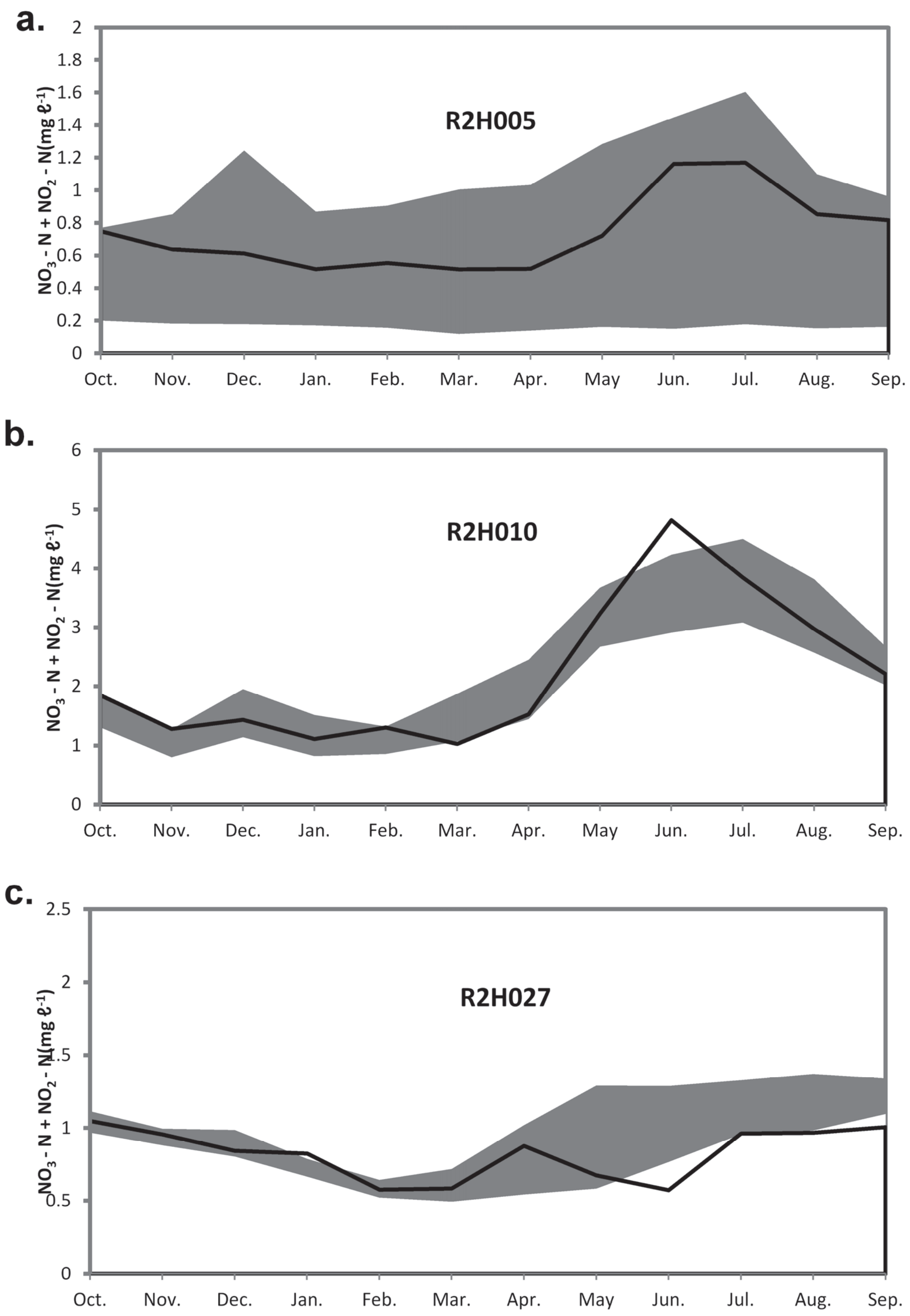


Figure 6.4 Monthly averaged simulated NO_3-N + NO_2-N for the Buffalo River under present conditions (1999-2005; solid line) and under near future climate scenarios (2046-65) as well as future Intermediate Development Scenario water requirements shown as a band of uncertainty (minimum and maximum values): a. Upper Buffalo; b. Middle Buffalo; c. Lower Buffalo.

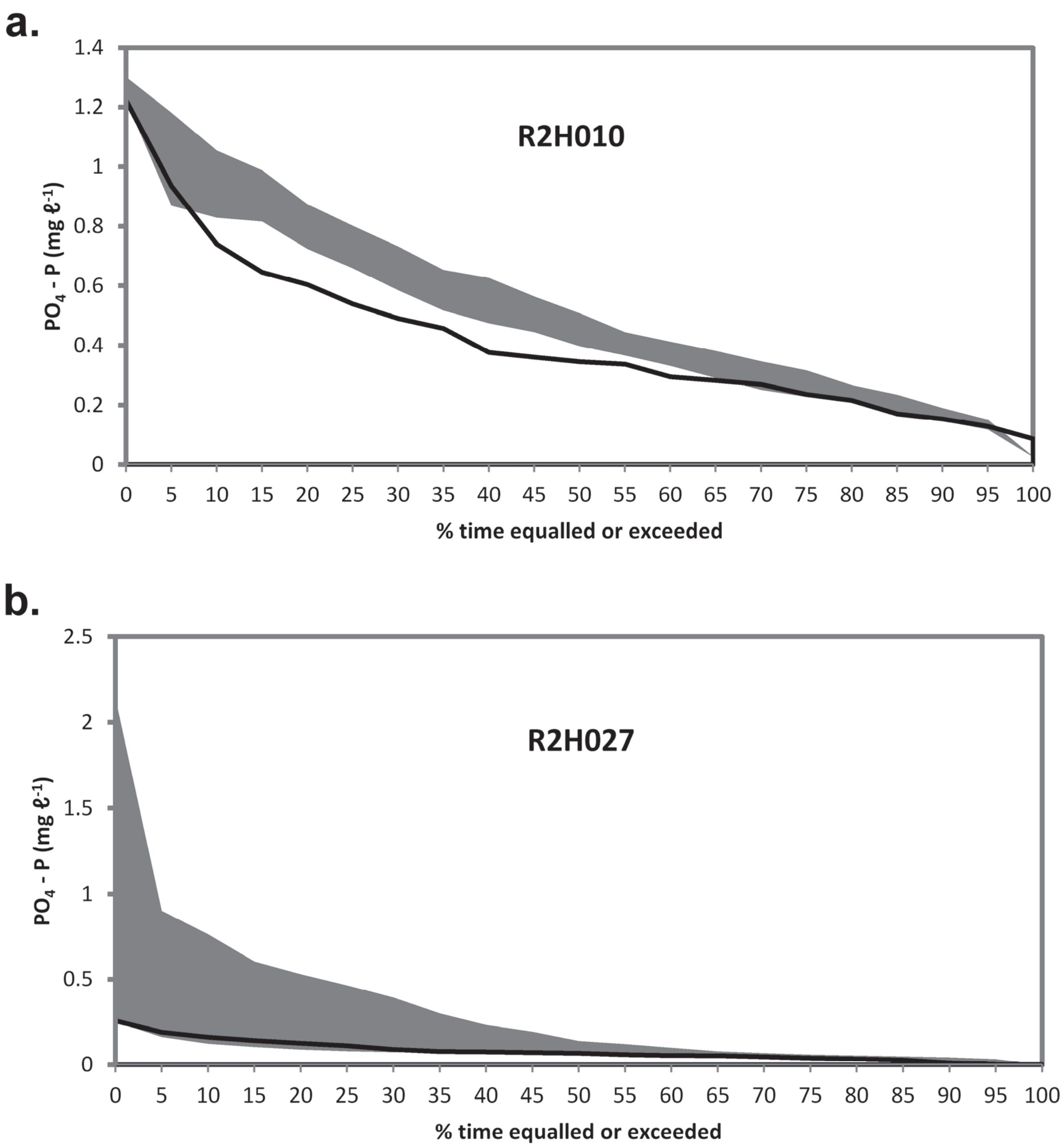


Figure 6.5 PO_4-P duration curve for the Buffalo River under present conditions (solid line; 1999-2005) and under near future climate scenarios (2046-65) with future Intermediate Development Scenario water requirements (grey band of uncertainty using minimum and maximum values): a. Middle Buffalo; b. Lower Buffalo.

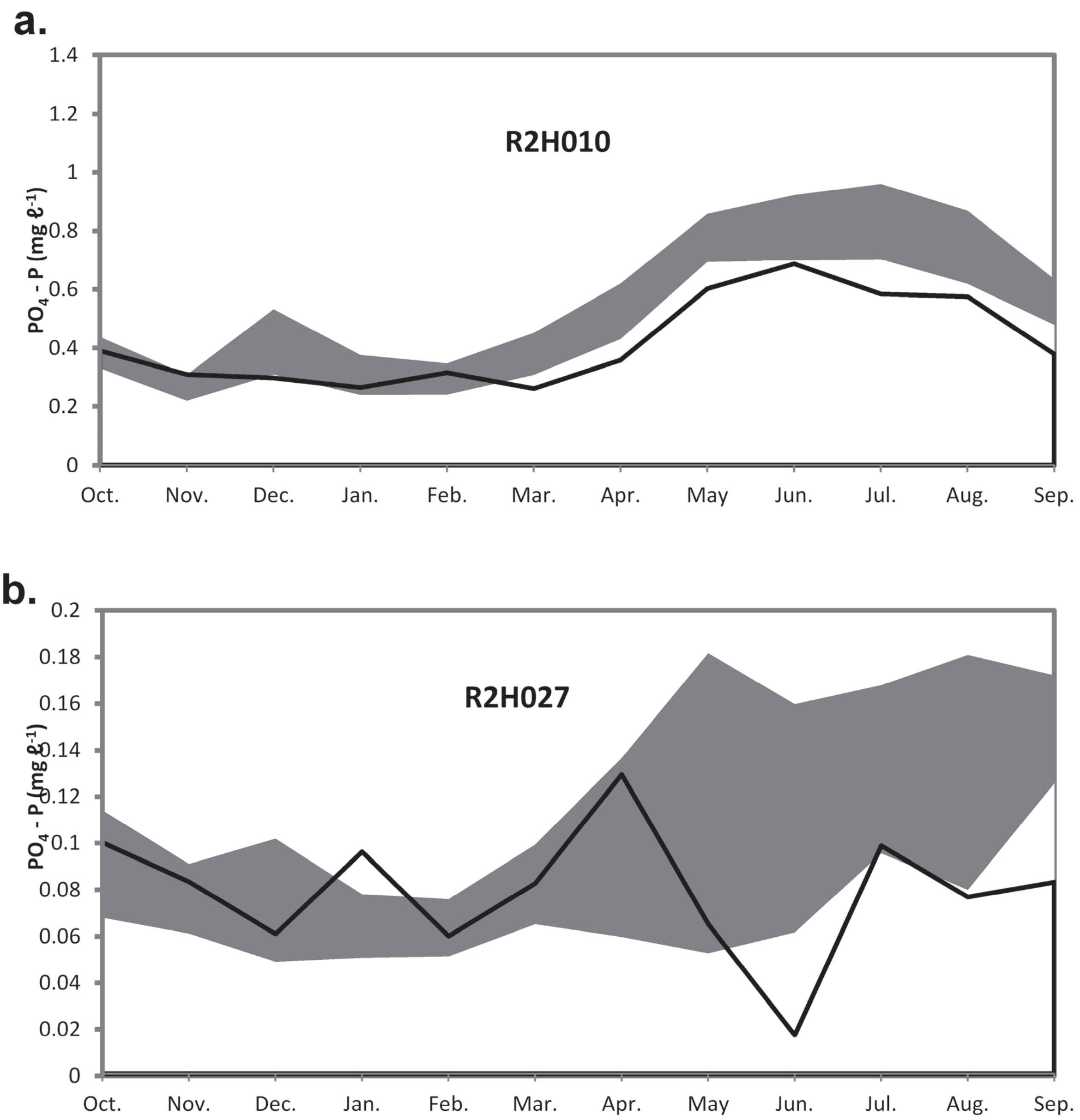


Figure 6.6 Monthly averaged simulated PO_4-P for the Buffalo River under present conditions (1999-2005; solid line) and under near future climate scenarios (2046-65) as well as future Intermediate Development Scenario water requirements shown as a band of uncertainty (minimum and maximum values): a. Middle Buffalo; b. Lower Buffalo.

The model indicated that the seasonal signature of EC within the Upper Buffalo River may be more uncertain over the Autumn to Spring months (see Figure 6.2a). The observed EC signature shows a peak over this period (see Figure 6.2a), and therefore, the simulated EC signature over this period may be most sensitive to changes in flow.

The model simulated EC for the Middle Buffalo River under future climate change and Intermediate Development scenarios showed very little change compared to the model simulation under the Current Development Scenario (see Figure 6.1b). Perhaps some higher dilution effects due to slightly increased flows are represented in the results. The simulated seasonal signature for EC under climate change and Intermediate Development scenarios was not drastically different from the Current Development Scenario simulation, and generally, the band of uncertainty around simulated results was fairly narrow (see Figure 6.2b).

The model simulated EC for the Lower Buffalo River under future climate change and Intermediate Development scenarios showed very little change compared to the model simulation under the Current Development Scenario (see Figure 6.1c). There appears to be a slightly diluted seasonal signature over the months May-September under the climate change and development scenarios compared to the Current Development Scenario (see Figure 6.2c).

Figure 6.3a shows that the duration curve of NO_3-N + NO_2-N for climate change and development scenarios for the Upper Buffalo River was very similar to the Current Development Scenario simulation, except for some unrealistic higher concentrations that are an artefact of calibration, probably due to the WEAP model's agricultural return flow calculation method. While the model monthly averaged simulation of NO_3-N + NO_2-N was similar to the Current Development Scenario simulation, the results showed wide uncertainty (Figure 6.4a). This could indicate that the downscaled GCM rainfall data vary in regards to seasonality, which in turn could influence water quality due to dilution.

Simulations of PO_4-P for the Upper Buffalo could not be performed because of shortcomings in the calibration. The simulation of PO_4-P for the Middle Buffalo River for climate change and the Intermediate Development scenarios shows simulated PO_4-P concentrations to be higher than that simulated for the Current Development Scenario (see Figure 6.5a). While the uncertainty band is fairly narrow, the overall higher concentrations as compared to that of the Current Development Scenario, could indicate that higher demand within the Intermediate Development Scenario leads to higher rates of return flow from WWTWs in the Middle Buffalo River. Higher volumes of return flow from WWTWs would in general raise the concentration of in-stream PO_4-P. The overall higher PO_4-P concentrations under climate change and Intermediate Development scenarios as compared to the Current Development Scenario is also evident in the seasonal PO_4-P signature in the Middle Buffalo River (see Figure 6.6a)

The model simulations for NO_3-N + NO_2-N for climate change and development scenarios for the Middle Buffalo River show no difference to that simulated for the Current Development Scenario (see Figure 6.3b). The simulated seasonal signature is also very similar to that of the Current Development Scenario (see Figure 6.4b). In both cases, the model simulated very narrow uncertainty bands.

The model simulations for PO_4-P in the Lower Buffalo River for climate change and development scenarios showed a high degree of uncertainty, especially at the upper range of PO_4-P concentrations (see Figure 6.5b). This wide range of uncertainty is also reflected in the seasonal simulations (see Figure 6.6b). The WEAP model effectively re-sets water quality results downstream of the Laing Dam to that of the historical signature. Therefore, any variability in simulated PO_4-P across the climate change scenarios, must be due to differences in flow, because of dilution effects.

Model simulated NO_3-N + NO_2-N results for the Lower Buffalo River for climate change scenarios and the Intermediate Development Scenario, don't differ drastically from the Current Development Scenario simulation (see Figure 6.3c). Some uncertainty in the simulated results is evident, especially within the monthly averaged NO_3-N + NO_2-N simulation (see Figure 6.4c).

6.3 Updated results for climate change and development scenarios considering water transfers and the upgrading of waste water treatment works

Subsequent to the 3rd reference group meeting, additional information on the operation of the Amatole system and the consequences on water quality had to be taken into account. These were: 1) The decomissioning of the Breidbach, the King Williams Town, and the Bhisho WWTWs, and the upgrading of the Zwelitsha WWTW (DEDEA, 2011) and; 2) the intermittant high flows in the Yellowwoods River due to water transfers from the Wriggleswade Dam to the Buffalo River. The proposed upgrading of the Zwelitsha WWTW and the decomissioning of various smaller WWTWs has fairly important consequences for water quality. It is estimated that the upgrading of the Zwelitsha WWTW will result in moderate improvements to the water quality of the Middle Buffalo River and the Laing Dam (DEDEA, 2011). The decomission of the Bhisho and Breidbach WWTWs should also have an impact on the water quality of the Yellowwoods River, as well as result in a return to natural emphemeral flow within this river. The transfer of good quality water from Wriggleswade Dam through the Yellowwoods River is also likely to result in improvements in the quality of water in the Yellowwoods River.

Additional results are shown for the Middle Buffalo River (near R2H010) and the Yellowwoods River for PO_4-P and NO_2-N + NO_3-N, as the transfer and the regionalisation of the WWTW will effect prodominantly these parts of the Amatole system for nutrients. The results are also shown for all climate change scenarios under Intermediate Development, and all climate change scenarios under Higher Development.

6.3.1 Updating the WEAP model to consider the regionalised WWTW

A mass-balance point source nutrient model (Slaughter and Hughes, In Press) was used to estimate the future effluent nutrient concentrations within effluent released from the regionalised Zwelitsha WWTW for the future climate change and development scenarios. The model assumed random effluent concentrations on a daily time step, within a minimum and maximum effluent concentration range. These minimum and maximum values were estimated using the information of likely influent water quality given by BCM (2011) and treatment efficiencies were estimated by information on the University of Cape Town Biological Nutrient Removal (UCTBNR) process (Sötemann et al., 2002). Daily effluent concentrations were averaged on a monthly scale for input into the WEAP model. In addition, the influences of the King Williams Town, Breidbach and Bhisho WWTWs were removed from the model.

6.3.2 Updated WEAP water quality results: climate change scenarios under the Intermediate Development Scenario

From the nutrient results for the Middle Buffalo River at R2H010, it appears that in-stream nutrient concentrations will increase under climate change scenarios and the Intermediate Development Scenario compared to the Current Scenario (see Figure 6.7-10). PO_4-P and NO_2-N + NO_3-N appear to increase fairly considerably. Nutrients within the Yellowwoods River decrease dramatically compared to the Current Scenario (see Figure 6.11-14).

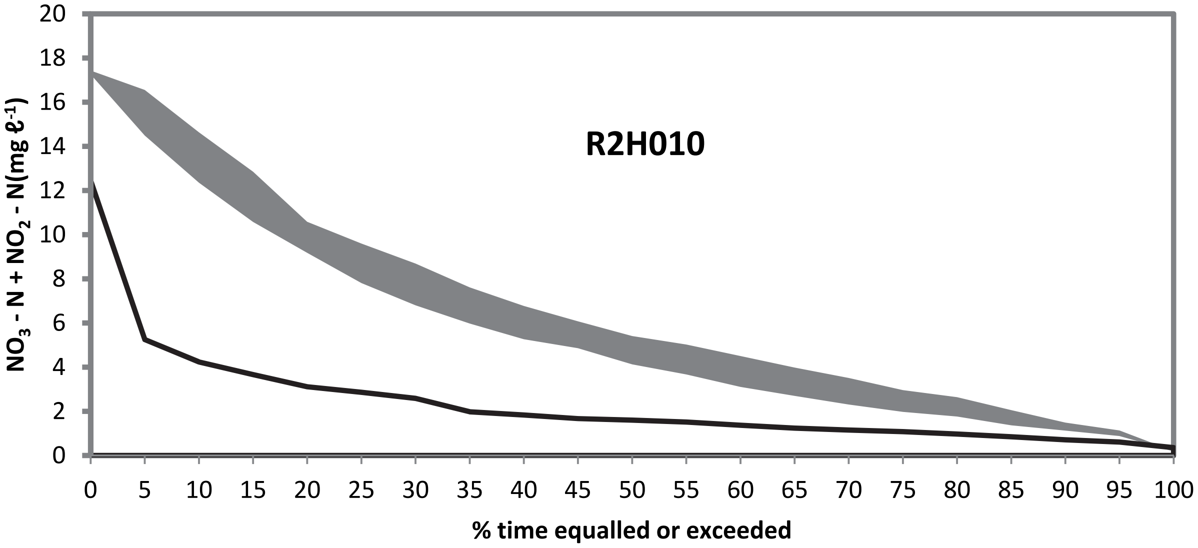


Figure 6.7 NO_3-N + NO_2-N duration curve for the Middle Buffalo River near R2H010 under present conditions (solid line; 1999-2005) and under near future climate scenarios (2046-65) with future Intermediate Development water requirements (grey band of uncertainty using minimum and maximum values).

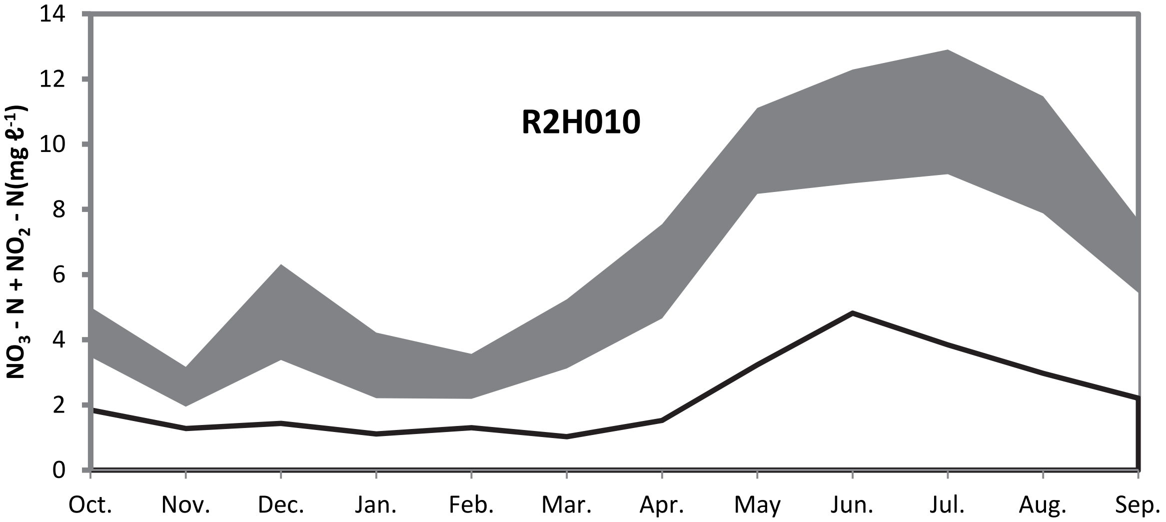


Figure 6.8 Monthly averaged simulated NO_3-N + NO_2-N for the Middle Buffalo River near R2H010 under present conditions (1999-2005; solid line) and under near future climate scenarios (2046-65) as well as the future Intermediate Development Scenario shown as a band of uncertainty (minimum and maximum values).

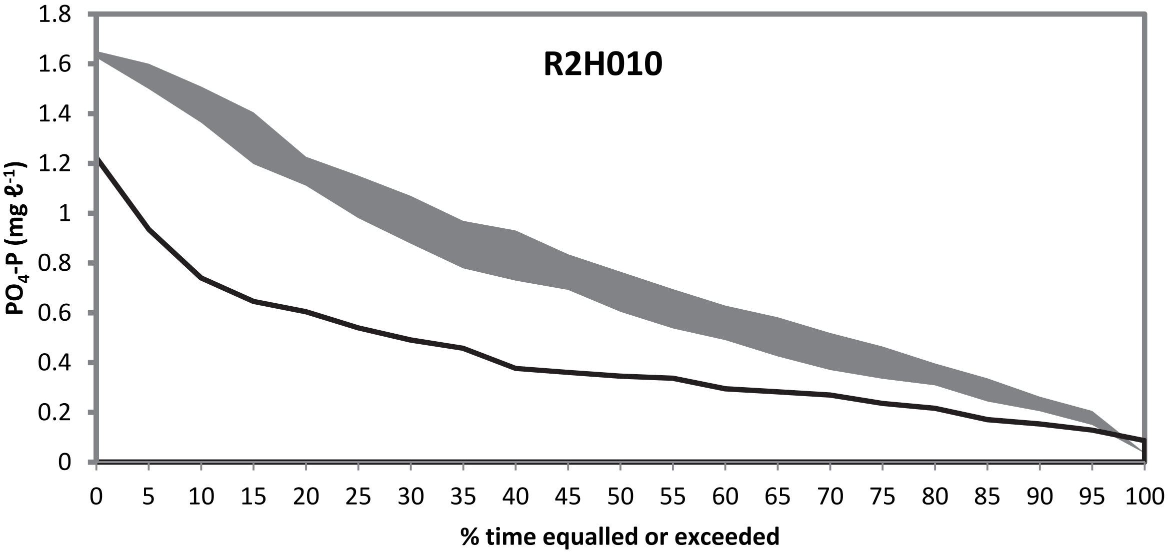


Figure 6.9 PO_4-P duration curve for the Middle Buffalo River near R2H010 under present conditions (solid line; 1999-2005) and under near future climate scenarios (2046-65) with future Intermediate Development Scenario water requirements (grey band of uncertainty using minimum and maximum values).

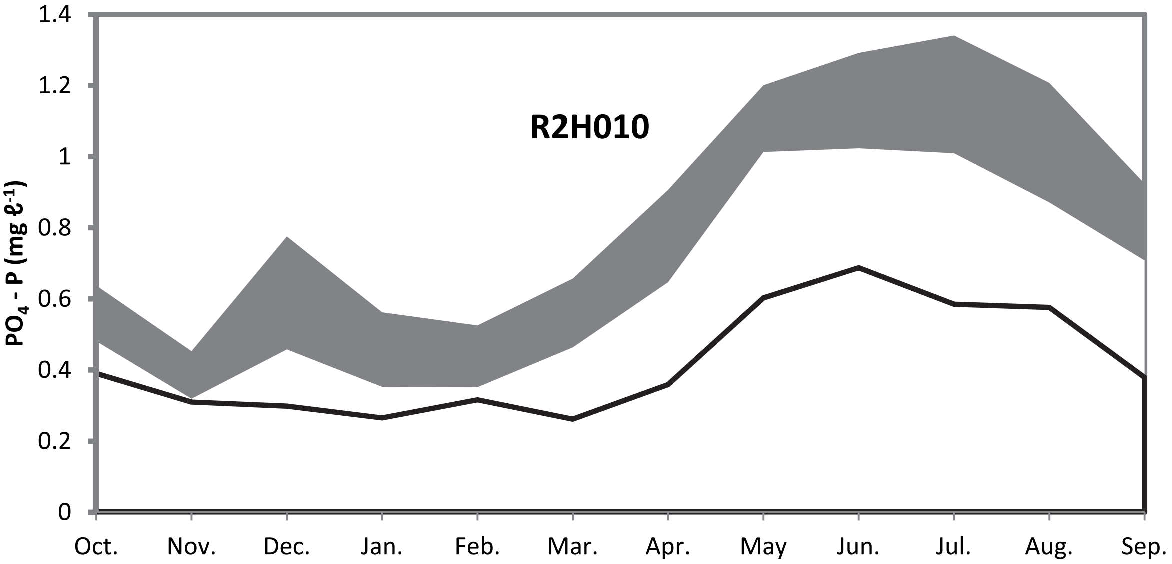


Figure 6.10 Monthly averaged simulated PO_4-P for the Middle Buffalo River near R2H010 under present conditions (1999-2005; solid line) and under near future climate scenarios (2046-65) as well as the future Intermediate Development Scenario water requirements shown as a band of uncertainty (minimum and maximum values).

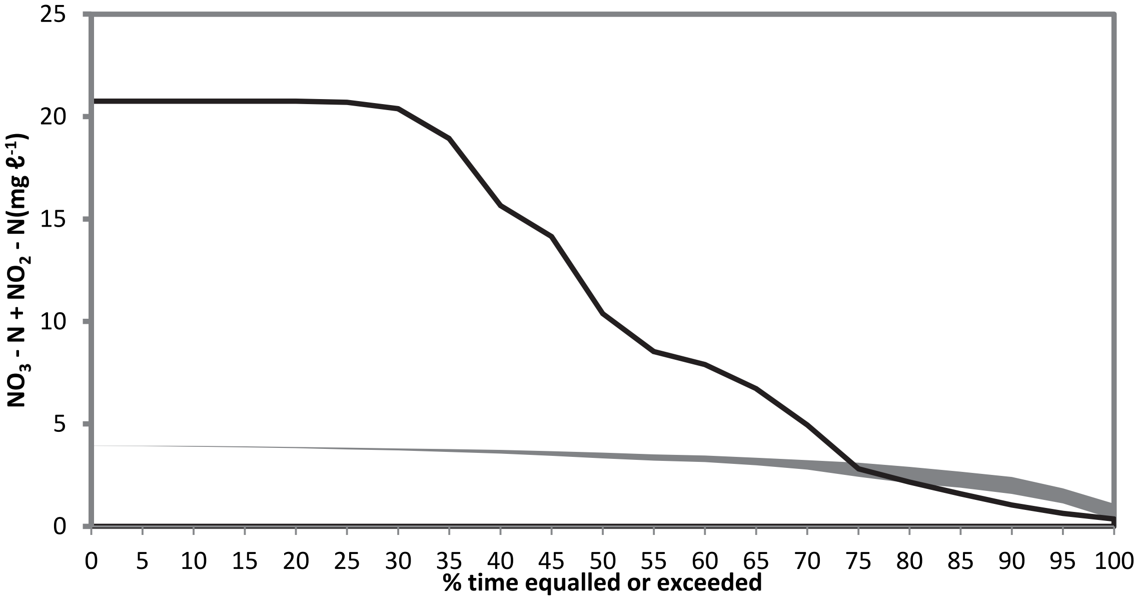


Figure 6.11 NO_3-N + NO_2-N duration curve for the Lower Yellowwoods River under present conditions (solid line; 1999-2005) and under near future climate scenarios (2046-65) with future Intermediate Development Scenario water requirements (grey band of uncertainty using minimum and maximum values).

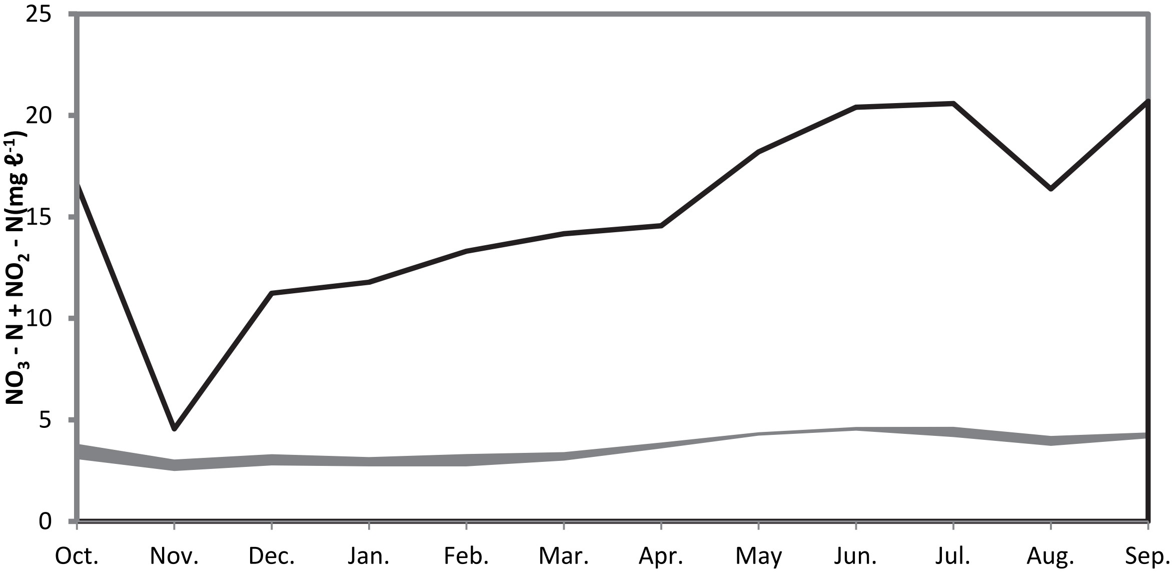


Figure 6.12 Monthly averaged simulated NO_3-N + NO_2-N for the Lower Yellowwoods River under present conditions (1999-2005; solid line) and under near future climate scenarios (2046-65) as well as the future Intermediate Development Scenario water requirements shown as a band of uncertainty (minimum and maximum values).

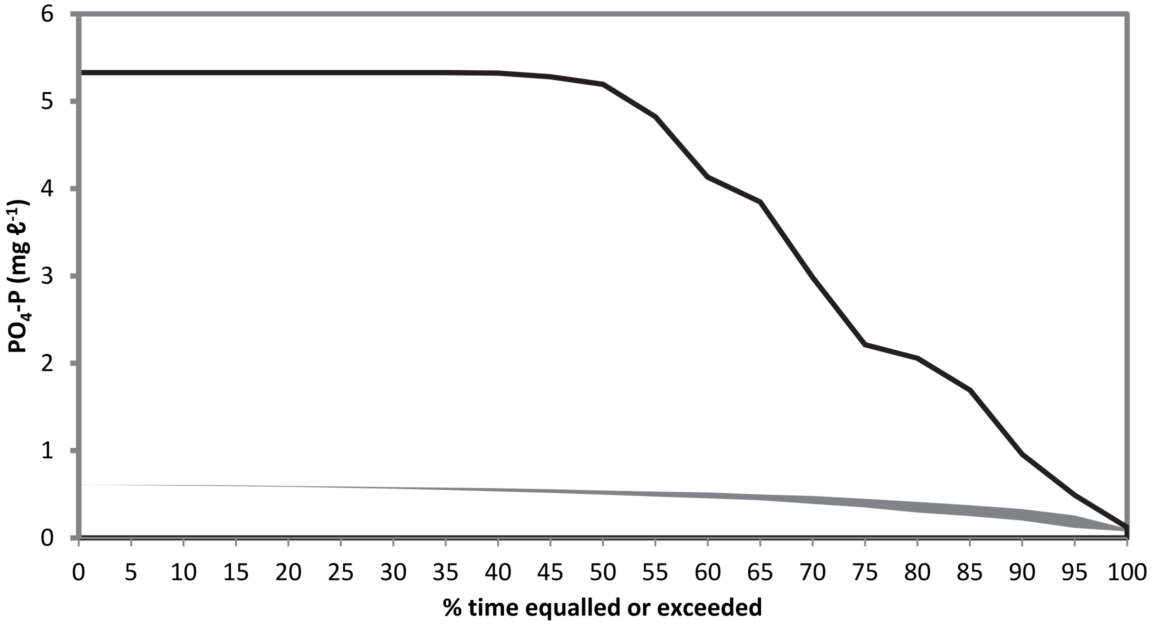


Figure 6.13 PO_4-P duration curve for the Lower Yellowwoods River under present conditions (solid line; 1999-2005) and under near future climate scenarios (2046-65) with future Intermediate Development Scenario water requirements (grey band of uncertainty using minimum and maximum values).

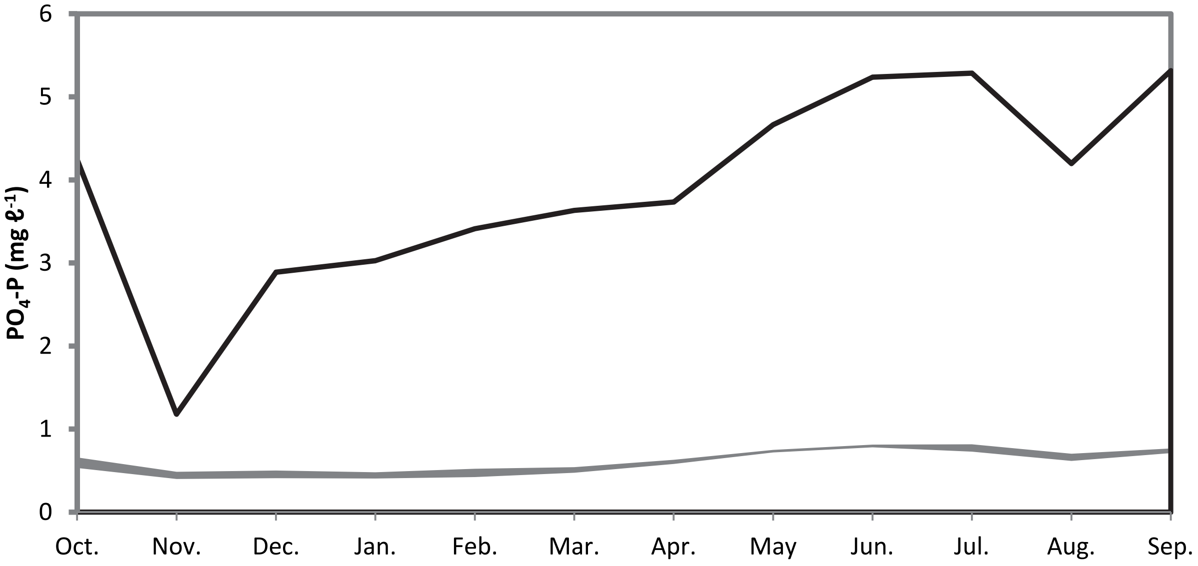


Figure 6.14 Monthly averaged simulated PO_4-P for the Lower Yellowwoods River under present conditions (1999-2005; solid line) and under near future climate scenarios (2046-65) as well as future Intermediate Development Scenario water requirements shown as a band of uncertainty (minimum and maximum values).

6.3.3 Updated WEAP water quality results: climate change scenarios under the Upper Development Scenario

As was shown for the previous section, nutrients in the Middle Buffalo River at R2H010 increase considerably compared to the Current Scenario (see Figure 6.15-6.18). Similar to results for climate change under the Intermediate Development Scenario, nutrients within the Yellowwoods River decrease dramatically compared to the Current Scenario (see Figure 6.19-6.22). Although there are minor increases in nutrient concentrations within the Middle Buffalo River under climate change under the Upper Development Scenario compared to climate change under the Intermediate Development Scenario, the differences are negligable.

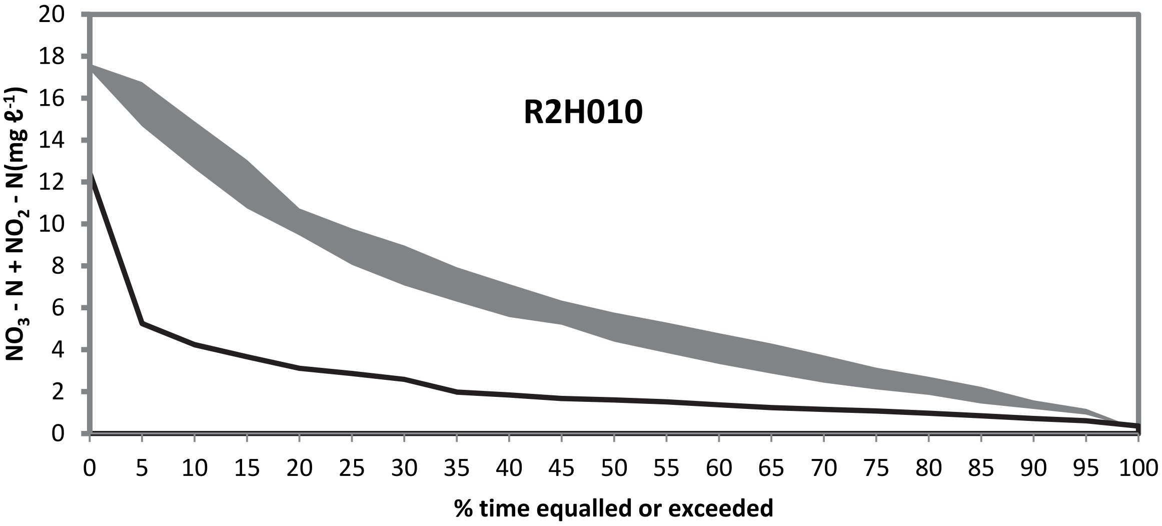


Figure 6.15 NO_3-N + NO_2-N duration curve for the Middle Buffalo River near R2H010 under present conditions (solid line; 1999-2005) and under near future climate scenarios (2046-65) with future Upper Development Scenario water requirements (grey band of uncertainty using minimum and maximum values).

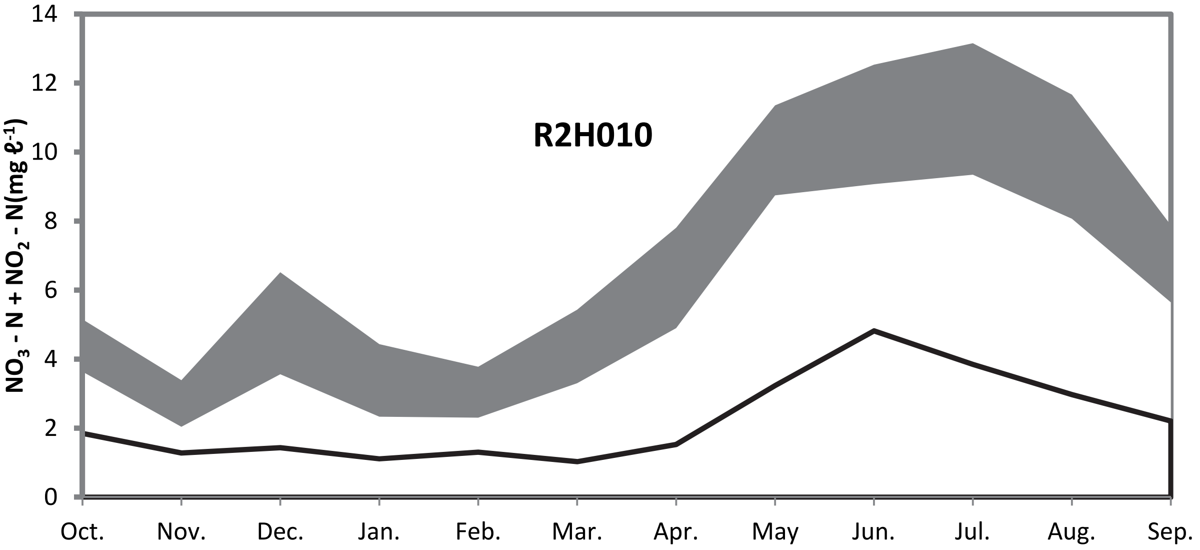


Figure 6.16 Monthly averaged simulated NO_3-N + NO_2-N for the Middle Buffalo River near R2H010 under present conditions (1999-2005; solid line) and under near future climate scenarios (2046-65) as well as future Upper Development Scenario water requirements shown as a band of uncertainty (minimum and maximum values).

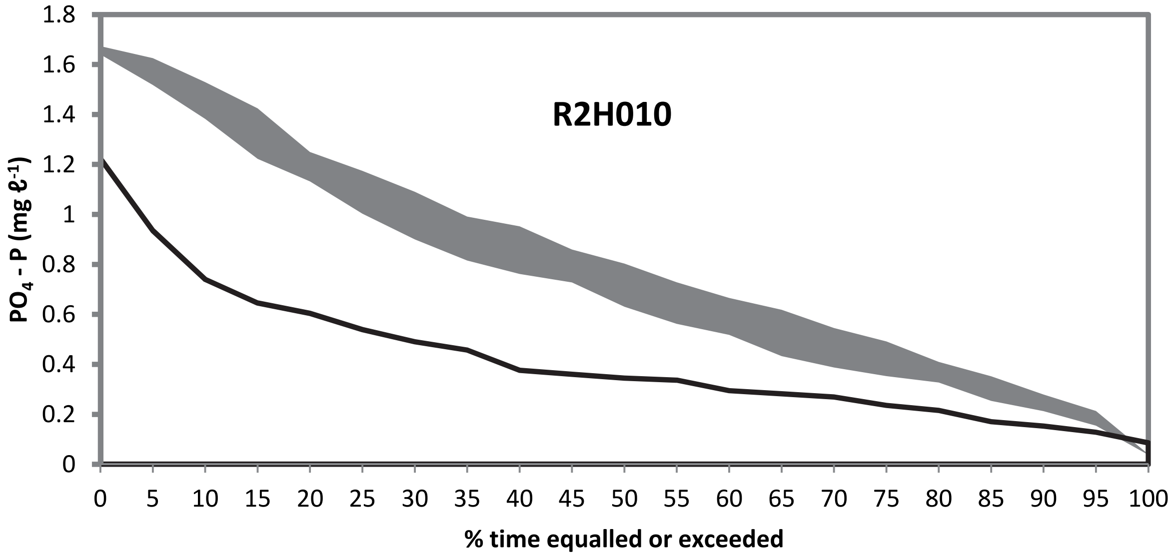


Figure 6.17 PO_4-P duration curve for the Middle Buffalo River near R2H010 under present conditions (solid line; 1999-2005) and under near future climate scenarios (2046-65) with future Upper Development Scenario water requirements (grey band of uncertainty using minimum and maximum values).

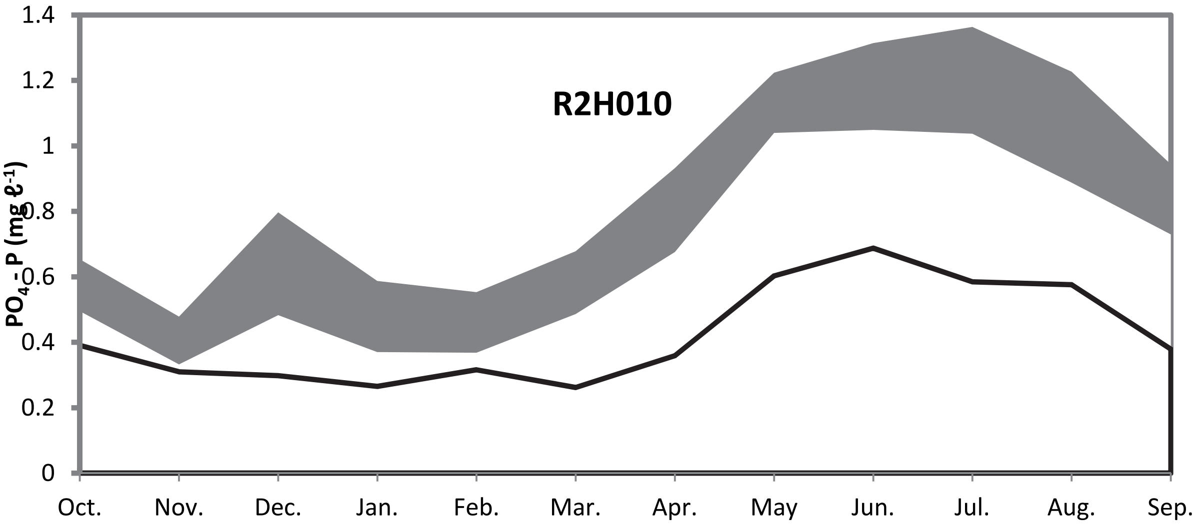


Figure 6.18 Monthly averaged simulated PO_4-P for the Middle Buffalo River near R2H010 under present conditions (1999-2005; solid line) and under near future climate scenarios (2046-65) as well as future Upper Development Scenario water requirements shown as a band of uncertainty (minimum and maximum values).

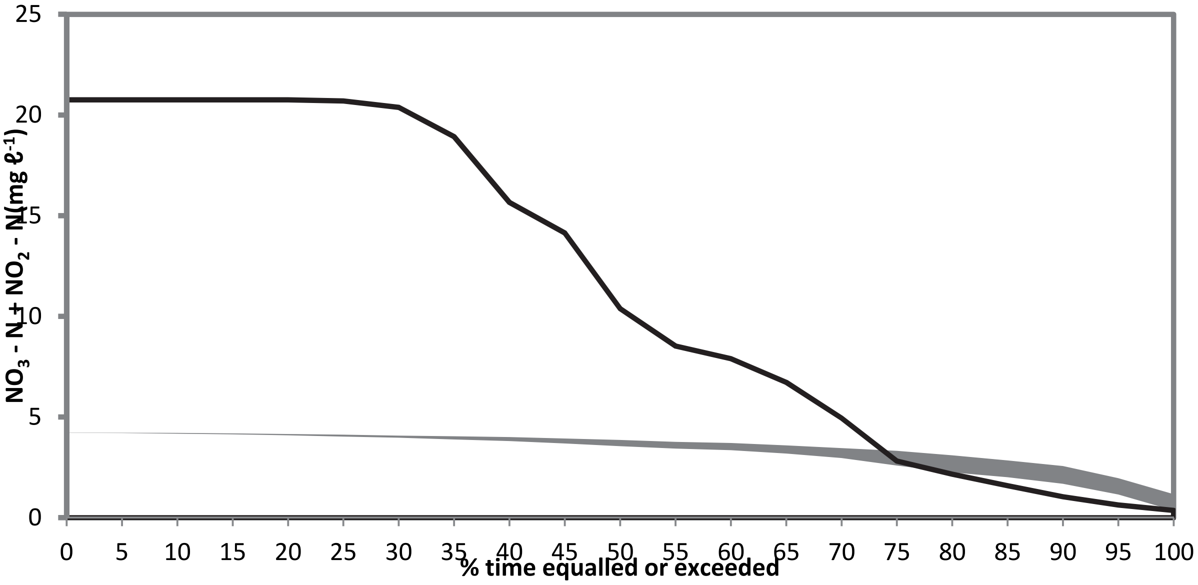


Figure 6.19 NO_3-N + NO_2-N duration curve for the lower Yellowwoods River under present conditions (solid line; 1999-2005) and under near future climate scenarios (2046-65) with future Upper Development Scenario water requirements (grey band of uncertainty using minimum and maximum values).

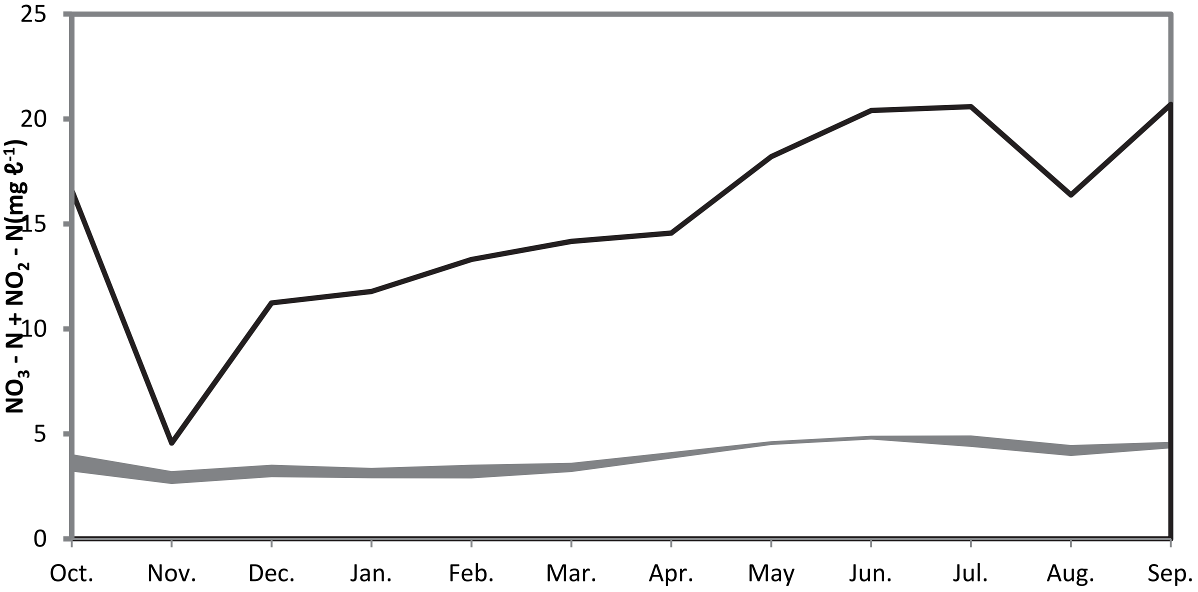


Figure 6.20 Monthly averaged simulated NO_3-N + NO_2-N for the lower Yellowwoods River under present conditions (1999-2005; solid line) and under near future climate scenarios (2046-65) as well as future Upper Development Scenario water requirements shown as a band of uncertainty (minimum and maximum values).

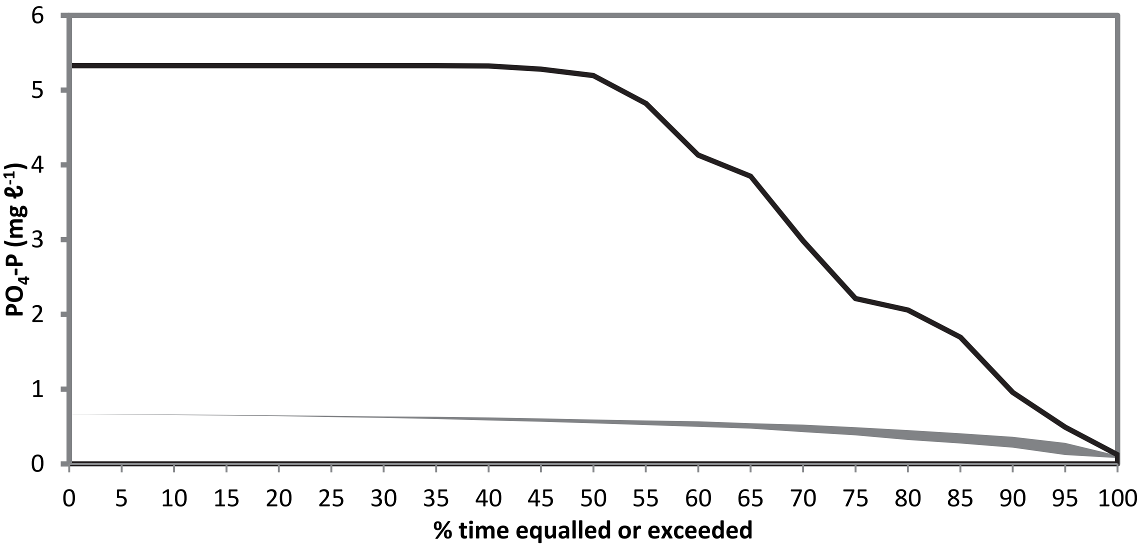


Figure 6.21 PO_4-P duration curve for the Lower Yellowwoods River under present conditions (solid line; 1999-2005) and under near future climate scenarios (2046-65) with future Upper Development Scenario water requirements (grey band of uncertainty using minimum and maximum values).

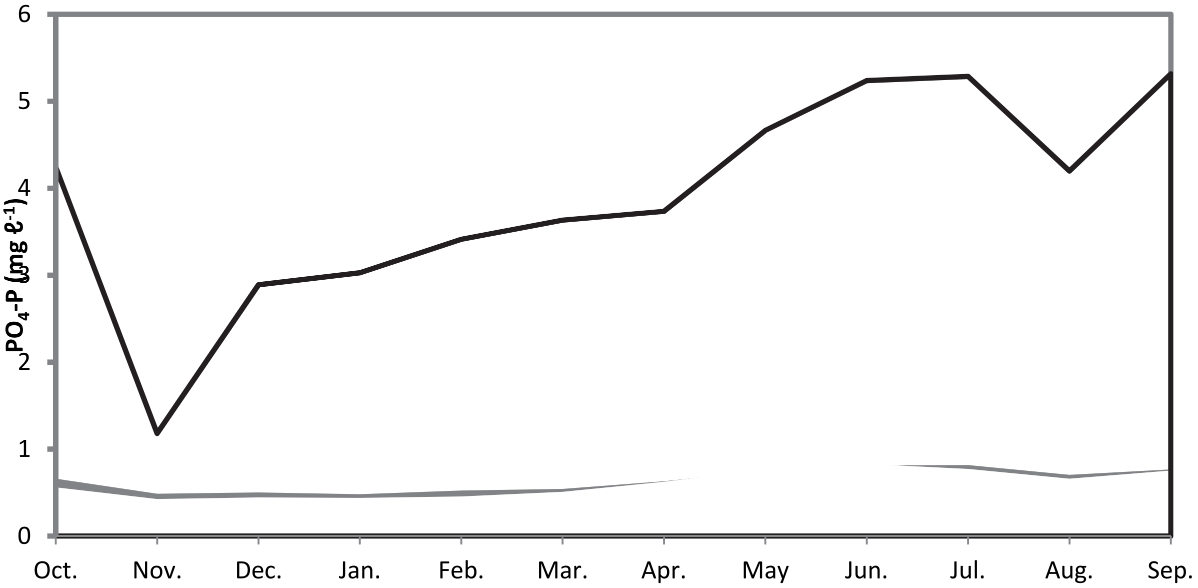


Figure 6.22 Monthly averaged simulated PO_4-P for the Middle Yellowwoods River under present conditions (1999-2005; solid line) and under near future climate scenarios (2046-65) as well as future Upper Development Scenario water requirements shown as a band of uncertainty (minimum and maximum values).

6.3.4 Discussion of updated WEAP water quality results for climate change scenarios under Intermediate and Upper Development

From the results of climate change and Intermediate and Upper Development shown in the previous two sections (6.3.2 and 6.3.3), it is evident that nutrients within the Middle Buffalo River between King Williams Town and Laing Dam increase dramatically compared to the Current Scenario. This is a contradiction to the expectation of moderate improvements to water quality within the Middle Buffalo due to the regionalisation of the Zwelitsha WWTW (BCM, 2011; DEDEA, 2011), although water quality within Laing Dam itself may improve because of the influence of relatively good quality water entering Laing Dam from the Yellowwoods River. However, there is a lot of uncertainty regarding the actual effluent volume and chemistry that will be released from the regionalised Zwelitsha WWTW in the future. BCM (2011) gives an approximation of expected influent water quality to the regionalised Zwelitsha WWTW. While it is confirmed that the University of Cape Town Biological Nutrient Removal process (UCTBNR) is likely to be adopted as the wastewater treatment technology within the regionalised Zwelitsha WWW, no information is given regarding the expected chemistry of the effluent released to the Middle Buffalo River. Sötemann et al. (2002) give an approximation of the treatment efficiencies for treating nutrients within effluents using the UCTBNR process, and this information was used to estimate the maximum effluent nutrient concentration originating from the regionalised Zwelitsha WWTW. However, the study by Sötemann et al. (2002) was performed on a laboratory scale, and information regarding the treatment priorities of the expected regionalised Zwelitsha WWTW is not available. While BCM (2011) and DEDEA (2011) confirm the expected capacity of the regionalised Zwelitsha WWTW, the temporal variability of actual effluent volume released from the WWTW in the future must be estimated by the WEAP model. Slaughter and Hughes (In Press) developed a simple mass-balance point source nutrient model that, given the minimum and maximum effluent flow and nutrient concentration from a point source, will estimate the in-stream nutrient concentrations immediately downstream of the point source (the model does not incorporate in-stream nutrient fate). The point source nutrient model was used to estimate the future temporal variability of effluent nutrient concentration originating from the Zwelitsha WWTW on a daily scale, and these data were averaged on a monthly scale and input into the WEAP model. The assumptions of random temporal variability of effluent concentration within the specified minimum and maximum effluent concentration introduce further uncertainty to the actual water quality implications of the regionalised Zwelitsha WWTW. It is however, certain that the increased release of effluent to the Middle Buffalo River between King Williams Town and Laing Dam under the proposed regionalisation of the Zwelitsha WWTW could have dramatic effects on the water quality of the Middle Buffalo River, and a priority of the proposed regionalised WWTW would be to implement sufficient wastewater treatment efficiencies.

Also evident from the results shown in the previous two sections, is the expected dramatic decrease in nutrient concentrations in the Yellowwoods River compared to the Current Scenario. Unlike the model simulations of water quality in the Middle Buffalo River between King Williams Town and Laing Dam, this change in water quality can be fairly certain, as under the proposed regionalisation of WWTWs, the two WWTWs releasing effluent to the Yellowwoods River (Breidbach and Bhisho WWTWs) are decomissioned, thereby eliminating two major point sources to the river. The periodic releases of water from the Wriggleswade Dam into the Yellowwoods River, will also result in improvements to water quality.

The model simulations of water quality to the Middle Buffalo River between King Williams Town and Laing Dam and the Lower Yellowwoods River for climate change under both the Intermediate Development and Upper Development scenarios, show only minor differences. This can be explained by the fact that under the Upper Development Scenario, water demand begins to outstrip supply, resulting in similar wastewater volumes being treated under the Upper Development Scenario compared to the Intermediate Development Scenario.

6.4 Results and discussion on the use of the model

The simulated range of EC for the Upper Buffalo River under climate change and the Intermediate Development Scenario shows no change to that of the simulated Current Development Scenario, while the seasonality of the simulations shows more uncertainty over the winter periods, when generally there is less flow, and salinity becomes more pronounced due to a lack of diluting capacity. There is some evidence of the range of salinity being slightly lower in the Middle Buffalo River for climate change and the Intermediate Development Scenario as compared to the Current Development Scenario. This could be due to a slightly greater dilution effect under the slightly greater flow predictions of the climate change models. The predictions of EC in the Lower Buffalo River for climate change and the Intermediate Development Scenario remain close to that of the Current Development Scenario, and show the same seasonal trend with very little uncertainty.

Unfortunately, it was not possible to assess the possible effects of climate change and the Intermediate Development Scenario on phosphate in the Upper Buffalo River, due to no success in calibrating the model for phosphate in the Upper Buffalo River. The simulations for the Middle Buffalo River show that a higher range of phosphate is expected, while the seasonal signature has the same trend but a higher range with some degree of uncertainty. It is likely that greater demand within the Middle Buffalo River under the Intermediate Development Scenario, leads to greater volumes of effluent from WWTWs being released, and therefore, greater loads of phosphate entering the Middle Buffalo River. There is some uncertainty regarding the expected effluent volume and nutrient concentration that will be released from the regionalised Zwelitsha WWTW. The simulations of phosphate under climate change and the Intermediate Development Scenario for the Lower Buffalo River show very little difference in range and seasonality, to that of the Current Development

Scenario. This however may be due to the shortcoming of WEAP not being capable of simulating water quality in reservoirs.

Within the Upper Buffalo River, the simulations of nitrate + nitrite under climate change and the Intermediate Development Scenario showed a very similar range to that of the Current Development Scenario, with very little uncertainty. The simulations of seasonality however, showed more uncertainty. Within the Middle Buffalo River, the climate change and Intermediate Development Scenario showed a dramatically increased range compared to the Current Development Scenario, while the seasonal simulations for climate change and Intermediate Development show the same temporal trend but a higher range compared to the Current Development Scenario. Again, it must be stressed that the lack of information regarding expected effluent volumes and nutrient concentration to be released from the regionalised Zwelitsha WWTW, results in a lot of uncertainty in these results. The simulations of nitrate + nitrite for the Lower Buffalo River for climate change and the Intermediate Development Scenario show a large range of uncertainty and generally higher concentrations of nitrate + nitrite as compared to that of the Current Development Scenario. This is due to the NO_3-N + NO_2-N signature given to flow coming into the river from R20F. The signature has a diffuse signature, which would alter final NO_3-N + NO_2-N concentrations under the different flow inputs given by the climate change scenarios.

Generally, it appears that climate change does not affect the range of concentrations of any of the water quality variables modelled. However, the nine climate change models assessed may be adding to the uncertainty of the seasonality of concentrations simulated. This is expected, as the climate change models investigated do not simulate flows that are drastically different from those produced from the Current Development Scenario. It appears that greater volumes of effluent released into the Middle Buffalo River due to greater demand under the Intermediate Development Scenario, lead to a higher concentration range of phosphate in the Middle Buffalo River compared to that in the Current Development Scenario.

Uncertainty within the climate change and development scenario water quality results has been restricted to that derived from the range of climate change models investigated. Ideally, more factors that contribute to uncertainty within the modelled water quality results should be considered, such as the uncertainty in the measured data used to calibrate the model, the uncertainty in the model structure, as well as the uncertainty in the monthly to daily patching technique. The comprehensive incorporation of uncertainty into the water quality modelling exercise would require a massive amount of research, and therefore, the further investigation of uncertainty has been left to future research.

CHAPTER 7. WATER QUALITY MODEL WQSAM

by

Andrew Slaughter

7.1 Overview of the Water Quality Systems Assessment Model (WQSAM)

The Pitman model is a monthly time step rainfall-runoff model, first developed in the 1970s (Pitman, 1973). The model conceptualises the natural water balance of river basins, and incorporates parameters to control these model processes (Hughes et al., 2010). The output of the Pitman model with revised surface-ground water routines (Hughes, 2004a) includes simulations of surface runoff depth, interflow runoff depth, ground water volume, upstream inflow volume, direct abstractions, pool volume, abstractions from dam volume, and downstream flow volume.

The yield model that was used in this study is called the Water Resources Modelling Platform (WReMP) (Mallory *et al*., 2011). WReMP accepts incremental flow from the study sub-catchments, typically generated by the Pitman model, and models the user extractions, return flows and reservoir yields along the modelled system. WReMP is very similar in structure and function to the Water Resources Yield Model (WRYM), and it is anticipated that any function that WReMP fulfils in this study could be equally provided by WRYM.

The WReMP/WRYM models and the Pitman model are similar in that they perform a water mass-balance. However, while the Pitman model simulates natural flow, the WReMP model adds another level of modelling by incorporating human demands. SPATSIM (Spatial and Time Series Information Model) (Hughes, 2004b) is a modelling platform from which the Pitman and other models can be run, includes a simple geographical representation of study catchments, and facilitates the storage of data such as observed and simulated data and model parameters. WQSAM has been developed in a way that allows the model to be run from within the SPATSIM modelling framework. The monthly inflow and outflow data, as well as reservoir storage data generated by WReMP for the various nodes are input into WQSAM. The nodal structure within WReMP is also replicated within WQSAM. For the subsequent descriptions of WQSAM, the reader may refer to Figure 7.1, which gives a conceptual representation of the model components. As can be seen from Figure 7.1, WQSAM consists of functionality at the lowest level (Figure 7.1a) to interface with output from the yield model (WReMP or WRYM), the loading of the network configuration used and the storage of various flow types, evaporation and storage to SPATSIM. The second level of WQSAM (Figure 7.1b) facilitates the disaggregation of monthly simulated incremental flow volumes to daily incremental flow, using observed rainfall data. The third level of WQSAM (Figure 7.1c) facilitates the separation of daily incremental flows to the flow components: surface water flow, interflow and groundwater flow. The next level (Figure 7.1d) facilitates water quality modelling, with the water quality variables planned for at this stage being salinity (TDS), nutrients (nitrite + nitrate, phosphates, ammonia), and sediment. A decision support system (DSS) will be incorporated as part of WQSAM to help guide management decisions. This would possibly include guidelines for collecting water quality data and notifications of extra monitoring required.

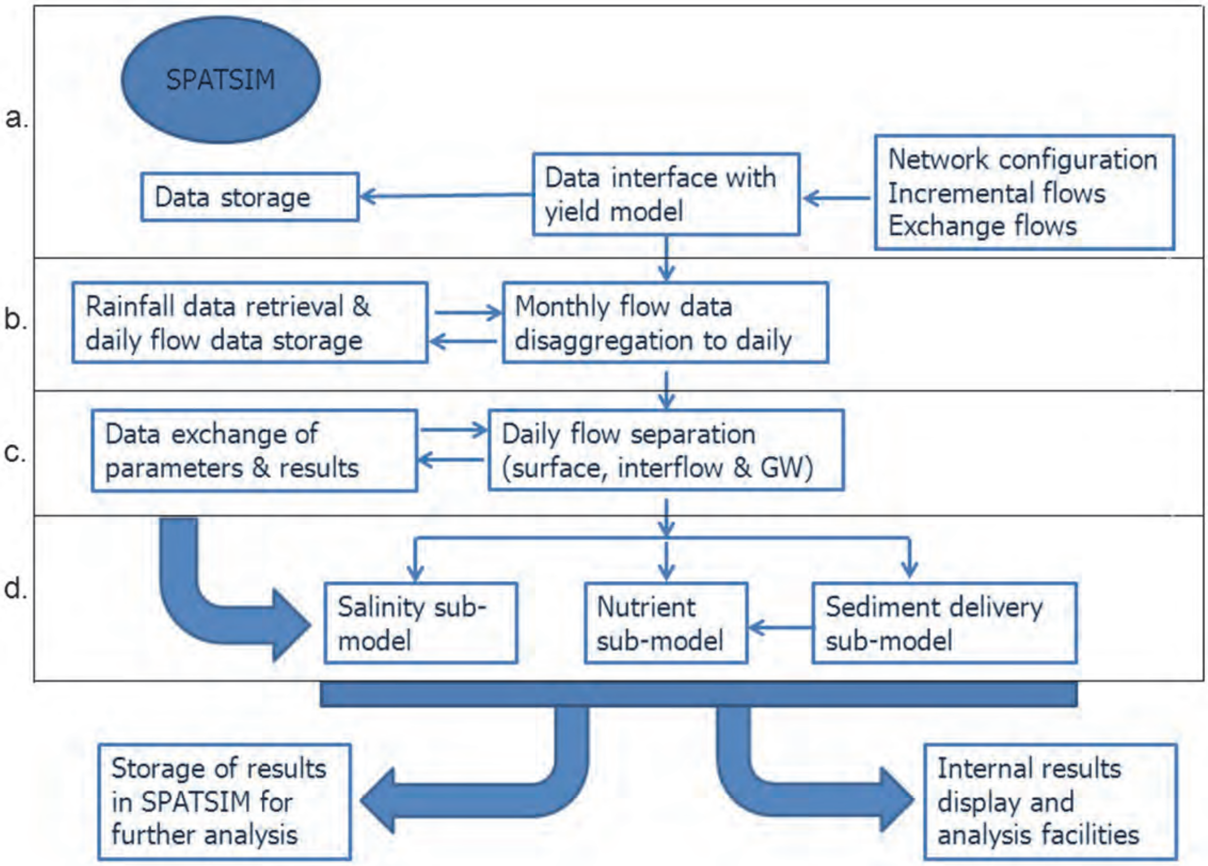


Figure 7.1 Conceptual representation of the model components in the Water Quality Systems Assessment Model: a) Input of WReMP output data and storage to the modelling framework Spatial Time Series and Information Modelling (SPATSIM) system, and replication of the nodal structure from the Water Resources Modelling Platform (WReMP) to the Water Quality Systems Assessment Model (WQSAM) and SPATSIM; b) Disaggregation of simulated monthly incremental flow to daily and storage to SPATSIM; c) Base flow separation of simulated daily incremental flow to the flow components surface water flow, interflow and ground water flow; d) Water modelling components for salinity, nutrient and sediment modelling.

7.2 Input of data from WReMP to WQSAM and SPATSIM

7.2.1 Documentation

There are two properties of WReMP that are required to be loaded into SPATSIM and WQSAM to facilitate water quality modelling: 1) the network structures of nodes and; 2) the nodal flow information. SPATSIM is used as a data storage platform, as well as a platform from which to launch WQSAM. Within SPATSIM, features are added corresponding to nodes used in WReMP, and each feature is given various time-series as well as array attributes that hold various forms of data: parameter data; WReMP output data; historical monitoring data and; WQSAM simulated water quality data. Table 7.1 lists all the required attributes of nodal features created in SPATSIM.

WReMP includes an interface to link nodes between WReMP and SPATSIM and to load the necessary output files from WReMP. The output data from WReMP are then saved to the respective attributes within SPATSIM. These data and the corresponding attributes are:

1. Nodal incremental flows: The monthly flow values (10^6 m^3) are obtained from the first column within the WReMP output file ‘inflows.out’, and are saved to the SPATSIM attribute ‘Monthly Flow Volume’ (attribute 5 in Table 7.1).
2. Nodal inflows: The other nine columns in the WReMP output file ‘inflows.out’ consist of monthly flows (10^6 m^3) from upstream nodes or return flows, and are saved to the SPATSIM ensemble attribute ‘Yield Model Exchange Flows-in’ (attribute 29 in Table 7.1).
3. Nodal outflows: These are monthly outflows (10^6 m^3) from nodes, specified in the WReMP output file ‘outflows.out’. These eight columns of flows are saved back to the SPATSIM ensemble attribute ‘Yield Model Exchange Flows - out’ (attribute 30 in Table 7.1).
4. Evaporation: Monthly evaporation values (10^6 m^3) for storage nodes are obtained from the WReMP output file ‘YldStats.out’, and are saved back to the SPATSIM attribute ‘Evaporation’ (attribute 2 in Table 7.1).
5. Monthly storage: Monthly storage (10^6 m^3) for reservoir nodes can be obtained from the WReMP output file ‘YldStats.out’, and is saved back to the SPATSIM attribute ‘Storage’ (attribute 18 in Table 7.1).
6. Stream flow reduction: Monthly stream flow reduction values (10^6 m^3) can be obtained from the WReMP output file ‘YldStats.out’. These values are subtracted from the incremental flows (attribute 5 in Table 7.1) and saved to the SPATSIM attribute ‘Monthly Stream Flow Reduction’ (attribute 6 in Table 7.1).
7. During the process of saving data, WQSAM reads through storage volumes for particular nodes, and if any monthly volumes show storage > 0, the program sets the ‘hasStorage’ attribute to ‘true’ for that node within the SPATSIM attribute number 28 (Table 7.1), which contains various parameters relating to water quantity (see Table 7.2).
8. During the process of saving data, WQSAM reads through incremental flows for nodes. If a node contains an incremental flow of > 0, the parameter ‘isIncrementalNode’ (see Table 7.2) within the SPATSIM attribute number 28 (Table 7.1), is set to ‘true’.
9. During the process of saving data, WQSAM reads through the last channel within the inflows, representing return flows. For any node showing return flows > 0, the parameter ‘isReturnFlowNode’ (Table 7.2) is set to ‘true’ within the SPATSIM attribute number 28 (Table 7.1)

Table 7.1 Description of nodal attributes used in SPATSIM to facilitate water quality modelling by WQSAM.

Attr.	Name	Type	Description
1	Downstream Node	Node Name	Link to node immediately downstream. This link is used by WQSAM when routing loads of water quality variables downstream.
2	Evaporation	Time Series	Time series of evaporation expressed as monthly volumes (10^6 m^3 $month^{-1}$) generated by the WReMP model.
3	Monthly FDC	Array	A flow duration representation of simulated monthly incremental flows to nodes. The duration curve is used in the process of disaggregating monthly incremental flows to daily.
4	Monthly Flow Rate	Time Series	The monthly average simulated incremental flow (m^3 sec^{-1}).
5	Monthly Flow Volume	Time Series	The simulated monthly incremental flow to nodes as a volume (10^6 m^3 $month^{-1}$). This flow is disaggregated to daily incremental flows.
6	Monthly Stream Flow Reduction	Time Series	The monthly simulated volume of incremental flows for the nodes that is intercepted by forestry and alien vegetation (10^6 m^3 $month^{-1}$).
7	Node Name	Node Name	Unique identifier for the node. Used by WQSAM to route water quality loads through the system.
8	Observed daily flow	Time Series	Any observed daily flow (m^3 sec^{-1}) at a node location. Used for comparison with simulated daily flow disaggregated from monthly incremental flow.
9	Observed daily flow FDC	Array	The flow duration representation of observed daily flow, used in the process of disaggregating monthly to daily flows.
10	Patch disaggregated flows	Time Series	The daily simulated flow generated by disaggregating monthly incremental flows to daily.
11	Patch FDC Scaling	Array	A table of conversion factors to convert a monthly flow duration representation to a daily flow duration representation. This is used in the process of disaggregating monthly to daily flows.
12	Patch Hist. P data 1	Time Series	A time series of historical daily observed rainfall for a particular node. This rainfall is used to drive the process of monthly to daily incremental flow disaggregation. In the case of investigating future scenarios, this attribute could hold daily simulated future rainfall.

Table 7.1 continued

Attr.	Name	Type	Description
13	Patch Hist.P data 2	Time Series	A time series of historical daily observed rainfall for a particular node. This rainfall is used to drive the process of monthly to daily incremental flow disaggregation. In the case of investigating future scenarios, this attribute could hold daily simulated future rainfall.
14	Patch Hist.P data 3	Time Series	A time series of historical daily observed rainfall for a particular node. This rainfall is used to drive the process of monthly to daily incremental flow disaggregation. In the case of investigating future scenarios, this attribute could hold daily simulated future rainfall.
15	Patch Params	Array	A series of parameters used within the process of disaggregating monthly incremental flows to daily.
16	Simulated Daily Ground Water	Time Series	The simulated daily incremental flows are further broken down into ground water, interflow and surface flow, using a base flow separation technique. This attribute holds the simulated ground water flow.
17	Simulated Daily Interflow	Time Series	The simulated daily incremental flows are further broken down into ground water, interflow and surface flow, using a base flow separation technique. This attribute holds the simulated interflow.
18	Storage	Time Series	The volume (10^6 m^3) held within nodes which are storage nodes (this can be reservoirs, as well as dummy dams). Each value represents the storage within a node at the beginning of a month.
19	T/S Observed Ammonia	Time Series	Daily observed ammonia for a particular node.
20	T/S Observed N	Time Series	Daily observed inorganic nitrates + nitrites for a particular node.
21	T/S Observed P	Time Series	Daily observed inorganic phosphates for a particular node.
22	T/S Observed TDS	Time Series	Daily observed TDS for a particular node.
23	T/S Simulated Ammonia	Time Series	Daily simulated ammonia for a particular node, as generated by WQSAM.

Table 7.1 continued

Attr.	Name	Type	Description
24	T/S Simulated N	Time Series	Daily simulated inorganic nitrates + nitrites for a particular node, as generated by WQSAM.
25	T/S Simulated P	Time Series	Daily simulated inorganic phosphates for a particular node, as generated by WQSAM.
26	T/S Simulated TDS	Time Series	Daily simulated TDS for a particular node, as generated by WQSAM.
27	WQDSS Quality Parameters	Array	Range of parameters used for water quality simulations within WQSAM
28	WQDSS Quantity Parameters	Array	Range of parameters within WQSAM that are used for base flow disaggregation, and other processes.
29	Yield Model Exchange Flows - in	Time Series	Ensemble of nine Time Series flow volumes (10^6 m^3 $month^{-1}$), generated by WReMP as inflows to a particular node.
30	Yield Model Exchange Flows - out	Time Series	Ensemble of eight Time Series flow volumes (10^6 m^3 $month^{-1}$), generated by WReMP as outflows from a particular node.

Table 7.2 Parameters within the SPATSIM attribute WQDSS Quantity Parameters

Parameter	Name	Description
1	Antecedent Precip. Factor	Adjusts rainfall for a particular day upward according to antecedent (previous) rainfall. Required because runoff increases over saturated ground.
2	Antecedent Precip. Threshold	Defines the rainfall threshold (mm) from which runoff will occur.
3	BF Parameter (Interflow)	Alpha parameter value used within base flow separation of interflow from total flow.
4	BF Parameter (GW)	Alpha parameter value used within base flow separation of ground water from interflow.
5	hasStorage	Set to ‘true’ if a node has storage
6	isIncrementalNode	Set to ‘true’ if a node receives incremental flow
7	isReturnFlowNode	Set to ‘true’ if a node receives return flow

7.2.2 User guide

The network structure of nodes within WReMP is re-created within WQSAM. To achieve this, the first step is to create spatial elements within SPATSIM, with each spatial element representing a node (see Figure 7.2). For each node feature within SPATSIM, there are various linked attributes that could hold model parameter data, observed and simulated water quality and flow data, and rainfall data. Table 7.1 gives an overview of the current attributes within SPATSIM that are associated with nodes.

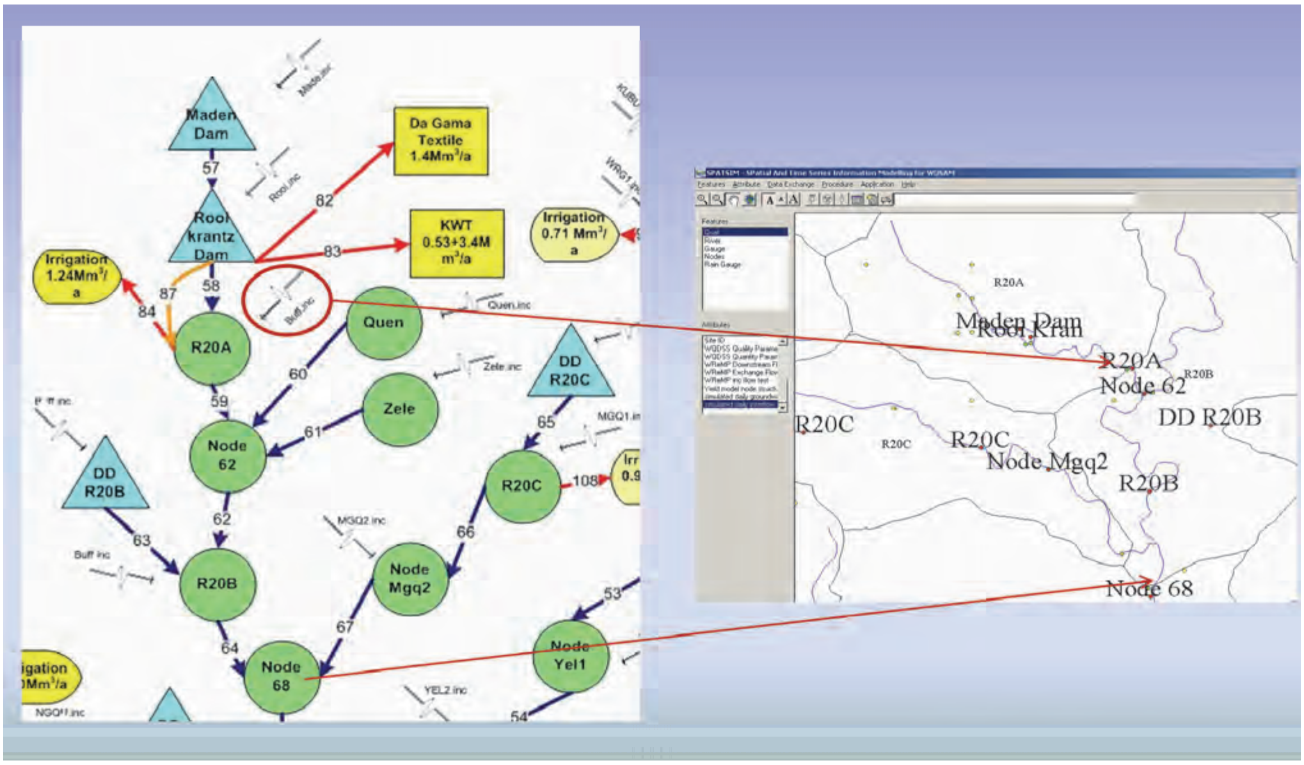


Figure 7.2 (a) A section of systems diagram for the WReMP setup of the Amatole system. (b) A screenshot of SPATSIM showing the nodal representation.

As the model develops further, this list of attributes is likely to change and expand. Once the nodes have been created within SPATSIM, and attributes have been linked to the nodes, WQSAM can be executed to load output data from WReMP. Figure 7.3 shows the frame within WQSAM that allows navigation between the different functions within the program. To link nodes between WReMP, WQSAM and SPATSIM and to import output data from WReMP:

1. The first button ‘Establish Node Structural Links’ on WQSAM’s navigational frame must be clicked on. The frame shown in Figure 7.4 then appears.
2. Within this frame, the file location of the WReMP output files are specified. These files are the ‘YldStats.out’ file, the ‘outflows.out’ file and the ‘inflows.out’ file. The file ‘inflows.out’ indicates the monthly flow volumes (10^6 m^3) to nodes, for a maximum total of ten inflow channels. The first channel within the ‘inflows.out’ file specifies the incremental flow to the node. The remaining channels (excluding the last) may be inputs from upstream nodes. The last channel specifies the return flow input. The file ‘outflows.out’ specifies the monthly flow volume (10^6 m^3) out of the nodes, for a maximum total of eight channels. The last channel specifies the monthly flow volume routed to the next node immediately downstream. Other outflows can be due to human use extraction, and extraction for irrigation. The file ‘YldStats.out’ specifies

forestry (alien vegetation) that intercepts a certain proportion of incremental flow. Once the relevant files are chosen, the button ‘Start process’ must be clicked, ensuring beforehand that the correct start year and month have been entered. Clicking the button will load the WReMP into dynamic memory, to be saved to SPATSIM later once nodal links are created. Once the loading is complete, the label on the ‘Start process’ button will change to ‘finished’.

3. Within this frame, a file called ‘nodes.txt’ is also input. This file is a section of the file used in WReMP called ‘Input.txt’ which contains a number of elements necessary to run WReMP. The section specifying the nodes for the system modelled is extracted from ‘Input.txt’ and placed into the ‘nodes.txt’ file. The essential information extracted from this file is the names of the nodes. The list of nodes used by WReMP is then listed in the list box on the right site of the frame. To open a ‘file open’ dialog box so as to choose the correct file, the button ‘WReMP Nodes’ must be clicked.
4. When the frame was opened, WQSAM read in the nodes set up in SPATSIM, and this list of nodes is displayed in the list box on the left side of the frame. Links between the list of nodes obtained from SPATSIM (left hand list in Figure 7.4) and the list of nodes obtained from WReMP (right hand list in Figure 7.4) can then be made. This is done by double-clicking on a node in the right hand list box, and a link between the clicked node from the WReMP input file, and the currently highlighted node in the left hand list box, representing the nodes in SPATSIM, is created.
5. Once the links between nodes are made, the button ‘load WReMP flow data to SPATSIM’ can be clicked, and WReMP output file data are saved back to SPATSIM. For a description of these data, see Section 7.2.1.

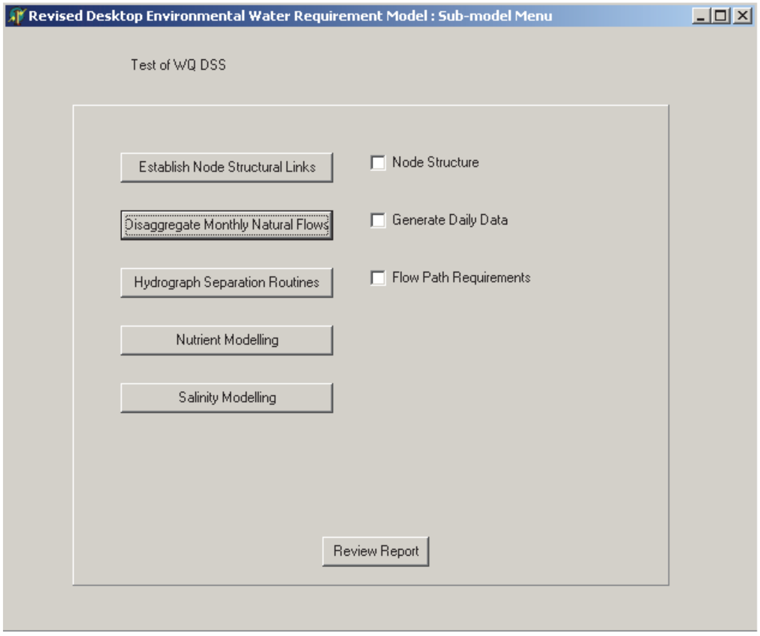
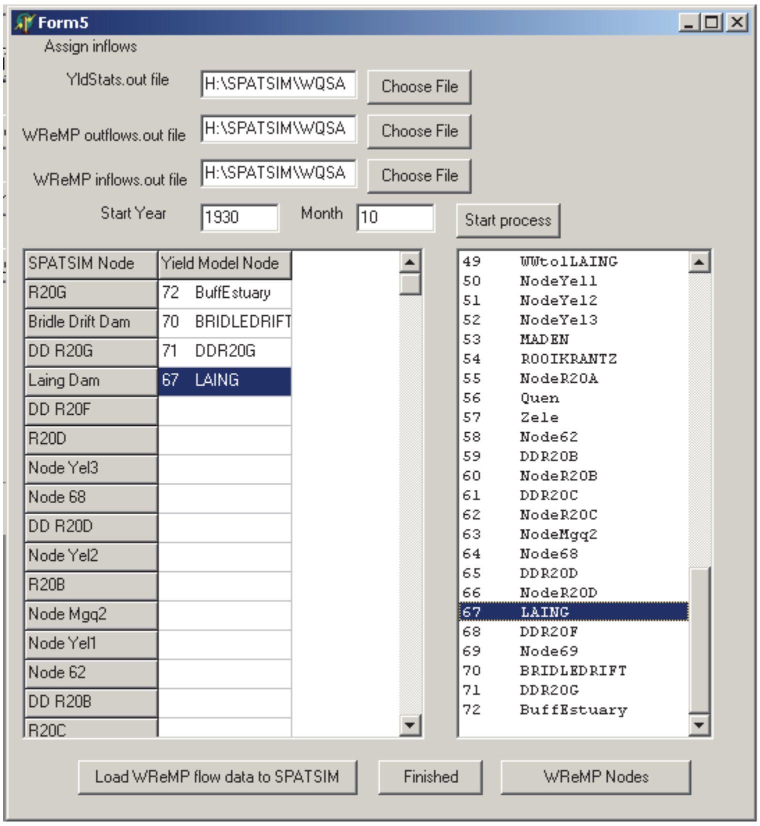


Figure 7.3 Screenshot of the navigational frame of WQSAM.



YldStats.out file: H:\SPATSIM\WQSA

WReMP outflows.out file: H:\SPATSIM\WQSA

WReMP inflows.out file: H:\SPATSIM\WQSA

Start Year: 1930 Month: 10

SPATSIM Node	Yield Model Node
R20G	72 BuffEstuary
Bridle Drift Dam	70 BRIDLEDRIFT
DD R20G	71 DDR20G
Laing Dam	67 LAING
DD R20F	
R20D	
Node Yel3	
Node 68	
DD R20D	
Node Yel2	
R20B	
Node Mgq2	
Node Yel1	
Node 62	
DD R20B	
R20C	

```
49      WWtolLAING
50      NodeYel1
51      NodeYel2
52      NodeYel3
53      MADEN
54      ROOIKRANTZ
55      NodeR20A
56      Quen
57      Zele
58      Node62
59      DDR20B
60      NodeR20B
61      DDR20C
62      NodeR20C
63      NodeMgq2
64      Node68
65      DDR20D
66      NodeR20D
67      LAING
68      DDR20F
69      Node69
70      BRIDLEDRIFT
71      DDR20G
72      BuffEstuary
```

Figure 7.4 Screenshot of the frame in WQSAM that facilitates input of data from WReMP to WQSAM and SPATSIM, and the re-creation of the nodal setup of WReMP within WQSAM and SPATSIM.

7.3 Monthly to daily disaggregation of incremental flows

7.3.1 Documentation

When first proposing the development of WQSAM, it was decided that water quality modelling should take place on a daily time step. This is because most water quality variables are affected by transient events such as rainfall, which cannot be accurately modelled on a monthly time scale. Since WReMP models water quantity within a system on a monthly time scale, some method of disaggregating monthly incremental flow to daily was needed. A process was developed using historical rainfall and the relationship between the duration curves of monthly and daily flow (represented as a table of conversion factors). The process is conceptually shown in Figure 7.5 and fits conceptually into WQSAM as shown in Figure 7.1b.

Within Figure 7.5, (A) a monthly flow duration curve (A2) is generated from the monthly simulated flow time series (A1). A1 would be monthly incremental flow volumes obtained from WReMP. Remember that flow reduction activity (FRA) volumes were subtracted from incremental flows. Incremental flows are read into WQSAM from SPATSIM attribute 5 (Table 7.1). The flow duration curve generated from monthly incremental flows is saved back to SPATSIM attribute number 3 (Table 7.1). A multiplication table is used to convert the monthly flow duration curve to a daily flow duration curve (A3), read in from SPATSIM attribute number 11 (Table 7.1). This multiplication table is generated for a particular system within SPATSIM (not WQSAM) by creating an observed daily flow duration curve, and observed monthly average flow duration curve, and the multiplication table is a table of conversion factors between the two duration curves (monthly to daily). In the second part of the process (B), a maximum number of three time series of daily rainfall is converted to ‘antecedent’ rainfall (B1). These rainfall data would be obtained from the SPATSIM attributes 12-14 (Table 7.1). The parameter used for converting to antecedent rainfall is obtained from SPATSIM attribute 28 (Table 7.1) and is parameter number 1 (see Table 7.2). Multiple time series of observed rainfall is used, as this gives a more realistic indication of rainfall within a particular area (there would most likely be spatial variation in rainfall). In addition, there may be missing data within a single rainfall time series, which would be ‘filled in’ by the other rainfall time series used. The daily antecedent rainfall duration table is produced which integrates all three rainfall time series (B2). WQSAM steps through the time series of antecedent rainfall (B1), finding the corresponding duration (percentage) for that rainfall (mm) on the daily antecedent rainfall duration curve (B2), finds the appropriate flow (m^3 sec^{-1}) for that duration (percentage) on the daily flow duration curve (A3) and produces a time series of daily simulated flow (AB1). Finally, daily flows are volume checked and corrected against the monthly simulated flows (A1).

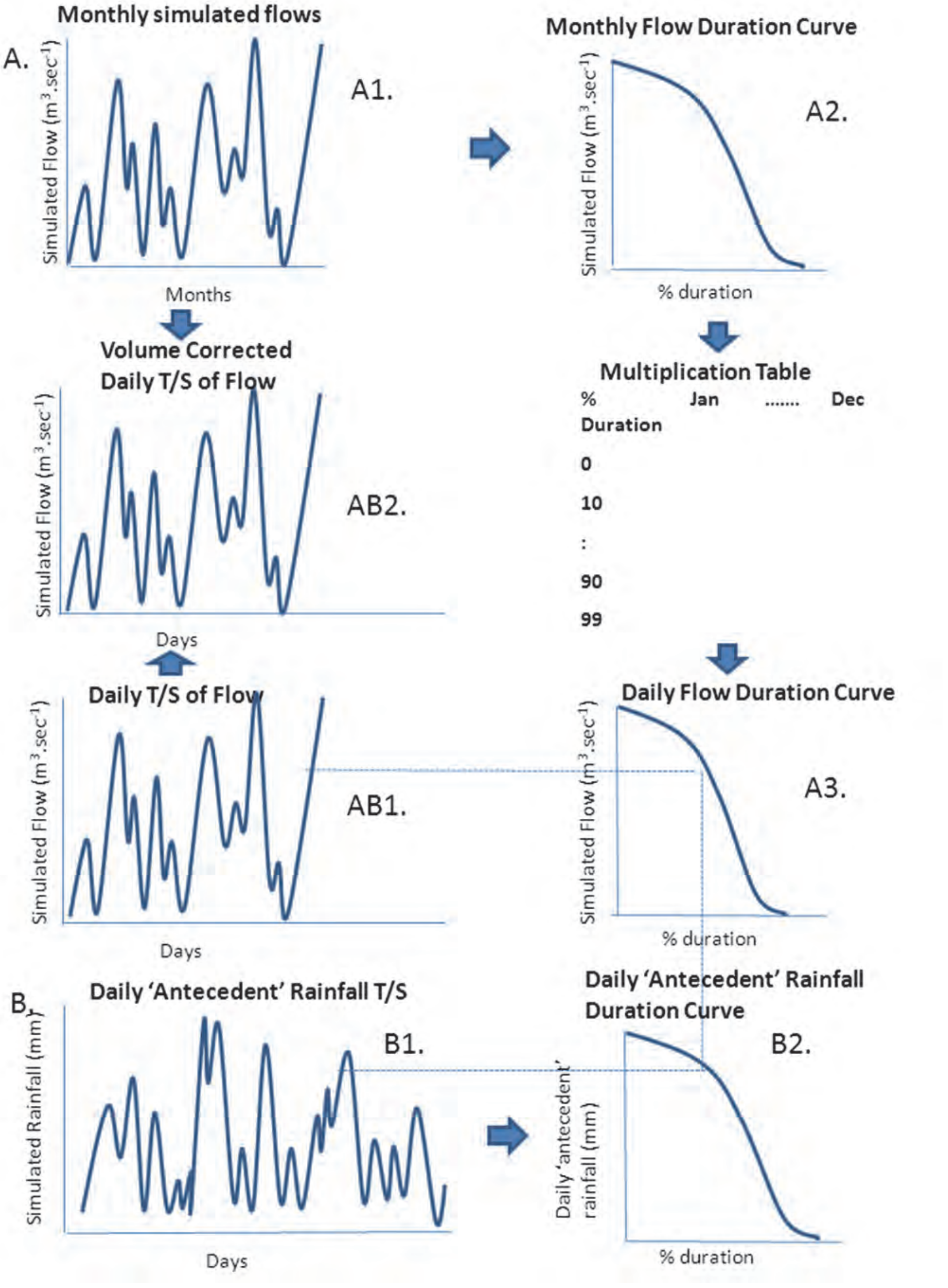


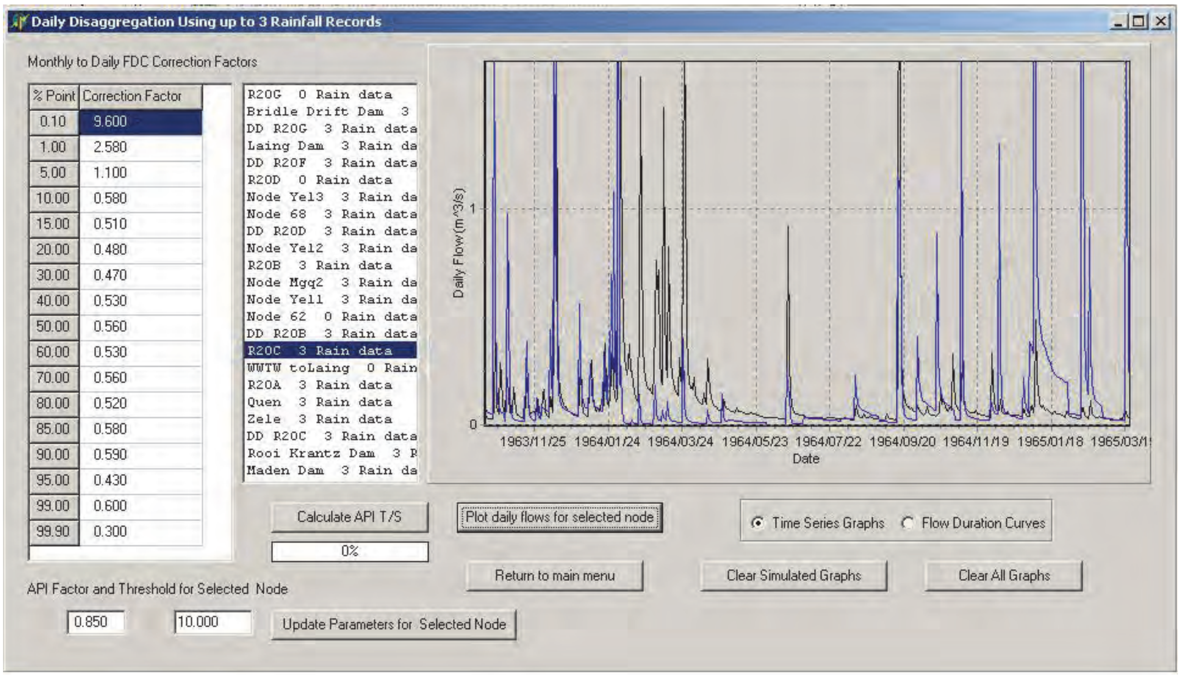
Figure 7.5 Conceptual diagram of the process of disaggregating monthly incremental flows to daily as used in the Water Quality Systems Assessment Model.

7.3.2 User guide

To facilitate monthly-daily incremental flow disaggregation, certain data and parameters must be available. Before the disaggregation process is started from WQSAM, the SPATSIM application must have certain data in place. These are:

1. Three time series of daily rainfall: These can be observed rainfall if historical conditions are being simulated, or future predicted rainfall if for example, climate change scenarios are being investigated. Within Table 7.1, these would be the attributes 12-14. Three time series of rainfall are required because rainfall within a region is spatially variable, and missing data within one time series can be ‘filled in’ by the other rainfall data.
2. A table of correction factors: These correction factors convert a monthly simulated flow duration curve to a daily simulated flow duration curve. For a particular region, this table can be generated by inputting daily observed flow data ($m^3 sec^{-1}$) into SPATSIM in a dedicated attribute (attribute 8 in Table 7.1). Using facilities in SPATSIM, a new time series of monthly average flow ($m^3 sec^{-1}$) can be created (attribute 4 in Table 7.1). A flow duration curve (FDC) for each flow (daily observed flow and monthly average flow) can be created by using the Procedure → TS summary facility in SPATSIM to create the attributes 9 and 3, respectively in Table 7.1. Outputting each of these FDCs to text files, will allow a table of conversion factors to be created (to convert monthly FDC values to daily). This table of conversion factors must be saved back as an FDC attribute in SPATSIM (attribute 11 in Table 7.1).
3. Edit the WQDSS Quantity Parameters attribute: This is attribute 28 in Table 7.1. See also Table 7.2 for more details of the parameters in this attribute. Here parameters for the three rainfall gauges can be edited. The Antecedent Precipitation Factor adjusts rainfall upwards according to previous rainfall, with a lower value indicating less of an effect of antecedent rainfall and would be appropriate for a catchment with low storativity. The Antecedent Precipitation Threshold can also be edited here, and defines the rainfall threshold from which runoff will occur.

The frame used to implement the process is shown in Figure 7.6. In this frame, the user can adjust the multiplication table (SPATSIM attribute 11 in Table 7.1), as well as the antecedent rainfall and threshold parameters saved back to SPATSIM attribute 28 (Table 7.1 and 7.2). The time series as well as duration curve of simulated flow can be compared to observed flow (if available) within this frame. This allows the user to adjust parameters in a calibration exercise to get a better fit between simulated and observed daily flows. Simulated daily incremental flows are saved back to SPATSIM attribute number 10 (Table 7.1).



Daily Disaggregation Using up to 3 Rainfall Records

Monthly to Daily FDC Correction Factors

% Point	Correction Factor
0.10	9.600
1.00	2.580
5.00	1.100
10.00	0.580
15.00	0.510
20.00	0.480
30.00	0.470
40.00	0.530
50.00	0.560
60.00	0.530
70.00	0.560
80.00	0.520
85.00	0.580
90.00	0.590
95.00	0.430
99.00	0.600
99.90	0.300

```
R20G  0 Rain data
Bridle Drift Dam  3
DD R20G  3 Rain data
Laing Dam  3 Rain da
DD R20F  3 Rain data
R20D  0 Rain data
Node Yel3  3 Rain da
Node 68  3 Rain data
DD R20D  3 Rain data
Node Yel2  3 Rain da
R20B  3 Rain data
Node Mgq2  3 Rain da
Node Yel1  3 Rain da
Node 62  0 Rain data
DD R20B  3 Rain data
R20C  3 Rain data
WWTW toLaing  0 Rain
R20A  3 Rain data
Quen  3 Rain data
Zele  3 Rain data
DD R20C  3 Rain data
Rooi Krantz Dam  3 R
Maden Dam  3 Rain da
```

API Factor and Threshold for Selected Node

0.850 10.000

● Time Series Graphs ○ Flow Duration Curves

Figure 7.6 Screenshot of frame in WQSAM used to disaggregate monthly incremental flows to daily.

7.4 Base flow separation of daily incremental flows

7.4.1 Documentation

The motivation behind this process in regards to water quality modelling within WQSAM is that each flow component can be assigned a water quality signature. For example, ground water is likely to have a different TDS signature to interflow and surface flow, depending on the geology in the study catchment modelled. In addition, surface flow may have a different nutrient signature to interflow and ground water flow, depending on land-use in a study catchment. Within this process, daily simulated incremental flows (SPATSIM attribute number 10, see Table 7.1) are read in. For each node, two parameters, namely the alpha parameter for interflow and the alpha parameter for base flow, are read in from SPATSIM attribute number 28 (Table 7.1). The base flow separation technique is taken from Hughes *et al*. (2003), using the formulas:

$$(\text{Interflow} + \text{Base\_flow})_i = (\text{Alpha}_{SF} \times \text{Surface\_Flow}_{i-1})$$

$$+ ((\text{Beta} * (1 + \text{Alpha}_{SF})) \times (\text{Total\_Flow}_i - \text{Total\_Flow}_{i-1})) \qquad \text{Equation 1}$$

$$\text{Surface\_Flow}_i = \text{Total\_Flow}_i - (\text{Interflow} + \text{Base\_flow})_i \qquad \text{Equation 2}$$

$$\text{Base\_flow}_i = (\text{Alpha}_{BF} \times \text{Interflow}_{i-1}) + ((\text{Beta} * (1 + \text{Alpha}_{BF}))$$

$$\times ((\text{Interflow} + \text{Base\_flow})_i - (\text{Interflow} + \text{Base\_flow})_{i-1})) \qquad \text{Equation 3}$$

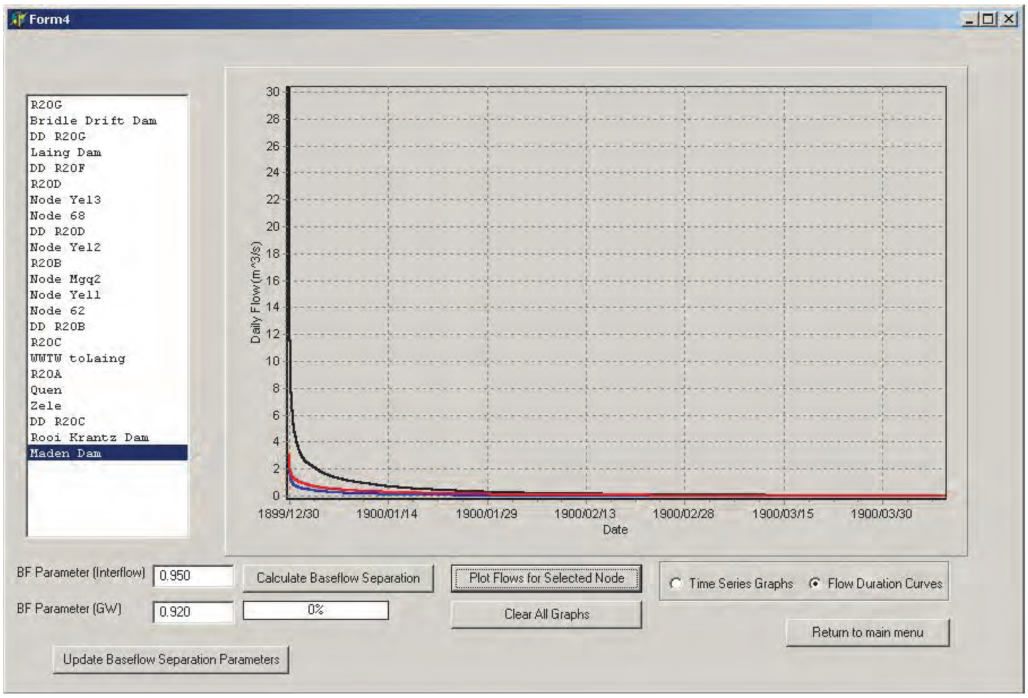
$$\text{Interflow}_i = (\text{Interflow} + \text{Base\_flow})_i - \text{Base\_flow}_i \qquad \text{Equation 4}$$

The Alpha_{SF} and Alpha_{BF} parameter values are obtained from SPATSIM attribute 28 (Tables 7.1 and 7.2), and are adjustable for particular nodes within WQSAM (see Figure 7.7). The Beta parameter in this case takes a constant value of 0.5, as recommended by Hughes *et al*. (2003) for base flow separation of daily flow data. The daily groundwater and interflow data are saved back to the SPATSIM attributes values 16 and 17, respectively (Table 7.1). The daily surface flow can be calculated from subtracting groundwater +

interflow from total flow (incremental flow), and was therefore not saved within the SPATSIM database.

7.4.2 User guide

The separation of daily incremental flows into groundwater, interflow and surface water flow components is implemented within WQSAM (Figures 7.1c and 7.7).



R20G
Bridle Drift Dam
DD R20G
Laing Dam
DD R20F
R20D
Node Yel3
Node 68
DD R20D
Node Yel2
R20B
Node Mgq2
Node Yel1
Node 62
DD R20B
R20C
WWTW toLaing
R20A
Quen
Zele
DD R20C
Rooi Krantz Dam
Maden Dam

BF Parameter (Interflow) 0.950
BF Parameter (GW) 0.920
0%
○ Time Series Graphs ● Flow Duration Curves

Figure 7.7 The base flow separation frame within WQSAM. The black line in the duration curve represents total flow, the red line represents interflow, and the blue line represents ground water flow.

The WQSAM frame (Figure 7.7) is used to derive surface water flow, interflow and groundwater flow from incremental flow and allows the plotting of the flows as a time series or duration curve, and alpha parameters can be adjusted as a calibration exercise.

7.5 Simple mass-balance water quality modelling

Conceptually, water quality modelling fits into the WQSAM construction as can be seen in Figure 7.1d. At this stage in the development of WQSAM, very simple water quality modelling has been implemented, by assigning water quality signatures to the flow components surface flow, interflow and groundwater flow. In addition, flow signatures have been assigned to return flows. This is likely to allow the simulation of the conservative water quality variable Total Dissolved Solids (TDS) to a certain degree, but will not be sufficiently accurate for non-conservative variables such as nutrients. Future advancements to WQSAM will include the simulation of in-stream effects, uptake of nutrients by flora and reservoir modelling. It is important to emphasise that WQSAM models water quality as water quality variable loads that are routed through the system. Concentration values for water quality variables can be calculated by using the flow volume at a particular node for a particular day.

Within the mass-balance modelling of water quality variables, the process of monthly to daily flow disaggregation introduced a number of complications. Firstly, WReMP simulates releases of water from storage nodes (reservoirs and dummy dams) on a monthly time scale. Since WQSAM works on a daily time scale, the evident solution to this discrepancy would be to evenly divide the monthly storage releases across the number of days in the month. However, because rainfall is not evenly spread across the month, storages within a storage node will change within the WQSAM simulation due to varying incremental flows, and the option of an even spread of storage releases across the month can lead to negative storage in some nodes, especially nodes with little total storage capacity, such as the Rooikrantz Dam in this case.

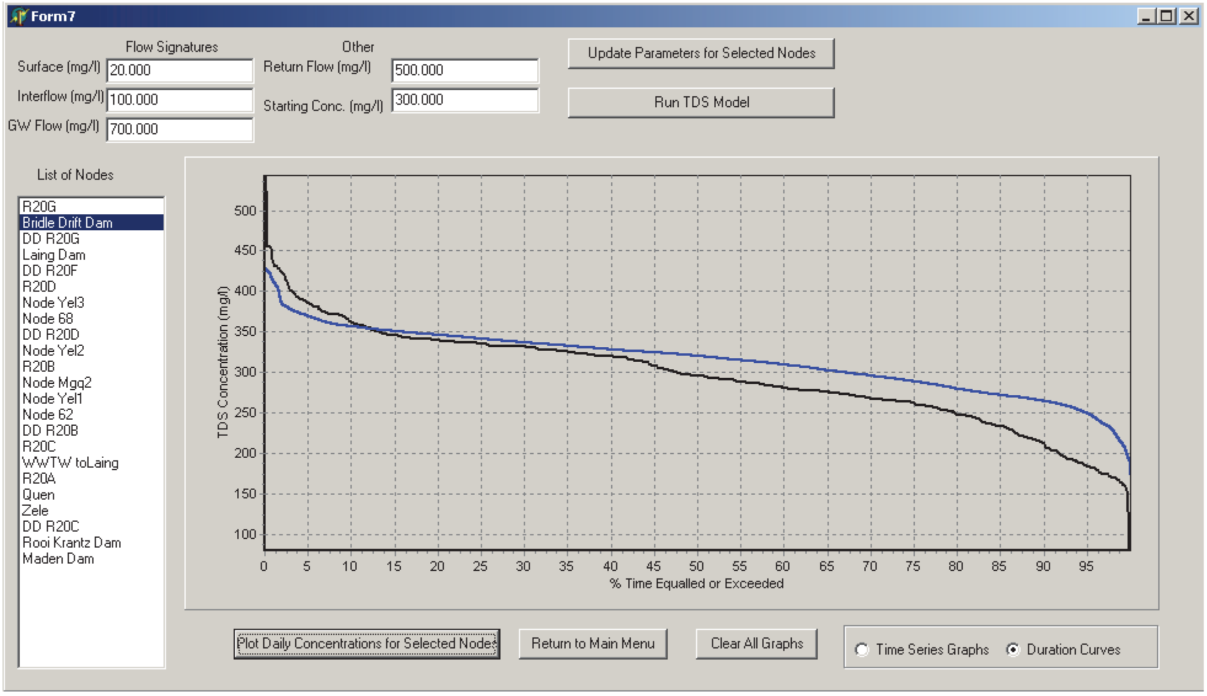
The second complication caused by the move to a daily time step occurs within nodes where there is run-of-river abstraction (mostly for irrigation). The abstraction volumes within WReMP are simulated on a monthly time scale, and an even disaggregation of an abstraction volume for a particular month across all the days could lead to more flow being taken from the river than is available, as incremental flows are spread unevenly across the month.

Both the aforementioned problems required a similar solution: that of a process that searches though the entire months incremental flows beforehand at a daily scale, and calculates storage releases or run-of-river abstractions according to the flow or storage available, but ultimately ensures that there is no storage release or abstraction deficit at the end of the month. The method used here should take note of limits to run-of-river abstraction (pumping limits) and limits to releases from dams. These limits would be specific to particular catchments and the method implemented here has been developed to take these limits into account, should they be specified.

While a certain amount of basic water quality simulation functionality has been developed into WQSAM at this stage, the model is not at a sufficiently developed stage or stable enough to be released for water quality simulation. Therefore, the following descriptions serve as documentation of the methods employed, and not as a user’s guide.

7.5.1 TDS modelling

At this stage, simple mass-balance TDS modelling has been implemented (see Figure 7.8). It was decided to implement TDS and nutrient modelling on two different frames, as the modelling of nutrients is likely to be much more complicated than that of TDS, and will have to allow for the adjustment of many more parameters. Within the TDS modelling frame, the user can adjust the TDS signatures for the three flow components: surface flow, interflow and groundwater flow. The user can also adjust the signature for return flow, especially important for modelling TDS within the reservoirs, where return flow occurs in this case (Amatole system). Important to the modelling process within storage nodes is the ‘Starting Concentration’ parameter, as one can expect a TDS load within reservoirs from the start of the water quality simulation period. The water quality signatures are saved back to SPATSIM attribute 27 (see Tables 7.1 and 7.3). Simulated TDS is saved back to the SPATSIM attribute 26 (Table 7.1). Within the TDS modelling frame in WQSAM, one can view simulated TDS and observed TDS (if available) as a time series or duration curve graph. A calibration exercise can be performed by adjusting parameters to get a better fit between simulated and observed data.



Surface (mg/l) 20.000
Interflow (mg/l) 100.000
GW Flow (mg/l) 700.000
Return Flow (mg/l) 500.000
Starting Conc. (mg/l) 300.000

Figure 7.8 Screenshot of the frame used to simulate TDS within WQSAM Support System.

The model loops though the days in a simulation period, from the upper-most node to the node furthest downstream, routing TDS load downstream. Loads of TDS in and out of the system are determined by the signatures of the flow components of incremental flows (surface flow, interflow and groundwater flow), return flows and starting concentrations of storage nodes. Appropriate load amounts are taken out of the system during abstractions for human use and irrigation. Within the modelling, daily dam releases, abstractions and evaporation balanced against daily incremental flow inputs and return flows, are reconciled with storage values for the beginning of the next month, as calculated by WReMP.

Although reservoir modelling as well as irrigation return flow still needs to be implemented for TDS modelling, the simple mass-balance modelling using flow component signatures as the model currently stands, produced a good TDS simulation when compared to existing data. This is even the case for reservoirs, where one can expect some stratification effects. The preliminary results of TDS modelling are shown in Figure 7.9.

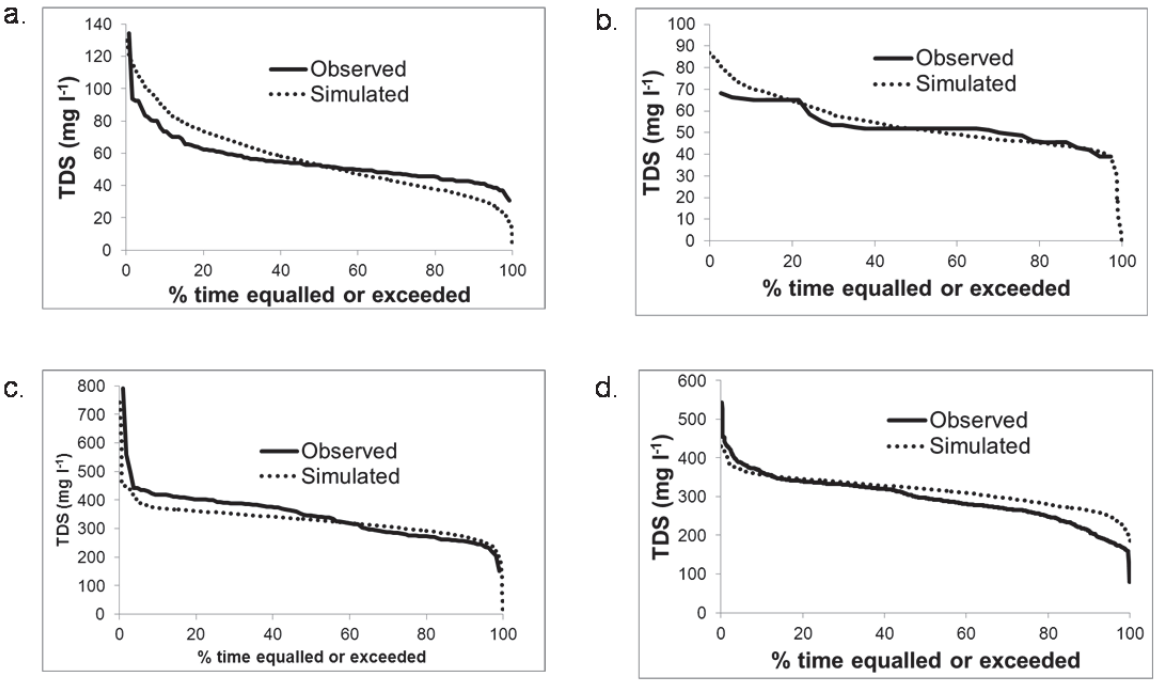
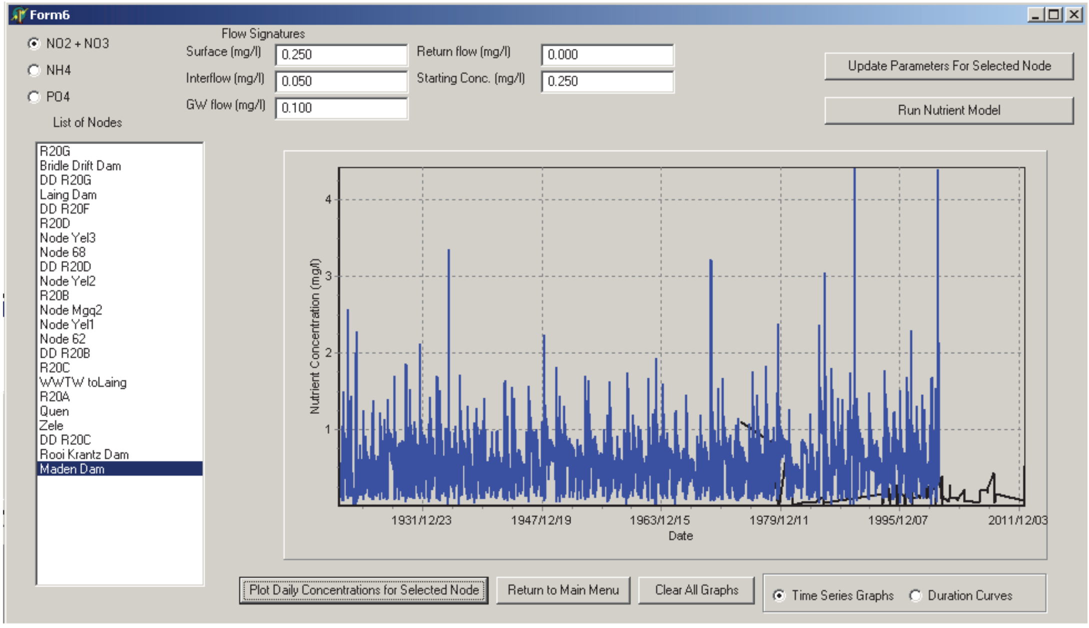


Figure 7.9 Preliminary simulated TDS results for the Buffalo River as simulated by the Water Quality Systems Assessment Model: a) Maden Dam; b) Rooikrantz Dam; c) Laing Dam; d) Bridle Drift Dam

7.5.2 Nutrient modelling

At this stage of model development, facilities are in place for simple mass-balance nutrient modelling (see Figure 7.10). The simulation of nutrients will not be accurate until some simulation of in-stream fate, uptake by flora and reservoir modelling is implemented. The nutrients modelled at this stage are nitrites + nitrates, ammonium and inorganic phosphates. As with TDS, signatures are given to the flow components (surface, interflow and groundwater flow), as well as return flow. The frame depicted in Figure 7.10 will also have to facilitate the updating of rate parameters controlling chemical speciation, sedimentation and uptake by flora. Water quality parameters are saved to the SPATSIM attribute number 27 (Tables 7.1 and 7.3). Within WQSAM, the nutrient modelling frame allows the facilities to view simulated nutrients (as a time series or duration curve) in comparison to observed data (if available), and parameters can be adjusted as a calibration exercise.



● NO2 + NO3
○ NH4
○ PO4

Flow Signatures
Surface (mg/l) 0.250
Interflow (mg/l) 0.050
GW flow (mg/l) 0.100
Return flow (mg/l) 0.000
Starting Conc. (mg/l) 0.250

List of Nodes
- R20G
- Bridle Drift Dam
- DD R20G
- Laing Dam
- DD R20F
- R20D
- Node Yel3
- Node 68
- DD R20D
- Node Yel2
- R20B
- Node Mgq2
- Node Yel1
- Node 62
- DD R20B
- R20C
- WWTW toLaing
- R20A
- Quen
- Zele
- DD R20C
- Rooi Krantz Dam
- Maden Dam

● Time Series Graphs ○ Duration Curves

Figure 7.10 Screenshot of frame used for nutrient modelling within the Water Quality Systems Assessment Model.

Table 7.3 Parameters within the SPATSIM attribute WQDSS Quality Parameters

Number	Name
1	TDS Surface Water Conc. (mg ℓ^{-1})
2	TDS Interflow Water Conc. (mg ℓ^{-1})
3	TDS Ground Water Conc. (mg ℓ^{-1})
4	PO_4 Surface Water Conc. (mg ℓ^{-1})
5	PO_4 Interflow Water Conc. (mg ℓ^{-1})
6	PO_4 Ground Water Conc. (mg ℓ^{-1})
7	NO_2 + NO_3 Surface Water Conc. (mg ℓ^{-1})
8	NO_2 + NO_3 Interflow Water Conc. (mg ℓ^{-1})
9	NO_2 + NO_3 Ground Water Conc. (mg ℓ^{-1})
10	NH_4 Surface Water Conc. (mg ℓ^{-1})
11	NH_4 Interflow Water Conc. (mg ℓ^{-1})
12	NH_4 Ground Water Conc. (mg ℓ^{-1})
13	TDS Return Flow Conc. (mg ℓ^{-1})
14	PO_4 Return Flow Conc. (mg ℓ^{-1})
15	NO_2 + NO_3 Return Flow Conc. (mg ℓ^{-1})
16	NH_4 Return Flow Conc. (mg ℓ^{-1})
17	TDS Starting Conc. (mg ℓ^{-1})
18	PO_4 Starting Conc. (mg ℓ^{-1})
19	NO_2 + NO_3 Starting Conc. (mg ℓ^{-1})
20	NH_4 Starting Conc. (mg ℓ^{-1})

CHAPTER 8. CURRENT MONITORING NETWORK

by

Sukhmani Mantel and Andrew Slaughter

Monitoring of systems can inform the importance of system parameters and change in their values over time, in addition to providing feedback into adaptive management and decision-making. Monitoring systems are, however, not necessarily stationary and they themselves need to be adapted, according to Lindenmayer et al. (2011), instead of being *ad hoc* monitoring systems. The authors define this approach as "*a monitoring program in which the development of conceptual models, question setting, experimental design, data collection, data analysis, and data interpretation are linked as iterative steps."* They further add that: *"An adaptive monitoring program is one that can evolve in response to new questions, new information, situations or conditions, or the development of new protocols but this must not distort or breach the integrity of the data record*." Such an approach could include change in the frequency of data collection depending upon unexpected rates of changes in key system variables, and arrival of new technology. Changing the monitoring methodology or process, however, should be done with caution and after consideration of reasons for the change, such as new research questions that require additional data. ***For the present case study where management and planning needs to be conducted under conditions of present uncertainty, in addition to increased uncertainty in the future, it is imperative to have a rigorous monitoring program in place as early as possible in order to reduce the uncertainty in data and predictions.***

8.1 Present water quantity and quality monitoring system in the Amatole area

Table 8.1a and Figure 8.1 present information on the stream flow gauging stations that are being monitored by the Department of Water Affairs (DWA) for water quantity in the Amatole area. These are monitored on a daily basis. Table 8.1b provides data on gauges that are not recording any longer and some of these are recommended for reinstatement below.

The water quality monitoring points for the DWA are presented in Figure 8.2. Those that are on the rivers are tabulated in Table 8.2, the ones on reservoirs are given in Table 8.3 and those assessing the effluent of WWTWs are presented in Table 8.4. These water quality points are not monitored regularly, but on a biweekly or monthly basis in general.

Information on the WTW monitoring points (water quality only) for Amatola Water and Amathole District Municipality (ADM) were received from Dr Nikite Muller of Amatola Water. The ADM monitoring points are being monitored by Amatola Water at present. The WTW monitor points assess the raw water quality coming into the plants, so they are indicators of water quality in the reservoirs. These data are listed in Table 8.5 and Figure 8.3. Data for the Buffalo City Municipality's (BCM) monitoring network could not be obtained despite various requests.

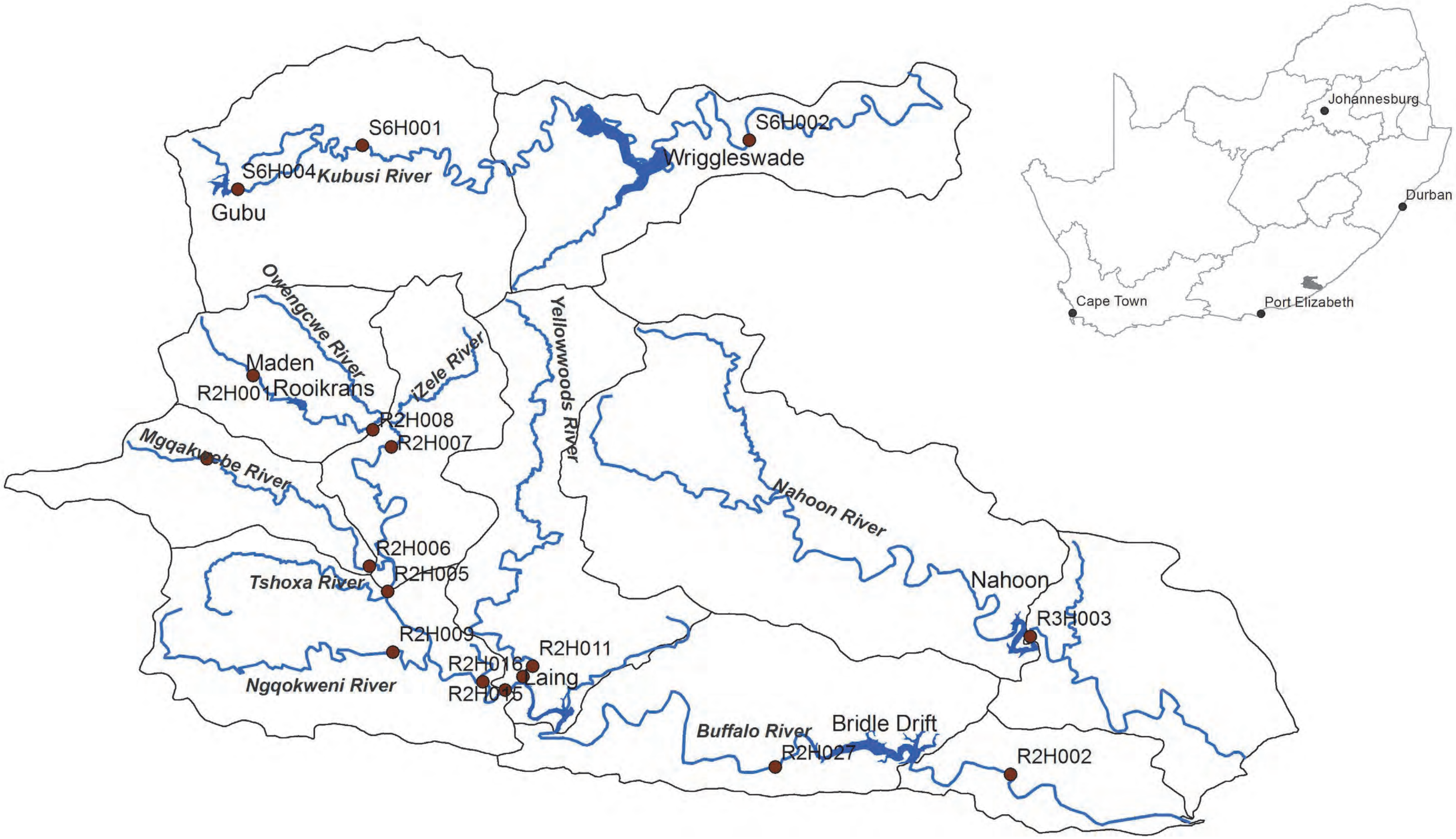


Figure 8.1 Stream flow gauging stations located on the Buffalo, Nahoon and Kubusi Rivers that are monitored by the DWA. Details are provided in Table 8.1a.

Table 8.1a Stream flow and reservoir outlet gauging stations presently monitored by the Department of Water Affairs. Data source: http://www.dwa.gov.za/Hydrology.

Station No.	Starting Date	Latitude (S); Longitude (E)	River or dam
R2H001	1946-10-01	32°43’55.0”; 27°17’37.0”	Buffalo River
R2H005	1947-10-01	32°52’31.4”; 27°22’58.3”	Buffalo River
R2H006	1948-07-05	32°51’30.3”; 27°22”14.6”	Mgqakwebe River
R2H008	1947-06-01	32°46’04.6”; 27°22’22.7”	Qwengcwe River
R2H009	1947-06-01	32°54’55.6”; 27°23’10.8”	Ngqokweni River
R2H010	1950-07-01	32°56’25.9”; 27°27’38.3”	Buffalo River
R2H015	1988-03-21	32°55’54.1”; 27°28’21.2”	Yellowwoods River
R2H016	1988-03-22	32^{0}56’06.5”; 27^{0}26’45.2”	Malakalaka River
R2H025	1998-12-16	32^{0}42’53.2”; 27^{0}33’11.5”	Wriggleswade Canal
R2H027	1994-02-24	32°59’29.9”; 27°38’24.1”	Buffalo River
R2H029	2001-10-25	32°59’41.2”; 27°44’02.0”	Buffalo River
R3H003	1965-01-15	32°54’18.6”; 27°48’33.8”	Nahoon River
R3H005	1993-08-16	32°41’57.5”; 27°33’51.1”	Wriggleswade Canal
R3H007	2003-03-12	32°58’53”; 27°56’57.0”	Nahoon River Estuary
R3H008	2003-04-23	32°57’52.5”; 27°54’55.1”	Nahoon River
S6H001	1947-04-12	32°34’45.7”; 27°21’57.3”	Kubusi River
S6H004	1971-09-22	32°36’30.0”; 27°16’59.9”	Gubu River
S6H005	1989-01-10	32°34’34.0”; 27°33’57.5”	Kubusi River
R3R001	1968-07-11	32°54’34.0”; 27°48’41.0”	Nahoon Dam
R2R001	1968-04-10	32°58’5.0”; 27°29’39.0”	Laing Dam
R2R002	1968-07-11	32°45’19.0”; 27°19’41.0”	Rooikranz Dam
R2R003	1972-02-07	32°59’21.0”; 27°43’52.0”	Bridle Drift Dam
S6R001	1975-02-27	32°36’36.5”; 27°16’40.3”	Gubu Dam
S6R002	1994-08-11	32°34’43.6”; 27°33’31.0”	Wriggleswade Dam

Table 8.1b Stream flow and reservoir outlet gauging stations that are out of operation. Data source: http://www.dwa.gov.za/Hydrology.

Station No.	Data available	Latitude (S); Longitude (E)	River or canal
R2H002	1968-09-01 to 1978-04-30	32°59’47.6”, 27°47’46.8”	Buffalo River
R2H003	1948-01-01 to 1950-02-28	32°57’02.6”, 27°28’44.8”	Buffalo River
R2H004	1947-07-01 to 1952-03-01	32°45’00.6”, 27°17’35.7”	Tyusha River
R2H007	1947-11-01 to 1981-12-30	32°46’45.6”; 27°23’06.8”	iZele River
R2H011	1957-03-01 to 1985-11-19	32°55’29.6”, 27°28’44.8”	Yellowwoods River
R2H012	1959-11-07 to 1997-10-13	32°47’13.6”, 27°15’46.7”	Mgqakwebe River
R2H013	1960-02-12 to 1970-11-29	32°48’39.6”, 27°10v58.7”	Mngqesha River
R2H019	1951-07-26 to 1973-01-17	32°45’19.6”, 27°19’39.7”	Canal to Trout Farm
R2H024	1973-01-17 to 1981-05-01	32°45’21.6”, 27°19’30.7”	Pipeline to Trout Farm
S6H002	1947-06-01 to 1995-08-21	32°34’32.7”; 27°37’21.8”	Kubusi River

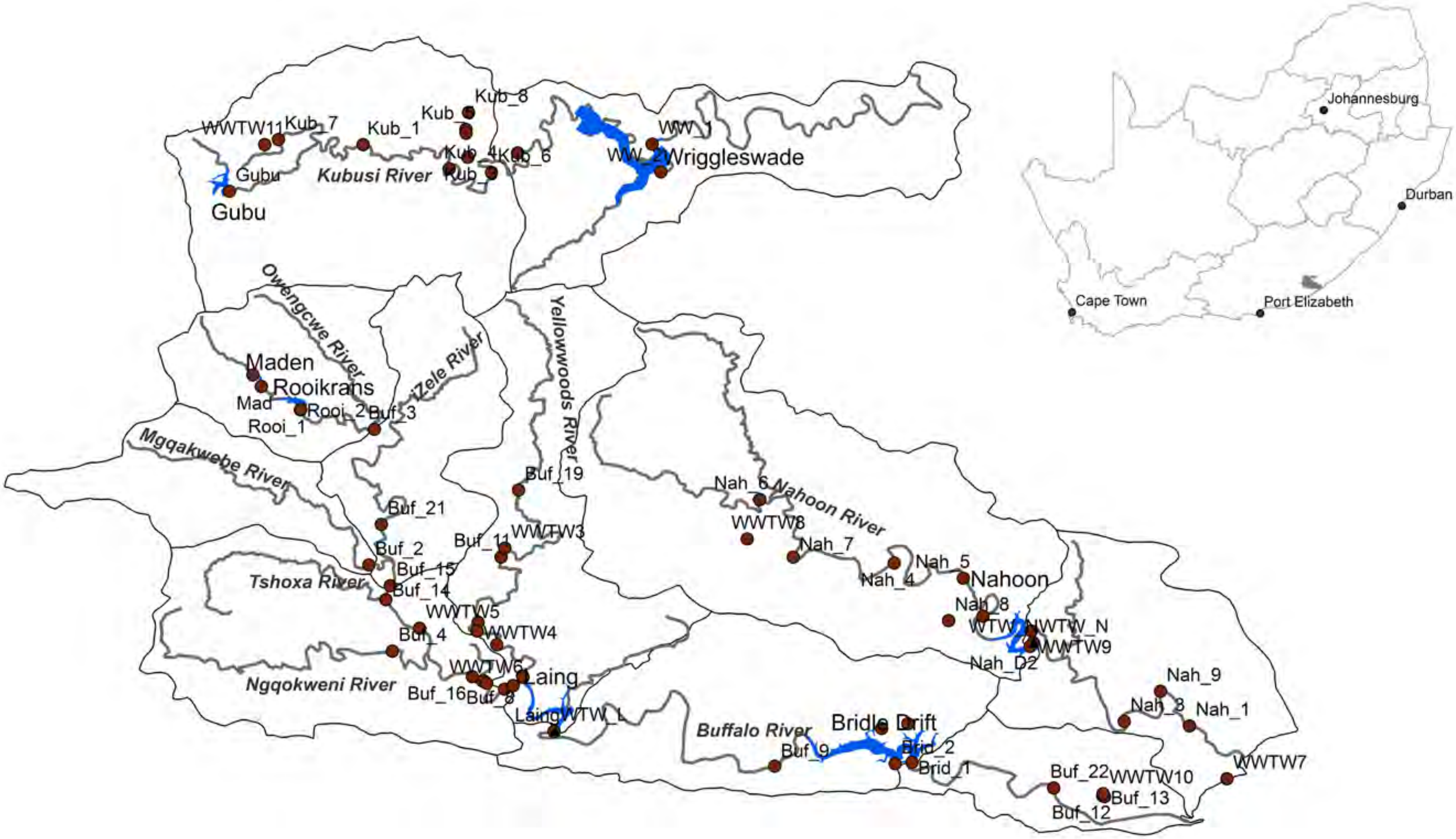


Figure 8.2 Water quality monitoring stations located on the rivers that are monitored by the DWA. Legend for labels is given in Table 8.2-8.4.

Table 8.2 Water quality stations on rivers presently (last monitoring date 2010 or 2011) monitored by the Department of Water Affairs. Data source: http://www.dwaf.gov.za/iwqs.

DWA ID	Label	Latitude (S); Longitude (E)	River
R20 102507	Buf_1	32°43’55.0”; 27°17’37.0”	Buffalo River
R20 102510	Buf_2	32°51’29.5”; 27°22’14.0”	Mgqakwebe River
R20 102512	Buf_3	32°46’5.0”; 27°22’27.0”	Qwengcwe River
R20 102513	Buf_4	32°54’55.0”; 27°23’10.0”	Ngqokweni River
R20 102514	Buf_5	32°56’25.9”; 27°27’38.3”	Buffalo River
R20 102517	Buf_6	32°55’54.1”; 27°28’21.2”	Yellowwoods River
R20 102518	Buf_7	32°56’6.0”; 27°26’48.0”	Malakalaka River
R20 1000010980	Buf_8	32°56’6.4”; 27°26’45.2”	Malakalaka River
R20 102522	Buf_9	32°59’29.9”; 27°38’24.1”	Buffalo River
R20 189334	Buf_10	32°53’46.1”; 27°26’35.1”	Yellowwoods River
R20 189335	Buf_11	32°51’10.0”; 27°27’30.1”	Yellowwoods River
R20 189768	Buf_12	33°0’40.9”; 27°51’28.3”	Buffalo River
R20 189769	Buf_13	33°0’42.7”; 27°51’32.6”	Buffalo River
R20 190229	Buf_14	32°52’52.2”; 27°22’54.4”	Buffalo River
R20 1000002455	Buf_15	32°52’18.7”; 27°23’5.1”	Buffalo River
R20 1000002458	Buf_16	32°55’56.2”; 27°26’21.1”	Buffalo River
R20 1000002477	Buf_17	32°56’17.3”; 27°27’58.7”	Buffalo River
R20 1000002481	Buf_18	32°55’57.1”; 27°28’22.1”	Yellowwoods River
R20 1000009969	Buf_19	32°48’30.2”; 27°28’11.6”	Yellowwoods River
R20 1000009970	Buf_20	32°54’40.1”; 27°27’19.8”	Yellowwoods River
R20 1000010299	Buf_21	32°49’52.5”; 27°22’43.8”	Buffalo River
R20 1000010989	Buf_22	33°0’22.0”; 27°49’31.2”	Buffalo River
R30 1000010301	Nah_1	32°57’53.7”; 27°54’55.8”	Nahoon River
R30 1000002333	Nah_2	32°53’31.7”; 27°46’42.0”	Nahoon River
R30 190227	Nah_3	32°57’43.0”; 27°52’19.6”	Nahoon River
R30 190544	Nah_4	32°51’24.6”; 27°43’10.0”	Nahoon River
R30 190732	Nah_5	32°52’1.0”; 27°45’55.2”	Nahoon River
R30 1000002329	Nah_6	32°48’52.6”; 27°37’48.3”	Nahoon River
R30 1000002331	Nah_7	32°51’10.4”; 27°39’8.4”	Nahoon River

Table 8.2 continued

DWA ID	Label	Latitude (S); Longitude (E)	River
R30 1000002332	Nah_8	32°53’42.3”; 27°45’19.9”	Nahoon River
R30 1000010300	Nah_9	32°56’31.0”; 27°53’46.3”	Nahoon River
S60 102557	Kub_1	32°34’45.0”; 27°22’0.0”	Kubusi River
S60 188275	Kub_2	32°35’4.6”; 27°28’9.4”	Kubusi River
S60 188276	Kub_3	32°35’15.0”; 27°26’10.6”	Kubusi River
S60 188278	Kub_4	32°35’42.4”; 27°25’25.6”	Kubusi River
S60 188279	Kub_5	32°34’8.4”; 27°26’6.0”	Kubusi River
S60 188280	Kub_6	32°35’51.2”; 27°27’6.9”	Kubusi River
S60 190039	Kub_7	32°34’32.8”; 27°18’37.5”	Kubusi River
S60 190731	Kub_8	32°33’28.2”; 27°26’12.2”	Kubusi River

Table 8.3 Water quality stations below and within reservoirs presently (last monitoring date 2010 or 2011) monitored by the Department of Water Affairs. Data source: http://www.dwaf.gov.za/iwqs.

DWA ID	Label	Latitude (S); Longitude (E)	Reservoir
R20 102523	Laing	32°58’7.3”; 27°29’36.6”	Laing Dam
R20 103283	Rooi_1	32°45’18.4”; 27°19’30.4”	Rooikranz Dam
R20 102524	Rooi_2	32°45’17.3”; 27°19’30.7”	Rooikranz Dam
R20 190353	Mad	32°44’22.7”; 27°17’56.7”	Maden Dam
R20 102525	Brid_1	32°59’21.0”; 27°43’52.0”	Bridle Drift Dam
R20 187302	Brid_2	32°59’24.0”; 27°43’12.0”	Bridle Drift Dam
R30 102530	Nah_D1	32°54’34.9”; 27°48’42.0”	Nahoon Dam
R30 1000002334	Nah_D2	32°54’43.7”; 27°48’34.4”	Nahoon Dam
S60 102562	Gubu	32°36’36.5”; 27°16’40.3”	Gubu Dam
S60 102563	WW_1	32°34’43.6”; 27°33’31.0”	Wriggleswade Dam
S60 188277	WW_2	32°35’49.9”; 27°33’51.8”	Wriggleswade Dam
R20 103071	WTW_L	33°01’55.0”; 27°29’39.0”	Laing Dam Raw Water
R30 103074	WTW_N	33°05’26.0”; 27°48’43.0”	Nahoon Dam Treated & Raw Water

Table 8.4 Water quality stations below WWTWs presently (last monitoring date 2010 or 2011) monitored by the Department of Water Affairs. Data source: http://www.dwaf.gov.za/iwqs.

DWA ID	Label	Latitude (S); Longitude (E)	WWTW
R20 188286	WWTW1	32°57’59.6”; 27°42’39.7”	Potsdam
R20 188290	WWTW2	32°57’48.6”; 27°43’42.3”	Mdantsane
R20 189333	WWTW3	32°50’49.0”; 27°27’39.1”	Bhisho
R20 189339	WWTW4	32°54’7.2”; 27°26’32.8”	Breidbach
R20 1000002466	WWTW5	32°54’0.5”; 27°24’15.0”	Schornville
R20 1000002474	WWTW6	32°56’11.8”; 27°26’55.6”	Zwelitsha
R30 189513	WWTW7	33°0’0.0”; 27°56’25.0”	East Bank
R30 189759	WWTW8	32°50’27.3”; 27°37’18.1”	Berlin
R30 190006	WWTW9	32°54’6.9”; 27°48’37.9”	Nahoon Dam
R20 1000010992	WWTW10	32°0’35.6”; 27°51’28.8”	Central
S60 189382	WWTW11	32°34’44.7”; 27°18’5.1”	Kubusi
S60 189508	WWTW12	32°34’17.6”; 27°26’6.3”	Stutterheim

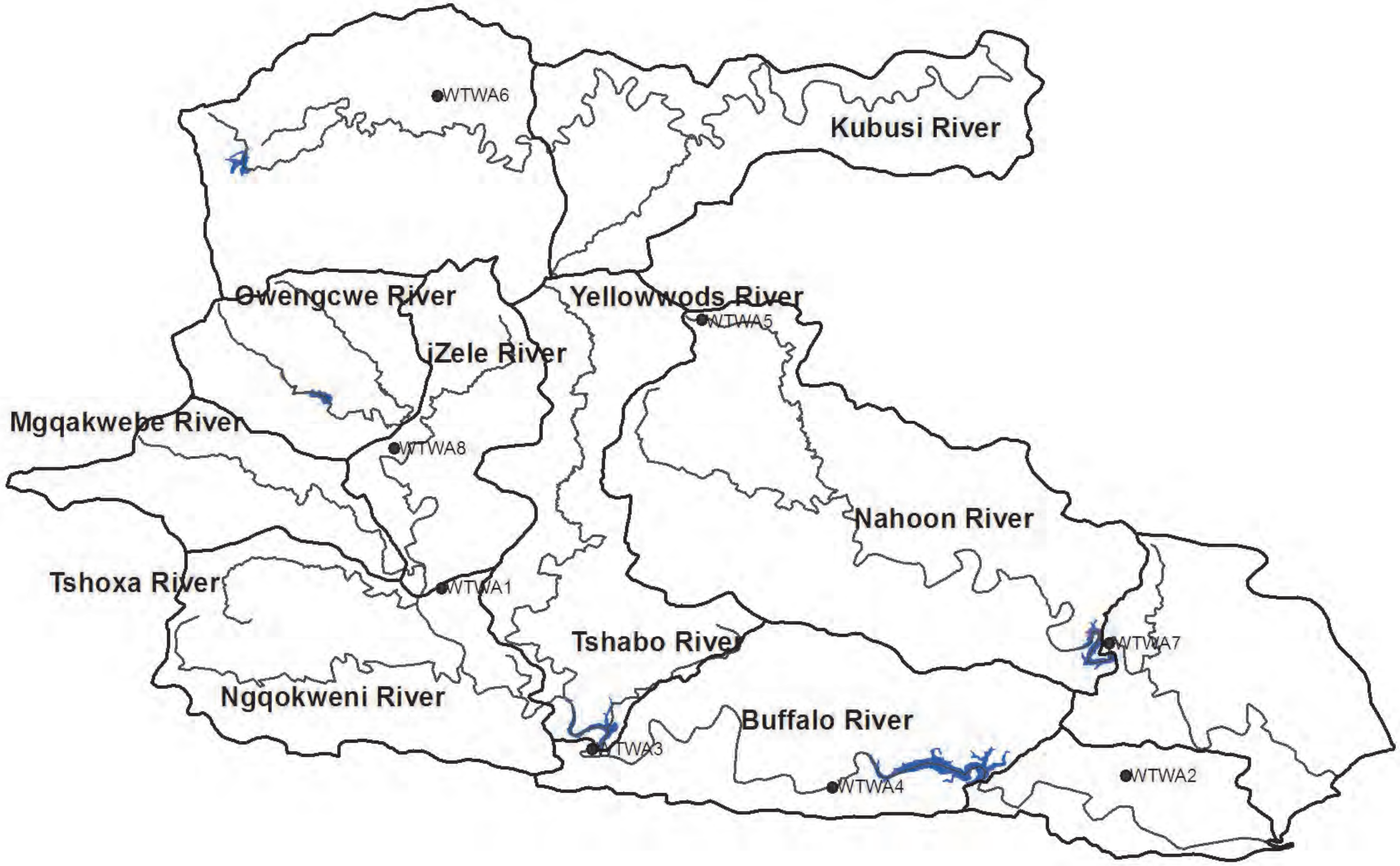


Figure 8.3 Water quality monitoring stations for water treatment works located on the Buffalo, Nahoon and Kubusi Rivers that are monitored by Amatola Water for water quality. Legend for labels is given in Table 8.5.

Table 8.5 Water treatment works monitoring network for Amatola Water and Amathole District Municipality. Data obtained from Dr Nikite Muller of Amatola Water.

WTW name	**Label**	**Latitude (S); Longitude (E)**	**River**
King William's Town	WTWA1	32°52’7.5”; 27°23’49.9”	Buffalo River
Umzonyana	WTWA2	32°59’6.0”; 27°49’15.0”	Buffalo River
Laing	WTWA3	32°58’6.6”; 27°29’25.9”	Buffalo River
Needs Camp	WTWA4	32°59’31.2”; 27°38’21.9”	Buffalo River
Kei Road	WTWA5	32°42’10.4”; 27°33’29.8”	Nahoon River
Stutterheim	WTWA6	32°33’50.6”; 27°23’41.6”	Kubusi River
Nahoon	WTWA7	32°54’11.5”; 27°48’39.0”	Nahoon River
Rooikranz	WTWA8	32°46’57.9”; 27°22’5.3”	Buffalo River

CHAPTER 9. INSTRUMENTS AND DATA FOR DEVELOPING RESPONSES TO CLIMATE AND DEVELOPMENT CHANGE

by

Denis Hughes and Sukhmani Mantel

9.1 National response to climate and development changes

The water sector is listed as one of the key adaptation sectors under the Climate Change Response Green Paper with the note that: "*Present population growth trends and water use behaviour indicates that South Africa, as a water scarce country, will exceed the limits of its economically usable, land-based water resources by 2050*" (RSA, 2010: p. 8). Climate change is recognised as "… *only one of several drivers currently informing water resource planning and decisions in South Africa. Most critically, surface water resources were already over-allocated and experiencing water stress by the year 2000 in five of 19 Water Management Areas… Demand is expected to increase with economic growth, increased urbanisation, higher standards of living, and population growth*" (DEA, 2011: p 77).

For effective response to climate change, the South African Government recognizes that there is a need for "*national policy in order to ensure a coordinated, coherent, efficient and effective response to the global challenge of climate change*" (RSA, 2010: p. 4). According to this National Climate Change Response Green Paper, the principles by which the response has been guided are (RSA, 2010: pp. 5-6):

- Principle of common but differentiated responsibility and respective capabilities
- Precautionary principle
- Polluter pays principle
- A people-centred approach
- Informed participation
- Inter-generational rights

Importantly, the precautionary principle is part of the uncertainty in the knowledge about climate change, suggesting a "*risk-averse and cautious approach which takes into account the limits of current knowledge about the consequences of decisions and actions*" (RSA, 2010: p. 6).

As outlined in Chapter 1, adaptation strategies to future climate and development changes need to be developed in the context of the institutional framework that is present, the instruments that are available to develop the responses, and the information which informs the responses. According to Kiker (2000), adaptation to climate change consists of actions that "*attempt to reduce the vulnerability caused by climate change*".

9.2 Adaptation interventions and good governance

9.2.1 Responsibilities

In terms of roles and responsibilities of various institutions, the Climate Change Response Green Paper states that "*we must recognise that most of our climate adaptation and much of the mitigation efforts will take place at provincial and municipal levels and will be integrated into provincial development and spatial plans and into IDPs at municipal level*." The document further notes that "*Increasingly, South Africa's water security will depend on* *the extent to which it is able to refine and re-orientate its institutional arrangements to make the most responsible, equitable and effective use of its water, while strengthening environmental management of the natural resource base*" (RSA, 2010: p. 9). Thus, from the point of view of government departments as well as state owned enterprises, climate change response involves a review of policies, legislation and strategies, so that these align with the National Climate Change Response Policy (RSA, 2010: p.30). Social partners, including industry and business, organised labour and civil society, are expected to support the government role. As examples of actions, these social partners can contribute through improving energy efficiency, and through development and implementation of adaptation and mitigation plans.

For water services institutions, the importance of water demand management (WDM) is seen as critical as noted in the DEA (2011): "*DWA has put WDM high up on their agenda and they regard municipalities as the key implementers of WDM and water conservation programmes*" (DEA, 2011: p. 90). In this regard, municipalities should work in collaboration with the local and national DWA, South African Weather Service, water boards, water services authorities, and with users in the catchment for sustainability of the water resources.

9.2.2 Integrated land and water management

The national report on climate change communication by the DEA (2011: pp. 88-91) discusses adaptation measures for water resources to climate change and notes the importance of an integrated approach to land and water management for effective resilience to climate change. Under this approach, WDM is recommended as a necessity, instead of an option, for conserving water resources in many areas across South Africa. Similarly, adaptive management processes are supported by the National Climate Change Response, as the Green Paper states that South Africa will "*implement integrated water resource management including protecting and restoring natural systems, increasing conjunctive use of surface and ground water, and learning through adaptive management experiments*" (RSA, 2010: p. 10).

Integration of land and water management is critical from the point of view of quality of water available and reduction in loss of water (e.g. through alien vegetation). DEA (2011: p. 87) notes that at present alien vegetation results in a loss of 7% of surface water runoff and it is expected to increase in the future. In the present study, alien vegetation demands of a total of 3×10^6 m^3 y^{-1} were entered into the WEAP model. These demands could either increase or decrease in the future depending on the funding available for management programmes (such as the *Working for Water* programme managed by the DWA) implemented.

9.2.3 Instruments and supporting strategy

As part of the Reconciliation Strategy (DWAF, 2008), the Buffalo City Municipality is looking at various ways to increase the amount of available water and improve the water quality (UWP, 2012a and 2012b) through its Integrated Development Plans (IDP), Water Services Development Plans (WSDP) and the Eastern Cape Provincial Spatial Development Plan (ECPSDP, 2010). These measures include:

- Integrated operation of the dams in the Amatole system to increase yield of the reservoirs by approximately 10% (from 95×10^6 m^3 y^{-1} to 106×10^6 m^3 y^{-1} if water is transferred from the Wriggleswade Dam when or before the dam spills).
- Water conservation and demand management measures of approximately 6.2×10^6 m^3 y^{-1} over the next five years are possible according to BCM.
- Water re-use possibilities in the WWTWs (projects and amounts to be assessed).
- Removal of alien vegetation, particularly in the riparian zone, could free up water available in the rivers (amounts to be assessed).

- Surface water screening possibilities (three possibilities have been short-listed for further study but can only be implemented if 100% water savings that are possible through WC/WDM have been achieved by 2029; UWP, 2012a and 2012b).
- Sea water desalination.
- Control of pollution sources at their source.

If some or all of these measures are implemented, additional water will be available in the system and the water quality will be improved.

The reconciliation strategy should be considered as only one of the instruments available for developing responses, including the Water Services Development Plans (WSDP), Eastern Cape Provincial Spatial Development Plan (ECPSDP), Integrated Development Plans (IDP), developed at the local level as well as the National Water Resources Strategy, and the National Climate Change Response Strategy. The South African Climate Change Response Strategy, which developed from the discussions in the Green Paper (RSA, 2010), is available at http://www.climateresponse.co.za/home. Some of the strategies that are relevant to the water issues discussed in this report are (as-is from the document):

- *Taking a balanced approach to both climate change mitigation and adaptation responses in terms of prioritisation, focus, action and resource allocation.*
- *The short-term prioritisation of adaptation interventions that address immediate threats to the health and well-being of South Africans including interventions in the water, agriculture and health sectors.*
- *Prioritising the development of knowledge generation and information management systems that increase our ability to measure and predict climate change and, especially extreme weather events, floods, droughts and forest and veld fires, and their impacts on people and the environment.*
- *The recognition that sustainable development is also climate friendly development and that the more sustainable our development path is, the easier it will be to build resilience to climate change impacts.*

The Response Strategy further elaborates on adaptation actions for the water sector, which support the adaptation interventions and good governance aspects that have been discussed in this chapter.

9.2.4 Building resilience

It is notable that the DEA (2011) document stresses effective resilience to climate change impacts as a strategy for adaptation. As part of this, WDM is considered by the DEA (2011: p. 89-90) to be a primary measure for conservation of water resources, while in comparison, water infrastructure (such as dams and inter-basin transfers) "*is a long-term investment with a design life of 50-100 years, very expensive, essentially irreversible once constructed, and designed to cope with currently (but not necessarily future) expected extremes of floods and droughts*". Reservoirs are also vulnerable to evaporation loss, siltation and algal blooms, and thus their benefits in the long term should be considered carefully. The DEA (2011) document recommends the use of groundwater aquifers, where available, as an alternative to reservoirs. However, the use of these aquifers needs to be done with caution and awareness of expected changes in air temperature under climate change and anthropogenic pollution that can impact their recharge and water quality.

9.2.5 Maintenance: good governance and adaptation

Maintenance of infrastructure is essential for reducing leaks of precious water, as noted by the National Climate Change Response Green Paper. The Response Green Paper states that South Africa will "*invest in maintenance and renewals to minimize system losses in infrastructure networks. Maintenance deferred is infinitely more expensive and the country needs the most efficient networks possible to optimize currently available resources and* *protect future ones*" (RSA, 2010: p. 10). However, it must be noted that maintenance is part of good governance by water institutions and it should be taking place irrespective of climate change effects. Water losses in the Amatole system are approximately 20% similar to other water supply systems in the country. Gaining water by reducing leaks could go a long way towards meeting the current and future water demands in the system.

9.2.6 Monitoring

The results obtained by this project confirm the critical need for monitoring of socio-economic development (particularly, the changes in population and industrial water demands) in order to plan and manage the Amatole system effectively and efficiently under increased uncertainty in predictions for the future. Monitoring of the demands needs to be combined with monitoring of the catchment in terms of stream discharge, river and reservoir water quality, reservoir storage, and climate variables in order to reduce the uncertainty in the predicted scenarios for climate change and socio-economic development. An integrated monitoring network with combined monitoring stations of BCM, Amatola Water, Amathole District Municipality and DWA is essential for efficient and effective management. Importantly, the recent shift from chemical to microbial monitoring by the DWA (Dr Nikite Muller, communication during third project workshop, 2012) is of concern since there is a need for both chemical and microbial monitoring so that the scientists can make sense of the trends and the relationships.

This requirement for continued and additional monitoring for addressing the impacts of climate change on water resources is stressed by the Climate Change Response Green Paper says that South Africa will "*invest in monitoring capabilities across a range of disciplines in order to spot trends and understand them as well as track the efficacy of adaptive strategies*" (RSA, 2010: p. 9). This should provide the necessary incentive for the South African Weather Service (SAWS), Department of Water Affairs (DWA), Department of Environment and Tourism (DEAT), Agricultural Research Centre (ARC), municipalities, and other water institutions to work together towards an integrated monitoring system for the weather (including temperature, evapotranspiration and rainfall), water quantity and quality variables. This monitoring network would also contribute to the Early Warning Systems for weather and climate, floods, droughts etc. that are supported by the Climate Change Response Green Paper (RSA, 2010: p. 21).

Lastly, monitoring in the context of performance and goal setting under climate change is also crucial by water services institutions.

9.2.7 Water literacy

A critical part of adaptation is water literacy, particularly training and education of individuals in water services institutions that are responsible for implementing strategies that assist the National Climate Change Response Strategy. In addition, the education and involvement of the people in the Buffalo City Metropolitan Municipality, Amatola District Municipality and Amatola Water can be influential in various adaptation interventions, including integrated land and water management, infrastructure maintenance and management, water conservation and demand management. As can be noted from the social survey results for King Williams Town obtained by Ms Kelly Stroebel (Appendix C), the surveyed community had limited knowledge about their catchment, the threats to the catchment, and the importance of conservation activities. Some people expressed the desire for education and awareness programmes that the Municipality can implement. These programmes can not only help in greater awareness but can also assist in the people playing a more active role in catchment management, such as reporting leaks, reporting and reducing pollution, and water demand and conservation measures such as installing household water tanks. Since the population water demands is the dominant player in today's as well as future requirements (Figure 5.10), their involvement in sustainability and adaptation measures is essential.

9.2.8 Risk and Vulnerability Atlas

The Climate Change Response Green Paper states that one of the strategies to be followed in order to achieve the outlined objectives is "*the short-term prioritisation of adaptation interventions that address immediate threats to the health and well-being of South Africans including interventions in the water, agriculture and health sectors*" (RSA, 2010: p. 6). Of these, water is considered "*the primary medium through which climate change impacts will be felt by people, ecosystems and economies*" (RSA, 2010: p. 7). The Green Paper further promotes the use of South African Risk and Vulnerability Atlas (SARVA) stating that South Africa will "*maintain and update the South African Risk and Vulnerability Atlas (SARVA) as a tool to be used by provinces and municipalities to facilitate their climate change adaptation planning*" (RSA, 2010: p. 21). The use of SARVA to identify expected changes in climate in future specific to the area where a particular water service institution is located, can assist with prioritising of adaptive actions on the ground today.

9.2.9 Dialogue between institutions

An important consideration in reducing climate change uncertainty is the need for dialogue between various agencies producing downscaled climate change data. The results of this project, in addition to a presentation on results for Umgeni catchment by Mr Summerton of Umgeni Water during the third project workshop in 2012, showed the risk of looking at a limited selection of climate change scenarios since some of the 31 scenarios that they investigated produced opposite results. It is thus imperative that the various agencies, including CSAG (statistical downscaling), CSIR (dynamic downscaling) and SMHI (Swedish Meteorological and Hydrological Institute; dynamic downscaling) that are producing climate change products, discuss ways to reduce the uncertainty in future climate predictions. WRC recently indicated to the project team that they are planning such a workshop in March 2013 to bring these agencies together. The dialogue between institutions can be further extended to include activities around the science-policy and science-society interface in the sense of what is relevant information and how to communicate it to the different role-players (Sabine Stuart-Hill, *pers. comm.*).

9.3 Adaptive management in South Africa

Adaptive management is a concept developed in the 1970s and 1980s with the premise that socio-ecological systems are dynamic, complex and uncertain (Colvin, 2011 and references within). Adaptive management, similar to adaptive monitoring, is an iterative process of planning, action, monitoring, evaluating and adjustment.

Literature on adaptive management from a South African perspective is limited but valuable to any management agency. A South African specific adaptive management approach, called Strategic Adaptive Management (SAM), has been applied to the Kruger National Park and to the Inkomati Catchment Management Agency (Biggs and Rogers, 2003; Rogers and Luton, 2010). As presented in Chapter 2 of this report, the Strategic Adaptive Management process (Rogers and Bestbier, 1997; McLoughlin et al., 2011) for designing a decision support system in order to manage for a "desired future state" of river systems uses the procedure for setting Thresholds for Potential Concern (TPCs). The TPCs for the Amatole system have been provided in Table 2.2 and the corresponding text.

Two other South African projects that have interrogated socio-economic impacts of climate change and adaptation options are the WRC projects K5/1843 (*An evaluation of the sensitivity of socio-economic activities to climate change in climatically divergent South African catchments*) and K5/1965 (*Developing water related climate change adaptation options to support implementation of policy and strategies for Water for Growth and Development*). Schulze (2011) summarised the results of project K5/1843 in terms of expected agricultural and hydrological droughts, surface water supply, water quality, etc. The author also presents a comprehensive list of adaptation options for water related sectors in South Africa in the categories of:

- technical and structural options (such as storage, monitoring, warning systems, water demand management)
- knowledge, skills and participation (R&D, risk maps, communication)
- policy instruments (both national and international laws, agreements and strategies)
- risk sharing / spreading options (for private and public sectors)
- change of use / activity / location options (including land-use, crops, resettlement, etc.).

These are discussed in detail in the final report for the WRC project K5/1843 (Stuart-Hill and Schulze, 2011) and are a valuable resource for any water resources manager and water services institutions.

CHAPTER 10. CONCLUSIONS AND RECOMMENDATIONS

A recent paper by Wilby et al. (2010) draws together research investigating climate change impacts on freshwater ecosystems and adaptive management practices that should be implemented for future sustainability. Their report focuses on the uncertainty in projections for climate and the expected species and system responses and the limitations of monitoring networks in the context of this uncertainty. On a country scale, some countries are undertaking projects on assessing climate change impacts on freshwater resources. For example, the USGS (2011) draft report to congress on climate change impacts at country level provides an overview of challenges to freshwater resources in USA, arising both from climate change and other stressors. The aim of the USGS report is to strengthen management of the resources and to recommend adaptation strategies. The USGS report findings are of interest to this project and any other that is developing plans for water resources management:

- Assess the adequacy of observation network.
- Identify data gaps in water monitoring network.
- Improve data management.
- Determine adequacy of hydrological and other models.

It is important to recognize is that ***uncertainty is not the same as not having confidence in the predictions, but rather it equates to having a probability associated with a specific prediction*** (Tadross et al., 2011). However, ***climate change uncertainty is different in that all climate model outputs are considered equally likely and thus, there is no probability associated with a specific prediction***. ***Secondly, one cannot avoid uncertainty by using a single climate model, as that only leads to a wrong decision being made***.

10.1 Instruments and strategy for climate and developmental changes in the near future

The results of WEAP modelling indicated that the planned improvement in infrastructure and transfers from the Wriggleswade Dam should be sufficient to satisfy the water requirements under the Intermediate Development Scenario, but not for the Upper Development Scenario with a deficit of approximately 50.18×10^6 m^3 y^{-1}. As noted above, as part of the Reconciliation Strategy, the Buffalo City Municipality is investigating various interventions to increase the amount of available water and improve the water quality. Reconciliation meetings in this regard are on-going with the focus on building in flexibility through planning infrastructure as well as water re-use and water conservation for implementation in stages as a response to the high uncertainty in future (Mrs Thompson and Mr Ketteringham, communication during the project's Third Workshop). The reconciliation strategy is, however, only a starting point and it needs to be considered in the context of the various interventions discussed in Chapter 9 which provide guidance on climate change adaptation.

As mentioned previously, there are additional instruments that can be used for developing responses including the Water Services Development Plans (WSDP), Eastern Cape Provincial Spatial Development Plan (ECPSDP), and Integrated Development Plans (IDP). The National Climate Change Response Strategy also supports the various adaptation interventions discussed in Chapter 9.

10.2 Uncertainty in hydrological variability

Most sources of uncertainty in modelling are associated with imperfect knowledge about the inputs (i.e. climate variables or parameters describing the catchment response) or a lack of observations of the outputs (e.g. stream flow) and monitoring against which the model can be tested and refined. It is clear therefore, that attempts to reduce uncertainty should be focused on improving our knowledge and understanding of the inputs and/or improving the monitoring of the outputs. The latter is often expensive and is difficult to achieve short-term gains, given the high degree of variability of hydrological processes and the need to obtain representative observations over time. Within the Amatole system, there are several existing stream flow gauges, however, the value of the recorded data is affected by upstream impacts (abstractions and return flows, together with land-use change effects) that have changed over the period of record and are poorly quantified. These impacts affect the usefulness of the data for comparing with simulated stream flows of the natural catchment responses. One of the approaches that would potentially assist in reducing uncertainty is to try and improve the quantification of the upstream impacts and therefore, determine what conditions of development are represented by the observed stream flows. The likely result of such an exercise would be a ‘naturalized’ observed stream flow record that would also include a band of uncertainty. We would therefore, expect our natural flow simulations to have a similar band of uncertainty.

Where stream flow observations do not exist, it is often useful to establish short-term and inexpensive (i.e. not using constructed gauging weirs) monitoring programmes to establish some key quantities related to the flow regime of a catchment. This may include low flow responses during dry periods or high flow responses to single rainfall events. Additional monitoring programmes focused on environmental water quality or natural isotope signatures have been used in other parts of the world to identify major flow paths in headwater catchment areas. This type of analysis has not been used very extensively in South Africa and therefore, it is difficult to comment on the usefulness. Other approaches that have been used elsewhere involve assimilating additional information, apart from stream flow response, into the assessment of a model’s output. Some success has been achieved with the use of satellite data to estimate patterns of variation (in space and time) of soil moisture and actual evaporation. While the success of using these techniques is always subject to issues relating to ground-truthing and calibrating the satellite data signatures to the equivalent variables simulated by the model, they would appear to have a great deal of potential.

With respect to improving the inputs into hydrological models, one of the main focus areas should be the rainfall data that are used to force the model. No hydrological model can work properly without adequately accurate and spatially representative rainfall data and such data are becoming more difficult to obtain in South Africa. The greatest problem and the largest uncertainty occur in topographically steep areas where rainfall gradients can also be steep and are usually poorly represented by gauging networks. As with stream flow data, short-term field monitoring programmes can be of assistance in quantifying spatial rainfall patterns, but there is no real substitute for a well-managed and spatially representative continuous rainfall data collection network that remains active for many years. This is becoming increasingly important so that any climate change impacts on rainfall that occur in the future can be identified through analyses of observed data and related to the historical patterns of variation, rather than having to rely on highly uncertain outputs from down-scaled global or regional climate models.

Reducing uncertainty in the model parameters that determine the response of the catchment to variable climatic inputs can only really be achieved through improved conceptualisation of the prevailing catchment hydrology processes. This is not very straightforward to achieve at the catchment scale given the complex interaction of processes that occur. Understanding the dynamics of interaction between surface runoff and storage (soil water) processes and groundwater (recharge as well as groundwater contributions to stream flow) processes is very important for simulating the low flow regime of catchments. While it is often difficult to be confident about the results of using measured physical basin property data (topography, soils, geology, vegetation, etc.) to estimate parameters in an absolute sense, these techniques can be very valuable for identifying spatial variations in model parameters (in a relative sense) and expected catchment response. If such results are used together with limited observed stream flow response data (corrected for upstream anthropogenic impacts) there is a great deal of potential for reducing uncertainty.

All of the approaches referred to above are potentially applicable to the Amatole system, but at this stage, it is not possible to suggest which will have the greatest impact. This can, however, be seen as an opportunity to learn and understand.

10.3 Uncertainty in water availability and use

From a water management planning point of view, the difference in the quantity between water use and actual consumption is important. By reducing the losses in the system, water use can be reduced while keeping consumption the same. This is not only important from the water quantity (and water treatment cost) point of view, but also from the side of water quality, as the amount of water withdrawn from the river affects the concentration of ions, nutrients and contaminants in the resource (Jackson et al., 2001). Additionally, increased nutrients are expected to negatively affect the aquatic life in the rivers and estuaries, in addition to their effects on humans who use the resource directly (through deteriorated water quality for the water users extracting water from rivers) and indirectly (increased algal blooms would result in greater costs for water treatment).

Information for water use within the Amatole system is fragmented and difficult to come by in some cases. Available reports listing population numbers and a socio-economic breakdown are very often contradictory, and many reports report on data on a spatial or temporal scale that is inappropriate for modelling the Amatole system. For example, the Kei ISP report (DWAF, 2004b) reports on the Amatole region which includes catchments other than the Buffalo, such as the Kei River catchment.

Within WEAP, the Amatole system was divided into three demand areas, namely the Upper, Middle and Lower Amatole, with demand categories being specified as human settlements, industry, agricultural sites and alien vegetation. Population estimates used in WEAP were taken from the Amatole Reconciliation Strategy report, and were sourced from the 2001 population census, available on the Stats SA website, and extrapolated to 2005 using appropriate growth rates. The water use rates for domestic water requirement categories (DWAF, 2008: Appendix 1) were used to calculate the total water requirements for urban, semi urban and rural settlements. Industrial and irrigation demands were estimated from DWAF (2008). Other estimates for population in these regions are given by the Amatole Water Resource Systems analyses, which are extrapolated from mid 1980s data to 2005, and the Buffalo City Municipality's Water Services Development Plan, which is also based on the 2001 census data, but includes areas not relevant to modelling the Amatole system. Within these three sources of population numbers, population estimates range from 90 465 to 104 288 for the Upper Amatole, 122 196 to 186 752 for the Middle Amatole, and 478 017 to 808 897 for the Lower Amatole. Therefore, there are some significant discrepancies in population estimates amongst the different sources of information, which can contribute to uncertainty when setting up user demands within the models.

A comparison of the water use data within WEAP, as compared to that used in the WReMP setup for the Amatole system, further highlight the uncertainty in water use data for the Buffalo River (Table 10.1). Encouragingly, the total user amounts specified in the Amatole system under the two categories (irrigation and population/industry) for the two model setups are similar (see Table 10.1). However, the differences occur in the partitioning of the demands throughout the system, with for example, irrigation demand within WReMP occurring within the Upper and Middle Amatole, while some irrigation demand is also specified for the Lower Amatole within the WEAP model setup. Similarly, population and industry demands show similar amounts within the two model setups, although the total is higher for the WEAP setup. Uncertainty in regards to user and irrigation demands in the Amatole system, therefore, seem to stem from uncertainty in partitioning total demands within the catchment to the Upper, Middle or Lower Amatole system.

The WReMP model setup shows urban and industrial consumption to be between 50-60%. This value evidently lumps losses from dams to water treatment works (WTWs), consumption losses from population and industry, losses from demand sites to waste water treatment works (WWTWs), and losses from WWTWs to the river together. WEAP however, has the facilities to partition these losses, and they are listed in Table 5.2. The total losses for the WEAP model setup come to 44.6%, 40.9% and 44% for the Upper Amatole, Middle Amatole and Lower Amatole, respectively. Therefore, there are slight discrepancies in the consumption and loss values between the WReMP and WEAP model setups, and this information may be a significant source of uncertainty within the Amatole system.

Table 10.1 A comparison between the WEAP model and WReMP model setups of water demand values used within the Buffalo River.

	Irrigation (10^6 m^3 y^{-1})		**Population & Industry (10^6 m^3 y^{-1})**	
	WEAP	**WReMP**	**WEAP**	**WReMP**
Upper Amatole	1.24	3.33	7.44	5.31
Middle Amatole	1.90	2.55	9.17	10.61
Lower Amatole	1.26	0.00	43.26	40.80
Totals	4.40	5.88	59.87	56.72

10.4 Uncertainty in the status of water quality

Uncertainty in water quality within the Current Scenario for the Amatole system is greatly increased by the lack of water quality data for various parts of the catchment. Some tributaries of the Amatole system are ungauged; therefore, it is difficult and uncertain to specify a water quality signature for the inflow from these tributaries. Within WEAP, water quality monitoring data from nearby gauges have been used to specify the water quality signature in ungauged tributaries, with some adjustment due to differences in catchment areas, and therefore inflow amounts. Water quality data from gauged catchments, where it exists, is typically of a low temporal resolution. A patching method was therefore used, where flow as the independent variable was used to estimate water quality concentrations within water quality data gaps. These methods are however, highly uncertain, with a large range of possible water quality concentrations that could be associated with any particular flow. The water quality impacts from point sources on the Amatole system are also highly uncertain. Historical water quality monitoring data of WWTW effluent is of a very low temporal resolution, and overall averages, or interpolation between yearly averages, was used within the WEAP model to specify WWTWs water quality signature. The WEAP model cannot simulate water quality in reservoirs, and observed monitoring data of water quality in reservoirs has to be used within the model, or simulations have to be performed by a specialised reservoir model and input back into the WEAP model. Historical monitoring water quality data for reservoirs within the Amatole system are of a low temporal resolution, and monthly averages to obtain a seasonal signature were input into the WEAP model. Uncertainty due to insufficiencies in observed data and model uncertainty were not quantified in this modelling exercise, except for electrical conductivity.

Water quality is very much driven by flow and inputs of pollution. Flow is affected by rainfall, as well as return flow from human demands. Sources of pollution are primarily driven by return flow from human demands and land-use. Uncertainty in water quality is therefore affected by uncertainty in flow and user demands within the Amatole system. The uncertainty associated with future climate change scenarios and the possible effect on flow, is therefore the starting influence on uncertainty in water quality, and water quality uncertainty becomes greater as other factors are considered. Water quality uncertainty for future scenarios is also greatly affected by the uncertainty in development scenarios, with higher return flow rates associated with greater development.

10.5 Recommendations for monitoring

The following specific recommendations for water quantity monitoring are made for the Amatole system based on the analysis conducted in this project:

- Reinstating stream flow gauging station on iZele River (R2H007) in order to monitor inflow into Buffalo River. These data would be useful for modelling inflows and change in flows when removal of alien vegetation is undertaken.
- Consider installing a stream flow gauging station above the Nahoon Dam in order to monitor flow (natural flow and flow under water transfers from Wriggleswade Dam). Although transfers from the Wriggleswade Dam are monitored in the tunnels, a stream flow gauge would assist with calculation of the actual flows in the river reach under transfer conditions which would be useful for conducting a Reserve in future and for modelling the Nahoon River more accurately.
- Monitor the estuary water levels for the Nahoon River. This would require accounting for both flow and tidal effects, which admittedly is not an easy exercise.
- Monitoring and modelling of evaporation from dams for reducing the present day and future climate uncertainty when modelling reservoir storage.
- Monitor and collate water use data over time in terms of water requirements of various users, losses in the distribution and bulk water system. Notably the population water requirements are the major contributor the uncertainty in the total water requirements in the future (Figure 5.10), and thus, reducing the uncertainty in the socio-economic development demands will go a long way in managing the system sustainably.
- A second important consideration for the socio-economic data is that the Reconciliation Strategy (DWAF, 2008) data that was used in the present project is for the Upper, Middle and Lower Amatole system and it is not broken down by areas and social classes. Obtaining breakdown in water use data and the trajectory in future will assist in finding appropriate management solutions for the water requirements under future development.
- Lastly, as has been noted above in the report, environmental flow requirements (that are only available as preliminary calculations that are in the process of re-evaluation) have not been included in the model runs. Thus, the results presented here for water deficits are conservative numbers and updates to the environmental flows will require follow-up and management.

The following recommendations for water quality monitoring are made for the Amatole system:

- Within all reservoirs: Besides the water quality variables routinely measured by DWA, inclusion of Chlorophyll a, microbial water quality, yearly assessments of dam capacity, turbidity, vertical profiles of DO, temperature, salinity, nutrients and toxin profile of sediments would be useful for modelling and management.
- Monitor effluent return flows for water quality in order to meet environmental and user water quality objectives.

- Monitor estuarine water quality for meeting future environmental water quality objectives.
- In all river reaches: Besides water quality variables routinely measured by DWA, inclusion of turbidity in all river monitoring gauges, and microbial water quality within tributaries leading to reservoirs is recommended.
- In WWTWs, besides the water quality variables routinely measured by DWA, inclusion of NO_3, problematic toxins and microbial water quality is suggested.

A primary focus in the project has been on water quantity and quality from the point of view of societal needs. Many of the TPCs are focused on the environmental flows, and thus, from both the quality and quantity side of view, the importance of environmental flows (or the ecological Reserve) needs to be stressed. This will require follow through on the preliminary Reserve that has been conducted.

10.6 Costs of additional monitoring

When altering a monitoring programme (including changing frequency of data collection or adding new sampling points), it is important to assess the reasons and costs for implementing a new programme (Lindenmayer et al., 2011). In the present case, planning for future climate variability and uncertainty along with increased demand for development purposes provide sufficient reasons that need to be balanced against costs.

- Reinstating of old stream flow gauging stations that are not recording any longer should not be very costly and thus is highly recommended.
- Installing a new gauge above the Nahoon Dam will need to be considered carefully as the cost can run close to a million Rands or more. As noted above, this gauge would be useful for monitoring flows in Nahoon River originating as natural flows and transfers from the Wriggleswade Dam.
- Modelling and monitoring evaporation from reservoirs can be done using remote sensing data and is recommended for reducing uncertainty in present data and under conditions of future climate. At present, an MSc student at the IWR (Sbongiseni Mazibuko) is conducting his thesis in this area. The IWR is working with the CSIR Cape Town (Dr Wesley Roberts) to further collaboration in this area in future.
- Water use data is essential for proper planning of future development scenarios. These data can be collated from meter readings obtained by the Buffalo City Municipality.
- Additional cost for monitoring water quality by Amatola Water, who have their own water quality laboratory, is in the range of R3 000-3 500 per sample, not including the costs of monitoring water constituents like pesticides (Dr Nikite Muller, *pers. comm.)*.

10.7 Way forward: Integrated monitoring and collaboration

Although the original focus of the present project was on water boards, the report’s results should be of interest to all people involved in water services delivery and water resources management. The emphasis in the project has been on quantifying the uncertainty in future predictions of available water resources and their quality. The results emphasize the importance of considering both the uncertainties in climate and development together for appropriate management measures to be implemented. One of the critical recommendations for future water resources management that is of relevance to all catchments, and that was heard from various stakeholders involved in the project (DWA, Amatola Water Boards, UWP, WRC and scientists), has been the importance of integrated management and monitoring across various groups in the catchment. This integration is also critical in reducing the uncertainty in future predictions. Collaboration is the key to moving forward in order to meet the three aspired principles of the South African National Water Act (no 36 of 1998): equity, sustainability and efficiency.

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APPENDIX A. APPLICATION OF THE WATERSHED ASSESSMENT MODEL

by

Bret Whiteley, MSc Candidate

A1 WAM overview

The Watershed Assessment Model (WAM) is a deterministic, distributed and physically based hydrologic watershed model, which represents the complex water quantity and quality responses within the terrestrial portion of the hydrological cycle, based on detailed characterisation data (see Figure A1). WAM simulates each of the main constituents important to water quantity and quality (water, total suspended solids, biological oxygen demand, soluble and particulate nitrogen and phosphorus) within a watershed. The model interface is housed within a Geographical Information System (GIS). The model was first developed in the 1980s to take advantage of the spatial datasets that were coming available. Today, WAM is a fully integrated ArcMap application where watershed characterisation data can be easily imported, edited and simulation results reviewed via the ArcMap interface.

A2 WAM Buffalo River setup

The Buffalo River setup in WAM required parameterisation of each component of WAM including Global Parameters (simulation period and climate), Source Cell Parameters, To-Stream routing and In-Stream routing.

A3 Standard calibration procedure in WAM

WAM is a primarily physically based model, which means if the input physical parameters (land-use, soils, hydrography, boundary conditions, and weather) are correct, then the resulting simulation results should be reasonable. The standard calibration procedure is thus designed to verify that each physical process of the model is being accurately represented at each major step in the simulation process so the physical parameters can be verified. These simulation processes are loosely broken into three sections:

1. Source cell nutrient load and flow generation.
2. Cell to stream routing.
3. In-stream routing.

For each of the processes, there are specific calibration techniques that have been developed. Additionally, it is essential to first calibrate the hydrologic and hydraulic (H&H) processes to ensure that the correct flows and stages are being simulated in the reaches, and then once these are found to reasonably match observed data, the calibration for the sediment and nutrient concentrations can be conducted. The calibration procedure is thus broken into three sections:

1. Hydrologic and hydraulic (H&H).
2. Sediment and sediment bound nutrients concentrations.
3. Nutrient concentrations.

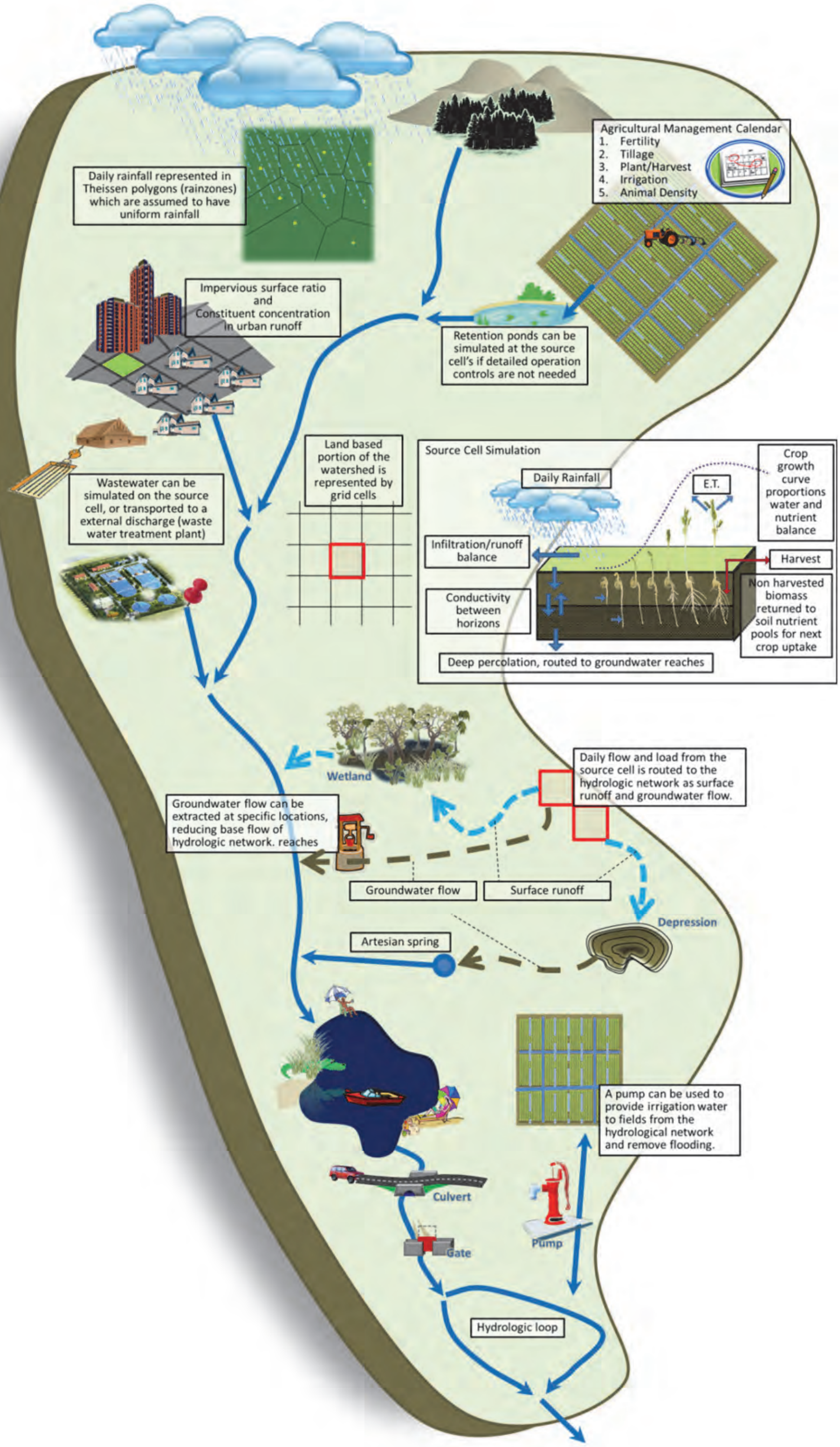

Figure A1 Conceptual watershed processes simulated in WAM

A4 Model results

Preliminary model results are presented in the Figures A2-A8 below.

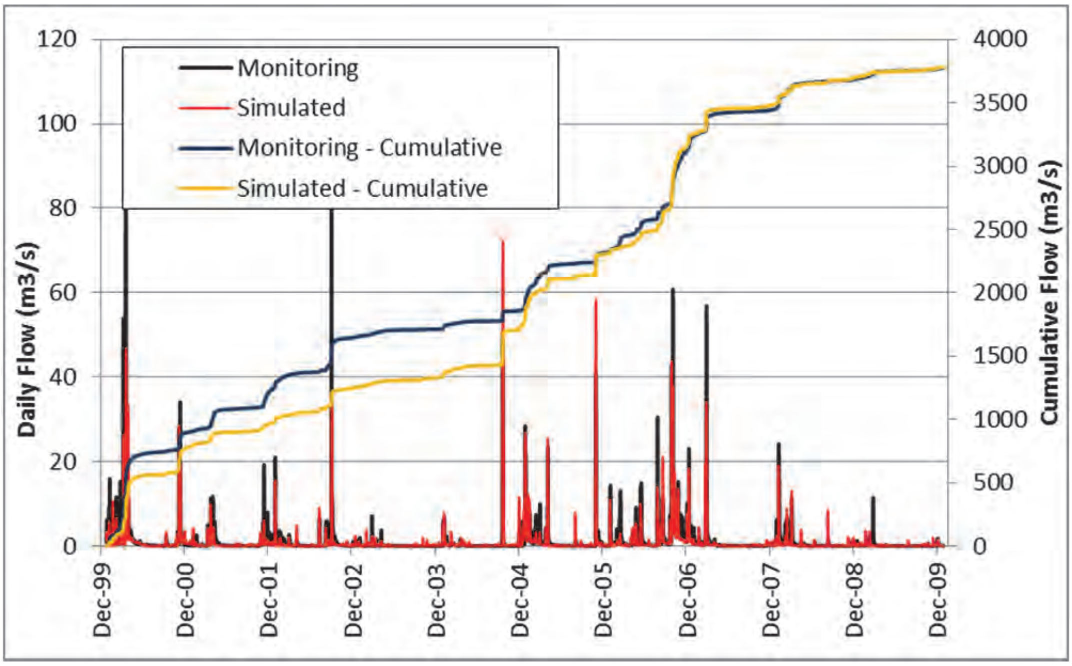

Figure A2 Visual comparison of flow at monitoring station R2H005.

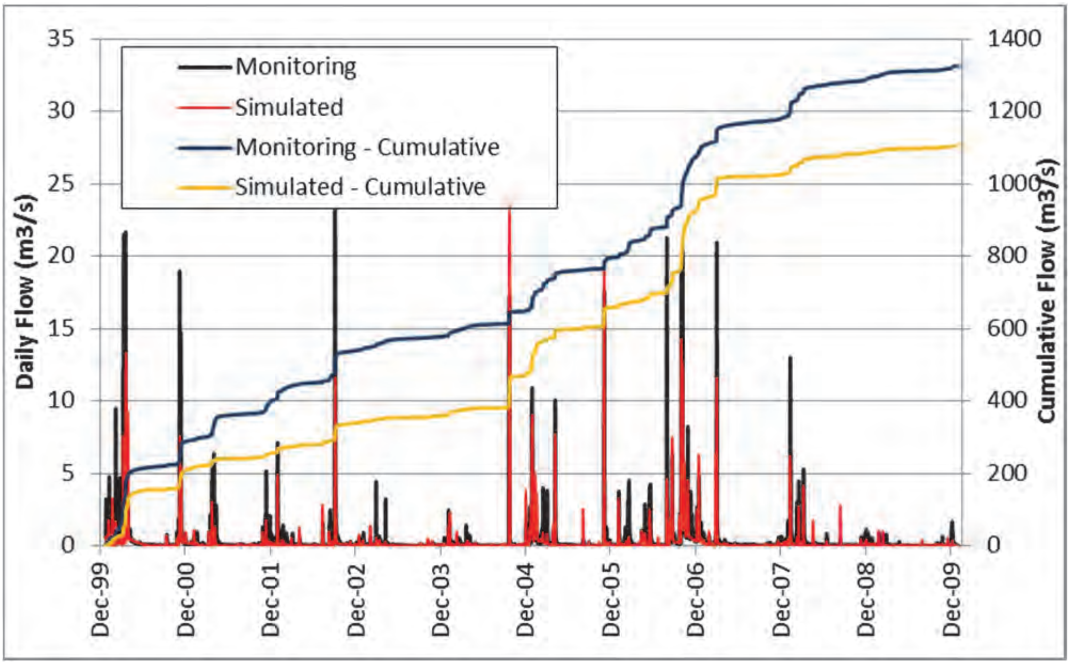

Figure A3 Visual comparison of flow at monitoring station R2H006.

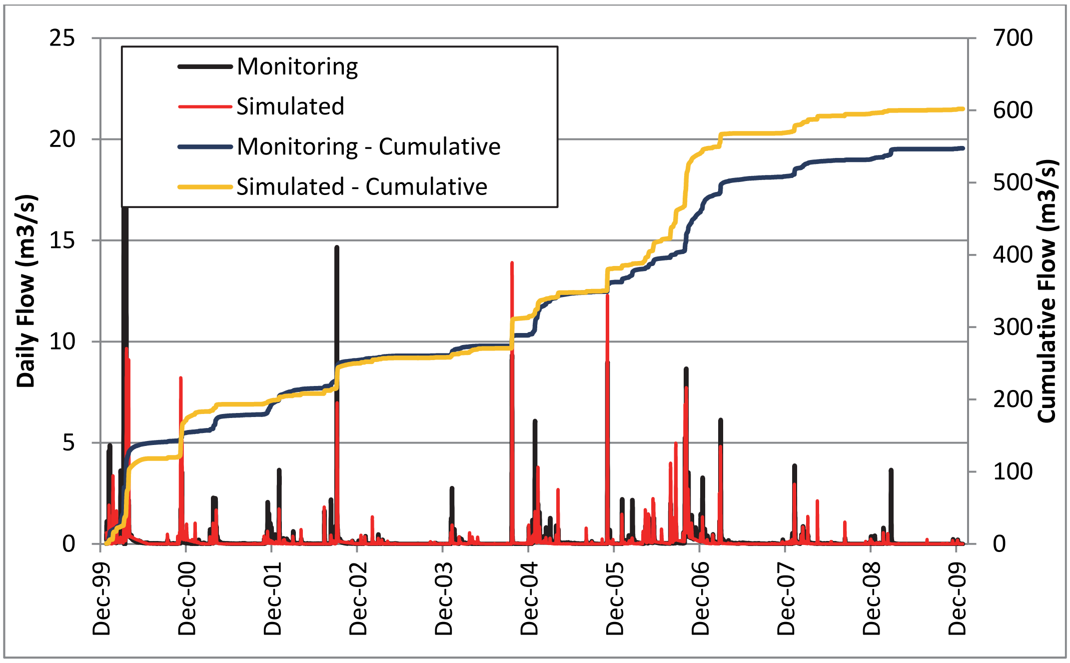

Figure A4 Visual comparison of flow at monitoring station R2H008

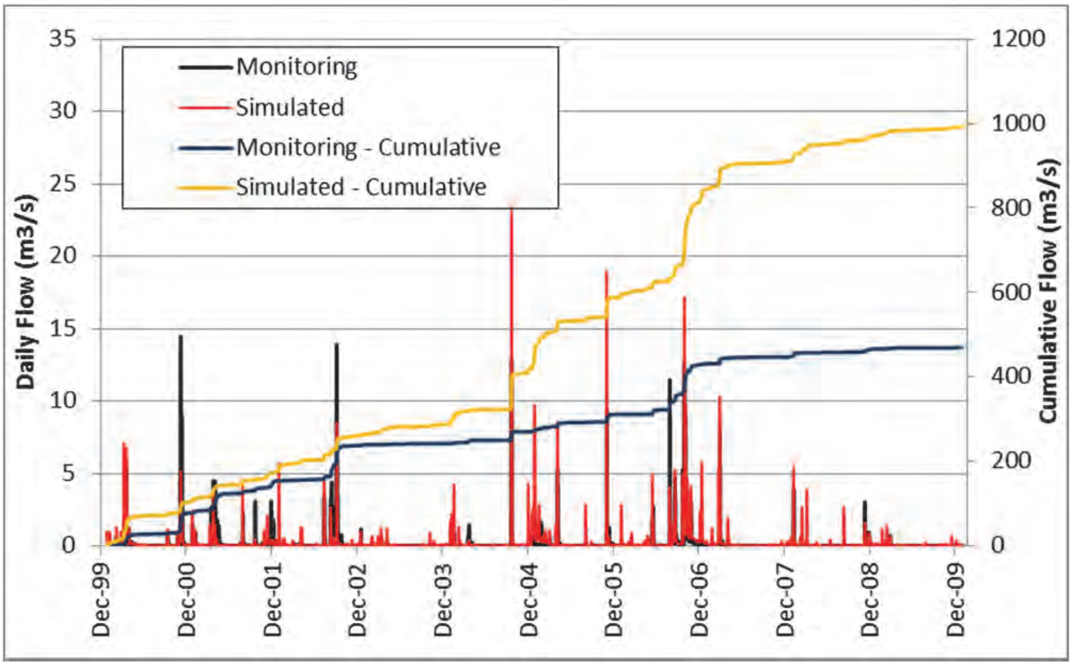

Figure A5 Visual comparison of flow at monitoring station R2H009.

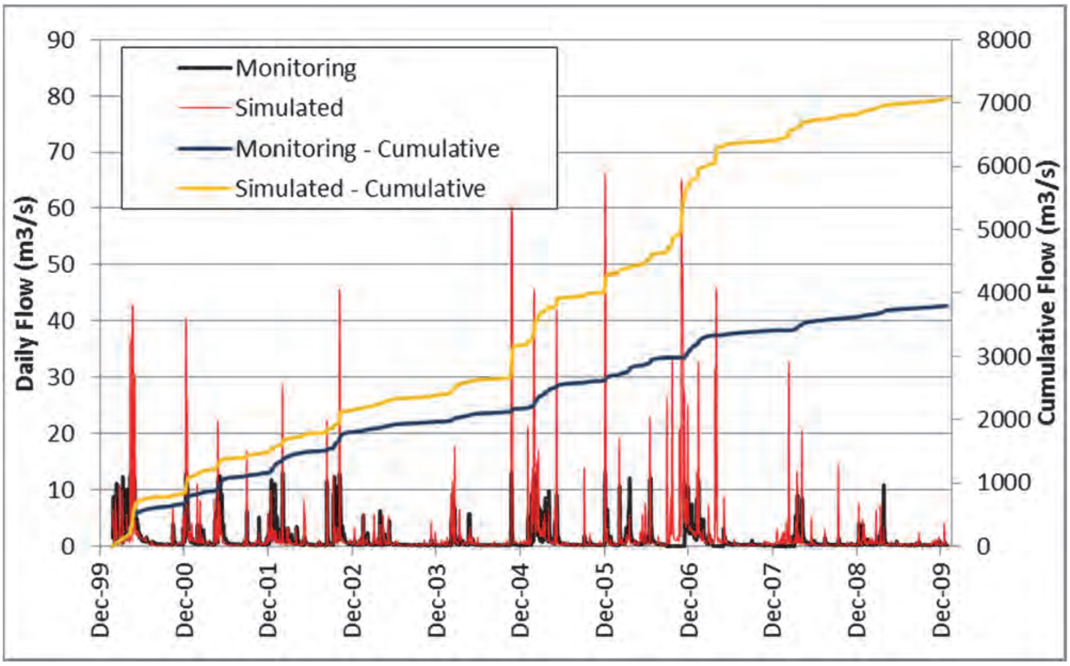

Figure A6 Visual comparison of flow at monitoring station R2H010.

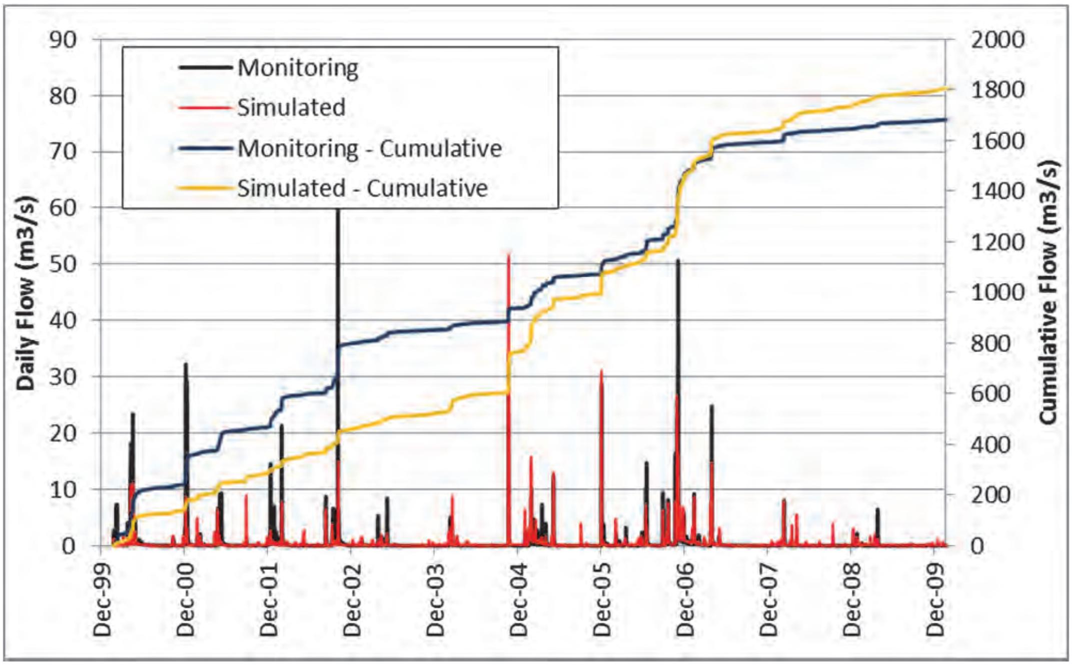

Figure A7 Visual comparison of flow at monitoring station R2H015.

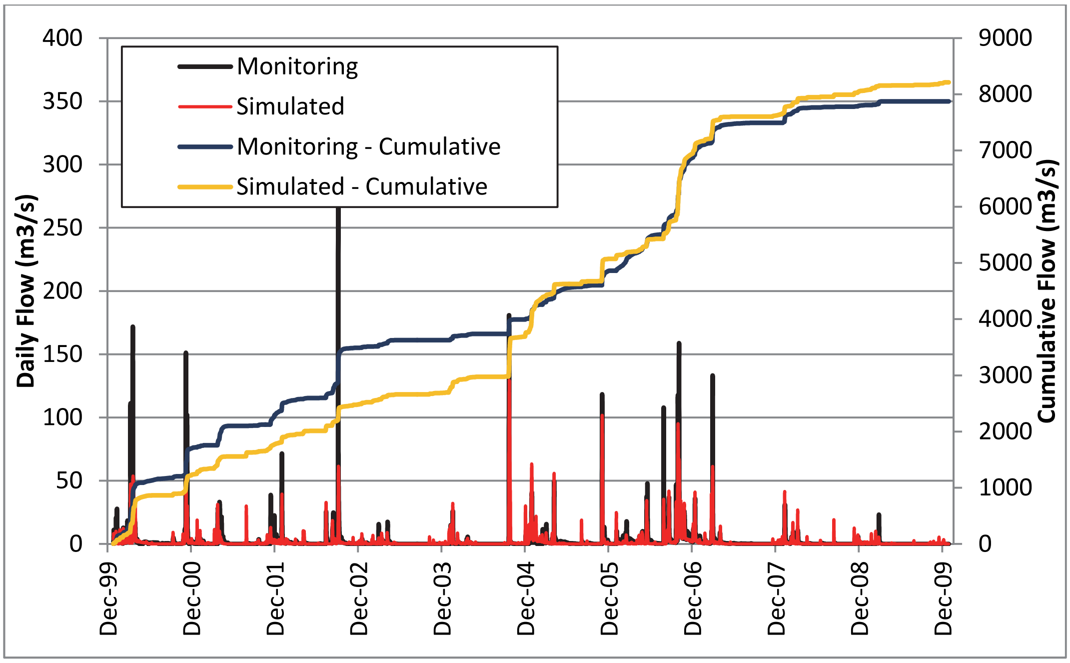

Figure A8 Visual comparison of flow at the discharge from Laing Dam.

APPENDIX B. DAILY CLIMATE CHANGE ANALYSIS

by

Thabiso Mohobane, PhD Candidate

B1 Daily rainfall analysis

Throughout the climate change and water resources modelling studies undertaken for this project, monthly time series of rainfall data have been used. However, these data sets have the potential to mask other possible changes in future climates that occur at sub-monthly time scales. These include extreme short-period rainfalls and relatively short durations of low rainfall. This chapter of the report provides some further detailed analyses of the CSAG-downscaled climate data for the nine GCMs for the near-future (2046-2065) and the far-future (2081-2100) scenarios compared to the equivalent climate model baseline data (1961-2000). In these analyses, the rainfall data have not been bias corrected to WR2005 rainfall characteristics, as the intention is to compare the changes predicted for each GCM. The raw CSAG data are based on quinary catchments, and two example quinary catchments were selected from the Amatole and Caledon basins.

Quinary 4010 is located within the upland part of the Amatole basin, while 4026 is located on the coast. Quinary 1749 lies within the more arid westerly parts of the Caledon basin, while 1676 is within the mountainous Lesotho parts of the basin in the north-east.

B2 Methods

Three analytical methods were used to detect changes in the daily rainfall characteristics as predicted by the nine climate models: 1) annual and seasonal threshold analysis; 2) probability of exceedence analysis and; 3) frequency of dry spells occurrences.

B2.1 Annual and seasonal threshold analysis

The maximum number of days of ‘dry spells’, defined as cumulative rainfall below several prescribed thresholds of 2, 5, 10, 15, 20 and 50 mm were determined in all the models for the three climate scenarios. The maximum lengths of the dry spells were analysed using all the data (annual time scale) as well as separate seasonal analyses, based on summer (October-March) and winter (April-September).

B2.2 Probability of exceedence

The daily rainfall data were ranked and differences between the climate scenarios assessed on the basis of the frequency (or probability) of rainfalls exceeded 0.1, 1, 10 and 15% of the time. The main focus was on the extreme rainfalls with low frequencies of exceedence.

B2.3 Frequency of dry spells

This analysis involves quantifying the frequency of dry spells, defined by cumulative rainfall below thresholds of 5, 10, 20, 50 mm, with durations of 10, 30, 60, 180, 270, 360, 720, 1 440, 1 800, and more than 1 800 days.

B3 Uncertainty results

B3.1 Annual and seasonal threshold analysis

For quinary 4010, there are no clear trends across the range of the nine GCMs with different directions of change from baseline to near future and near future to far future (Figures B1, B2a and B2b). The 20 mm threshold shows the most consistency with reductions in maximum durations into both future periods for several models. Much the same conclusion can be reached for quinary 4026, although all models suggest a quite substantial decrease in the maximum duration below 50 mm for the annual analysis. There are many situations where the direction of change between the baseline and near future is reversed into the far future period. The implication is that these changes are not significant trends but random fluctuations of maximum dry spell characteristics across several different simulated rainfall time series.

Within the Caledon basin, the data for quinary 1749 (the drier part of the basin) suggest a reduction in wet season spells below the low rainfall thresholds of 2 and 5 mm. However, as with the Amatole region it is very difficult to make any generalisations for either of the Caledon sample points, and the same reversal of change between the two future scenarios is often observed.

The overall conclusion is that there are few consistencies in the direction and magnitude of change in maximum spells below defined rainfall thresholds. This lack of consistency applies across the different GCMs for the same future scenario, as well as between future scenarios for the same GCM.

B3.2 Probability of exceedence

Table B1 illustrates the ratios of rainfall exceeded by the four percentiles for changes from baseline to near future and baseline to far future for quinary 4010 (also see Figure B3). While there are some models that suggest quite large increases in the extreme rainfalls (exceeded 0.5% of the time), other GCMs suggest decreases of as much as 20%.

As with the previous assessments of dry spells, there is little agreement between the different GCMs. However, there is more consistency within individual GCMs, such that a predicted increase (or decrease) in extreme rainfall for the near future typically continues into the far future. All of the other quinary catchments show similar results, albeit with different magnitudes of change.

B3.3 Frequency of dry spells

Within the Amatole region, the results suggest, rather inconclusively that the frequency of occurrence of relatively short dry spells below the rainfall thresholds up to 20 mm could increase (see Figure B4). Not all models agree with this trend but there are more GCMs suggesting an increase in frequency than a decrease. The patterns of predicted change for the 50 mm threshold are far less consistent with many differences between GCMs and within GCMs for the near and far future scenarios. The latter result is reasonably consistent with the conclusions reached in the section on annual maximum duration of dry spells. The Caledon region shows similar results with little consensus between the GCMs.

Table B1 Ratios of rainfall exceeded 0.5, 1, 10 & 15% of time for Baseline to Near and Baseline to Far future.

	NEAR: BASE					**FAR: BASE**			
Percentage Exceedence	**0.5**	**1**	**10**	**15**		**0.5**	**1**	**10**	**15**
CCCMA	1.0	1.1	1.2	1.2		1.0	1.1	1.2	1.4
CNRM	1.3	1.2	1.1	1.2		1.3	1.2	1.2	1.3
CSIRO	1.0	1.0	1.2	1.2		1.3	1.1	1.3	1.3
GFDL	1.0	1.0	1.0	0.9		1.0	1.0	1.1	1.1
GISS	1.0	1.0	1.0	1.0		1.3	1.0	1.1	1.1
IPSL	0.8	0.8	0.9	0.9		0.8	0.8	0.9	0.9
MIUB	0.8	0.8	1.0	1.1		0.8	0.8	1.2	1.5
MPI	1.0	1.0	1.1	1.0		1.0	1.0	1.2	1.3
MRI	1.0	1.0	1.2	1.3		0.8	1.0	1.2	1.2

B4 Discussion and conclusions

A great deal of uncertainty between different GCMs was noted within all of the hydrological simulations based on monthly rainfall and temperature data in both regions. The same conclusion is reached when original daily rainfall data for the nine downscaled GCMs are subjected to detailed analysis. The analyses used have attempted to identify any trends in the frequency or magnitude of both high rainfalls and the durations of dry periods or droughts. Contrary to what is often reported (without such detailed analyses of the data as reported here), the CSAG downscaled daily rainfall data do not support the idea that the climates of these two regions will become more extreme in the future.

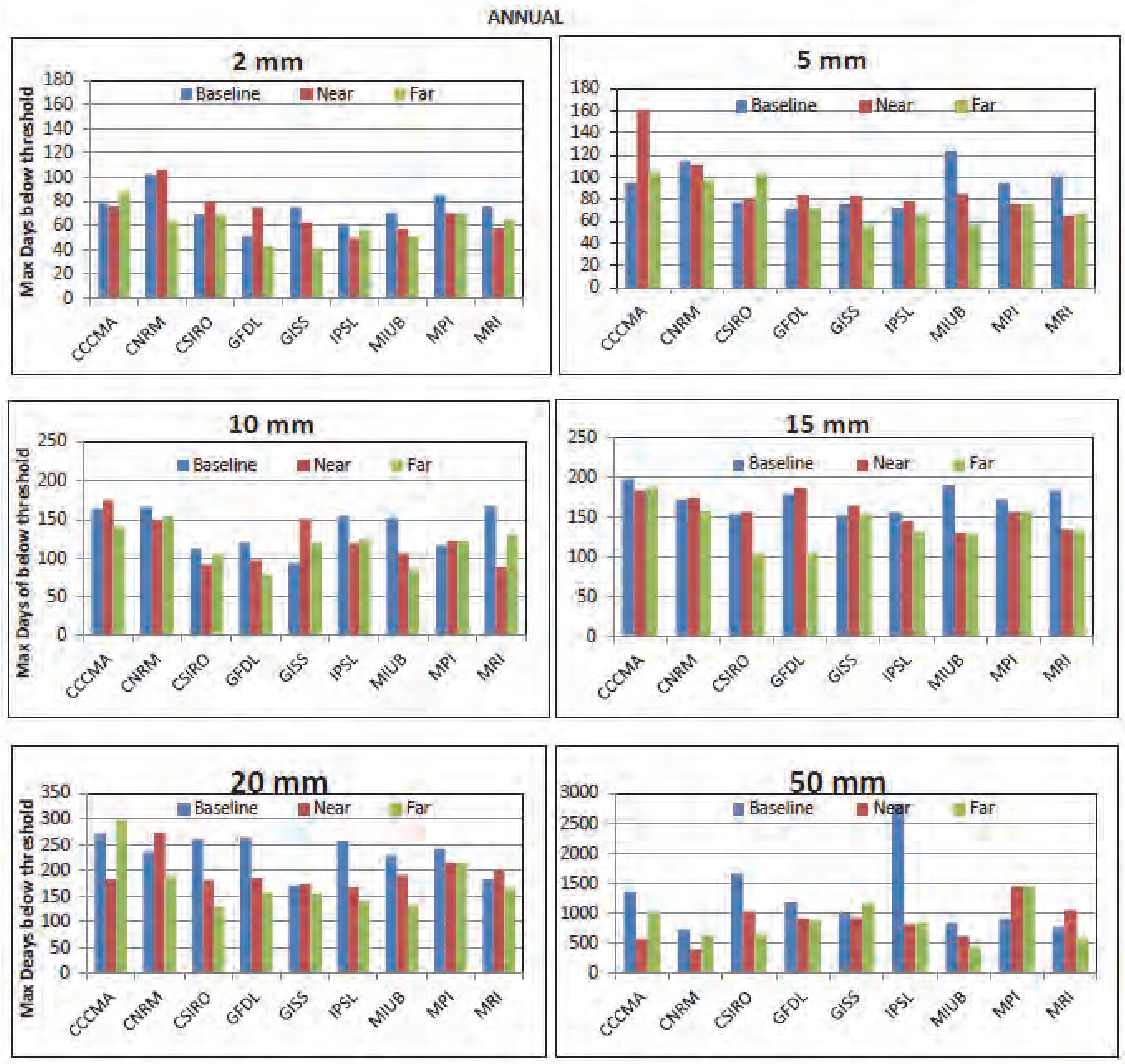

Figure B1 Maximum number of days with rainfall below the stated threshold at Quinary 4010.

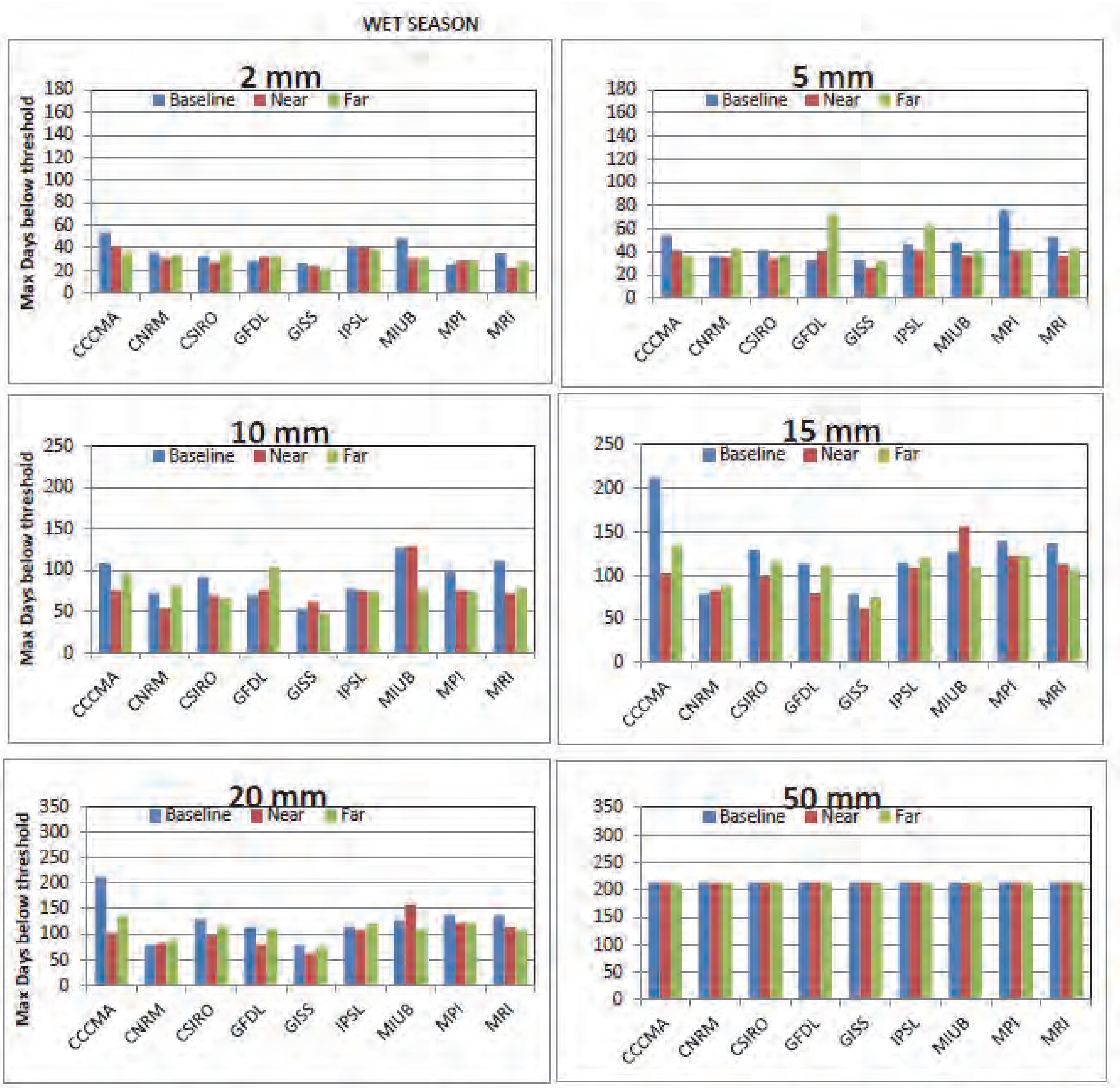

Figure B2a Maximum number of days with rainfall below the stated threshold at Quinary 4010 for wet season.

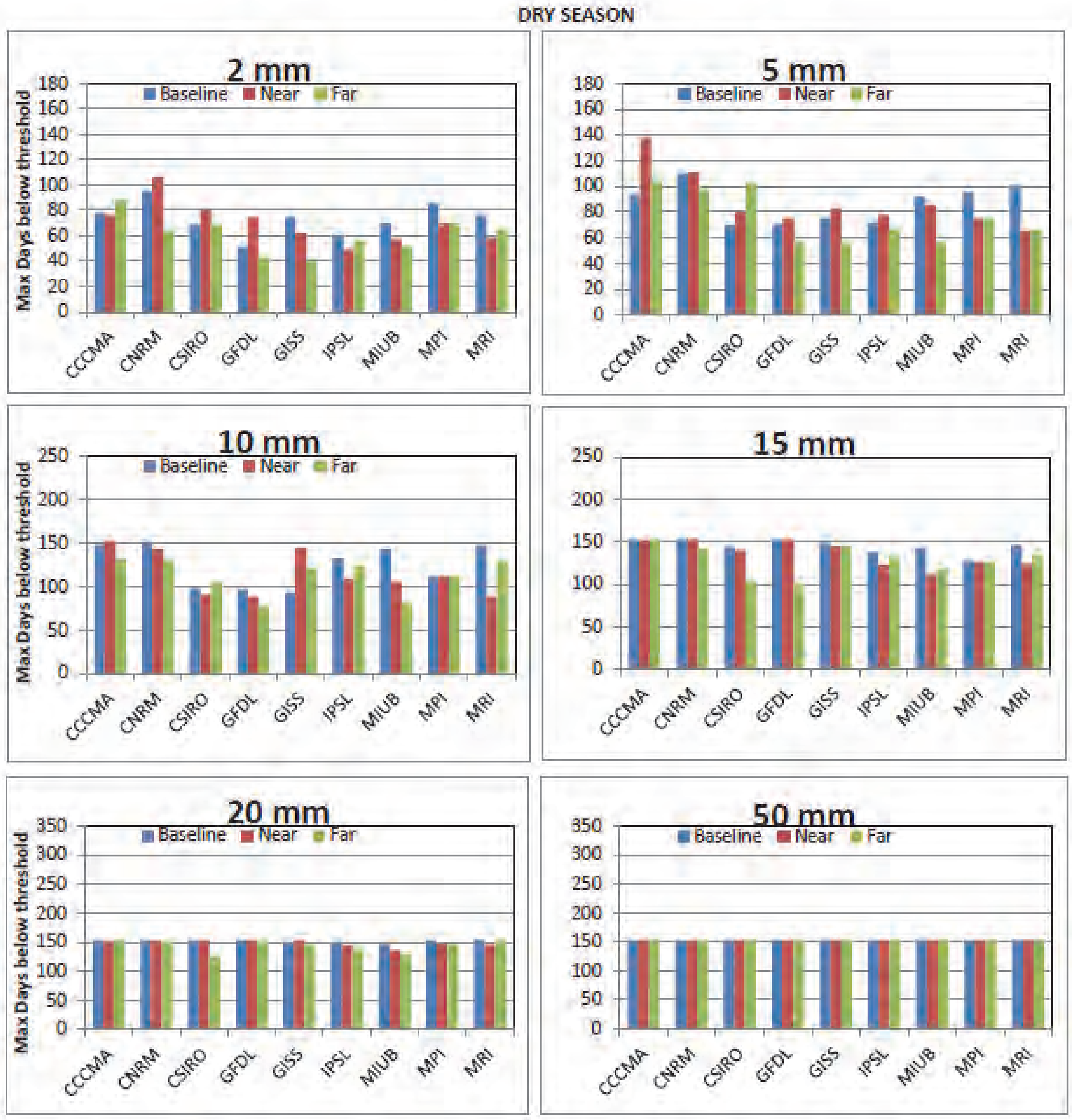

Figure B2b Maximum number of days with rainfall below the stated threshold at Quinary 4010 for dry season.

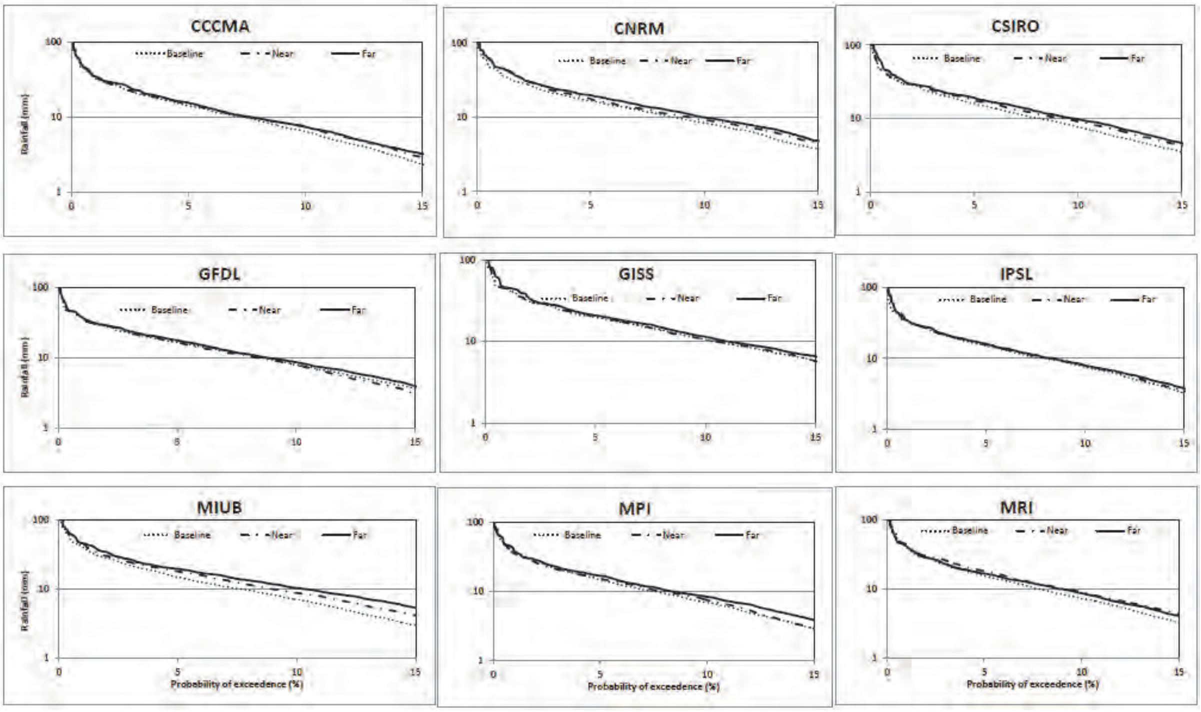

Figure B3 The amount of rainfall equalled or exceeded in Quinary 4010.

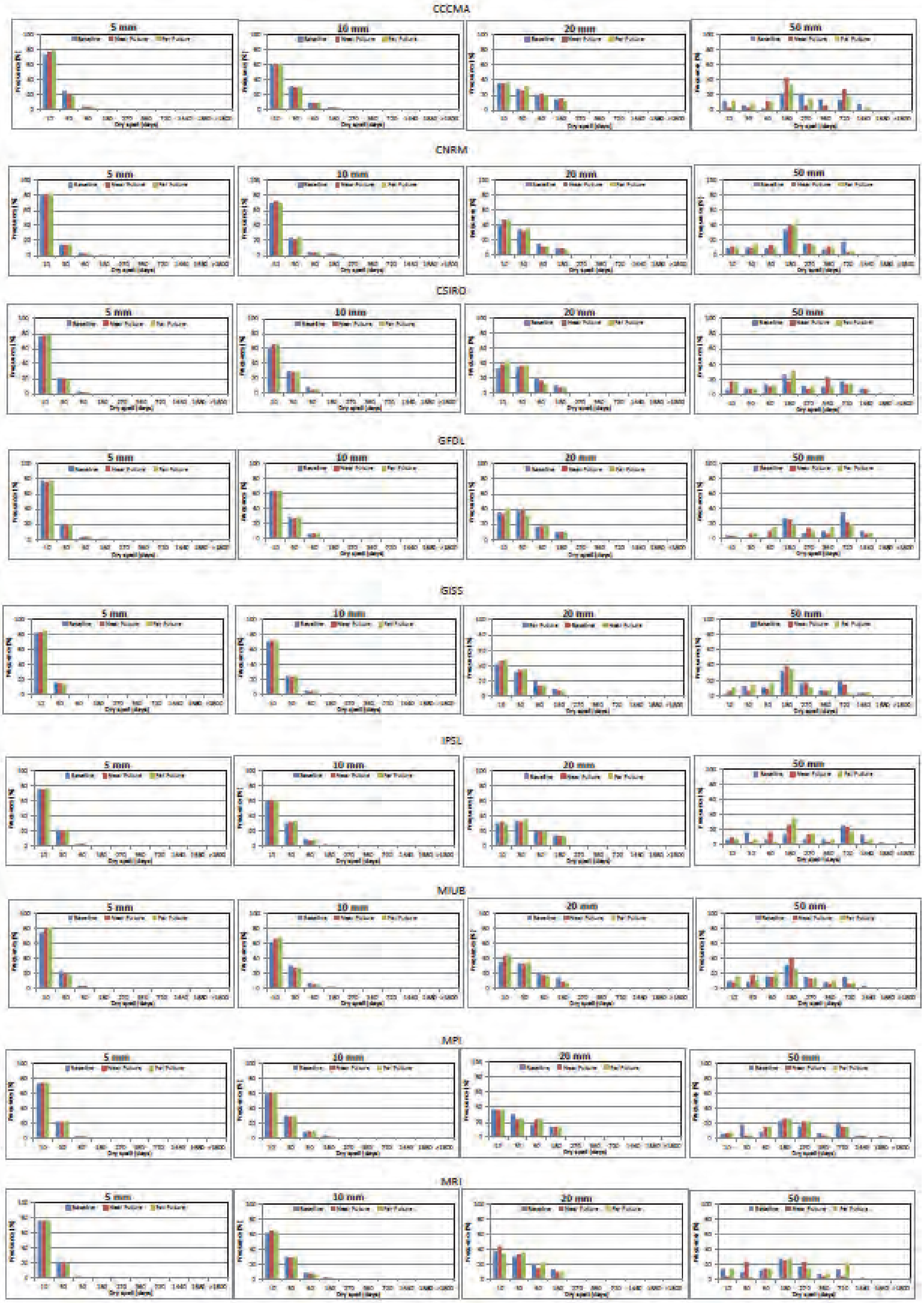

Figure B4 Frequency analysis of dry spell for prescribed rainfall thresholds at Quinary 4010.

APPENDIX C. WATER USE AND CONSERVATION BY HOUSEHOLDS IN KING WILLIAMS TOWN

by

Kelly Faye Stroebel, Honours Student

C1 Introduction

The access to basic water services is becoming increasingly difficult for the growing population in the 21st century yet, is a vital part of human development and survival. In South Africa, several changes were promoted by the 1998 National Water Act, yet despite the attempt at reforms, water is politically contested and often separated over socio-economic lines. This study aimed at assessing water use, quality, conservation as well as perceptions of future water supply under a changing climate in King William's Town.

C2 Study area and methods

This study was undertaken in King William's Town and the neighbouring township of Ginsberg (32° 53' 0" S, 27° 24' 0" E), which forms part of the Buffalo City Municipality in the Amathole district of the Eastern Cape. The Buffalo City Municipality contains 15% of the population in the Eastern Cape. King William's Town is situated on the upper stretches of the Buffalo River and receives about 502 mm of rain per year, with the majority of rainfall occurring during summer (River Health Programme, 2004). Questionnaires were administered to 60 households in the suburbs of King William's Town and 60 from the neighbouring township of Ginsberg in order to understand the households' socio-economic characteristics, water use and perceptions of quality and awareness and views on threats to their water supply in the future.

C3 Results and discussion

Water consumption patterns were found to be consistent across socio-economic groups, seen in Table C1. Although the households are consuming similar amounts of water on average, due to the large difference between the mean total household incomes per month for each group, the proportion of income spent on water per month varies widely. A major limitation of the study was that some respondents quoted their monthly water and electricity bill together, as they were not aware of their expenditure on water per month alone. Thus, only the households that showed their water bill (in order for only the amount spent on water to be established) were used to obtain the mean monthly water bill for each income group (Table C1).

Table C1 Socio-economic descriptive statistics of households, including expenditure on water, for each income group.

	Income Group							
	Urban High (n=30)		**Urban Middle (n=30)**		**Township Middle (n=30)**		**Township Low (n=30)**	
Mean (±S.D) total household income/month	R46 042.00 (9666.1)		R22 153.00 (6266.0)		R16 566.70 (7228.7)		R2 001.70 (1644.2)	
Mean (±S.D) Household size	4 (1.2)		4 (1.5)		4 (1.1)		3 (1.2)	
% of households relying solely on pension or social grants for income (unemployed)	0		13.3		15		46.7	
Mean (±S.D) household expenditure on water/month	R362.4 (87.7) (n=20)		R327.6 (93) (n=19)		R392.1 (103) (n=23)		R215.4 (93) (n=22)	
Mean proportion of total household income spent on water/month (%)	0.8		1.5		2.4		10.8	
Mean (±S.D) per capita expenditure on water/household/month	R93.6 (40.3)		R112 (62.2)		R125.3 (58.2)		R95.9 (73.7)	
No. years of formal education by household head (%)	< *7*	0 %	< *7*	0 %	< *7*	0%	< *7*	30 %
	7-12	13 %	*7-12*	43 %	*7-12*	30 %	*7-12*	50 %
	> *12*	87 %	> *12*	57 %	> *12*	70 %	> *12*	20%

Table C2 highlights that the highest proportion of households with rainwater tanks was in the urban high income class (27%), all of which were their own installations. This emphasises the influence of socio-economic factors such as income on households' ability to install and use alternative sources of water. Water supply and treatment technology may have a direct effect on the livelihoods of individuals in the household and may provide water for multiple uses, decreasing vulnerability during dry periods and increasing security of supply. Of the households that did have rainwater tanks in each income classes, 100% of households found them a useful asset for mostly non-drinking purposes such as watering their gardens and filling their pools. This may decrease monthly water costs (Table C1) as municipal water is not excessively used for these outdoor activities which use large quantities of water. Importantly, none of the rural low-income households had access to water from a rainwater tank; however, 90% stated that they would install one given a partial rebate from the municipality, as these were seen as costly items which were not of a major current priority to the households in this class.

Table C2 Use of collected rainwater by households with a rainwater tank for each socio-economic income group (UH=urban high-income, UM= urban middle-income, TM= township middle-income, TL= township low-income group).

	Income group (%)			
	UH	**UM**	**TM**	**TL**
Percentage of total households with rainwater tanks (n=30)	27	17	3.3	0
Percentage that have found it useful	100	100	100	0
Use of rainwater from tank for drinking	12.5	20	0	0
Use of rainwater from tank for non-drinking purposes	81.5	80	100	0
Households without tanks that would install one given a partial rebate from the municipality	77.3	64	100	90

A series of attitudinal questions regarding water conservation practices and attitudes were posed to the respondents. They rated their answer on a strongly agree to strongly disagree likert scale (n=30). The attitudinal statements posed were as follows:

"South Africa is a water scarce country"

"My community is doing what they can to conserve water"

"It is important that people use water sparingly and conservatively"

"People should shower rather than bath to conserve water"

"I am thinking about ways to save water in my household"

An ANOVA was performed on the mean score for each income group and it was established that there was a significant difference between the answers given by each income group (F=6.07, df=3; p<0.001). This indicated that the urban high and middle-income group showed demonstrated more knowledge towards water conservation issues and showed a higher level of concern regarding water scarcity and conservation. Thus, levels of knowledge regarding water concentration issues and attitudes are generally low in the township households and this issue needs to be addressed should the municipality aim to overcome concerns of water scarcity and demand through the promotion of water conservation.

Rainwater harvesting using household tanks appears to be one of the most promising alternatives for water supply in the face of increasing water scarcity and escalating demand. This highlights an important option for the municipality to consider in terms of residential water supply in the face of uncertainties, and they play a very important role in encouraging the use alternative sources of water and water conservation. The municipality should thus attempt to advertise the benefits households may obtain from engaging in water conservation activities, as this may ultimately decrease the pressure on their residential water supply services. Previous studies (Willis *et al.,* 2011) have shown that households with positive attitudes towards water conservation and sustainable use, and that have higher levels of environmental concern, have significantly lower levels of consumption in behaviourally influenced water end uses. This is consistent with the results of this study, as the urban high-income group, who had the largest percentage of households that engaged in all types of water conservation activities, had a lower mean monthly water bill than the urban middle and township middle-income groups (Table C1). Issues relating to the socio-economic characteristics of the township low-income group, such as unemployment and low education levels, may prevent them from affording alternatives or understanding the benefits of water conservation. Hurlimann (2011) found that there are several barriers the use of alternative water sources, mainly inflexibility of existing infrastructure, cost, policy and housing status. These barriers need to be addressed in the face of increasing demand and climate change.

C3.1 Awareness and understanding of threats

Respondents were asked an open-ended style question about what they understood in terms of threats to the catchment and what would change the availability and quality of the water in King William's town. This was aimed at understanding what people understood about threats posed by climate change across the socio-economic classes. The limitation of this result is that the knowledge on this topic was only gained from the respondent, who may have been the most educated member of the household. The urban high-income class showed a much greater understanding of the role of climate change in their water supply and quality, whereas the other classes demonstrated a lack of awareness of this as a threat. Several 'themes' were drawn from the respondents' understanding of climate change threats to water supply and quality, as well as some non-climatic threats that they identified as threatening, seen in Table C3. The urban and township respondents had different ideas and knowledge on threats from climate change, with 8% of township respondents having no ideas ("not sure') and 17% of urban respondents having no ideas or not willing to engage in discussion on this topic.

A few respondents highlighted some interesting points through this qualitative discussion. One respondent from the township middle-income group stated:

"There is no education and awareness program for the Buffalo River and the Municipality should implement this"

A respondent from the urban high-income group stated:

"The people in the RDP housing and the township are less wasteful than people in the suburbs. People in the suburbs are not aware of the water crisis"

As these comments and the information in Table C3 highlight, there are many discrepancies in the basic understanding of the notion of "threats posed by climate change" between the township and urban households. Many of the township residents did not consider climate change as possibly having a major effect on their water supply and quality in the future. The ideas that were put forward by township residents have ties to climate change (i.e. increase in frequency of storms), however, these respondents did not make this link, and saw other issues such as increase in dumping and pollution as more threatening. It must be acknowledged that the notion of "climate change" was not clear to many of the township respondents, which reflects the lack of knowledge, awareness and understanding of this concept in many rural areas of South Africa, resulting in an increase in vulnerability and an effect on the resilience of township communities. As the results indicate, there is a knowledge gap between the minority of the population who have received an adequate education, and the underprivileged majority who have not. This highlights a major barrier to climate change adaptation in South Africa, as the most vulnerable individuals lack a basic understanding of these threats and how to adapt to them.

Table C3 Main knowledge themes on climate change and non-climate related threats to King Williams Town's water supply and quality in the future of urban and township respondents.

	Urban respondents (n=60)	**Township respondents (n=60)**
Climate change related ideas	-Decrease in amount of annual rainfall, causing a lack of water in the catchment. -Lack of rainfall to fill the dams that supply King William's town with water. -More frequent droughts placing a stress on agriculture as well as residential water demand.	-Increase in frequency of storms which causes the water quality to worsen drastically. -Floods worsen the quality of the Buffalo River as waste is picked up and carried by the water.
Non-climate related ideas	-Growing informal settlements using and polluting water (washing, bathing, littering etc.). -Factories and industry releasing effluent which worsens the quality of water for the residents -Agricultural sector uses a large proportion of the catchment's water, polluting the Buffalo River.	-People dump waste and pollute the Buffalo River, causing a worsening of the quality. -Livestock are left to graze near the river and dead livestock are dumped on the river banks. -Factories release chemicals and waste into the river and the municipality should be responsible for cleaning the water. -Sewerage leaks into the river.

C4 Conclusion

This study highlights important information regarding household water use and activities and adequacy of water services in King William's Town in terms of water supply and quality, water conservation by households and the understanding of climate change threats to water supply at an individual and household level. Socio-economic variables have been found to be important in establishing differences in water uses across socio-economic groups in a South African context. Differences in levels of income have had an effect on households' ability to adapt to changes in water supply and frequency through the use of alternative sources as well as the engagement in water conservation activities. The results highlight how an increase in income and economic development at a household level will have an effect on overall residential water demand, and will increasingly place an immense amount of pressure on municipal water service delivery. The ability of municipal water service authorities and managers to cope with this increasing demand in the face of climate change is an important area for further study and understanding.

Nevertheless, it is important to primarily understand the reasons for different household water uses, quantities and attitudes in order to set the basis for integrated water resource management. Several factors need to be considered in the planning for climate change impacts on local water resources in King William's Town, such as future water use, demand, water resource management and conservation strategies and projected climate change impacts at a catchment level. It is thus clear that in the face of climate change impacts on water supplies and the level of uncertainty associated with these impacts, making modifications to processes and demands for existing systems and water users such as rainwater harvesting, water conservation, catchment level planning, stakeholder participation, and household education and awareness needs to be encouraged and supported by the municipality and government institutions so as to reduce vulnerability and increase resilience across all socio-economic groups.

C5 Acknowledgements

This study was funded and supported by the Institute for Water Research, Water Resource Commission and Department of Environmental Science, Rhodes University. I would like to sincerely thank Dr Sheona Shackleton and Dr Sukhmani Mantel for their supervision and support throughout the study. In addition, I would like to acknowledge and thank Kathy Cassidy, Dabula Maxam and Amy Bushell for aiding in GIS, sampling and collection.

APPENDIX D. PROJECT OUTPUTS

Conference presentations since inception of project:

- Hughes, D. and Muller, N. (2010) *Hydrological model and data analysis support for climate change adaptation strategies within a South African water board.* Presentation at the 3rd BHS British Hydrological Society International Symposium, Newcastle, UK.
- Hughes, D., Mantel, S.K. and Mohobane, T. (2011) *An assessment of the skill of down-scaled GCM products in simulating historical patterns of rainfall variability*. Presentation at the 15th SANCIAHS National Hydrology Symposium, Rhodes University, Grahamstown, South Africa.
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Scientific papers/ publication:

- Hughes, D. and Muller, N. (2010) Hydrological model and data analysis support for climate change adaptation strategies within a South African water board. In: *Role of Hydrology in Managing Consequences of a Changing Global Environment*, *Proc. 3rd BHS British Hydrological Society International Symposium*, Newcastle, UK.
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- Hughes, D.A., Mantel, S.K. and Mohobane, T. (in review) An assessment of the skill of downscaled GCM outputs in simulating historical patterns of rainfall variability. Submitted to *Water Research*.

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- Hughes, D., Mantel, S.K. and Slaughter, A.S. (2011a) *Quantifying Water Quantity and Quality Impacts Associated with Climate Change: Preliminary Results for the*

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- Hughes, D., Mantel, S.K. and Slaughter, A.S. (2011b) *Report on the outcomes of the Second Workshop*. Fourth deliverable for WRC Project K5/2018, Report number K5/2018/4. Water Research Commission, Pretoria, South Africa.
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APPENDIX E. WEAP MODEL SETUP

E1 Input hydrology for river tributaries

The input hydrology of the Buffalo River tributaries was estimated using the FAO rainfall-runoff option in the WEAP model. Rainfall data estimated for individual quaternaries from the WR2005 database (Middleton and Bailey, 2008) were entered for each tributary.

The other data required by WEAP for inflow determination of upstream reaches using the Rainfall-Runoff (FAO) method are:

Area – catchment area in Km^2 was obtained from WR90.

Kc (crop coefficient) – Set to 1.

Effective Precipitation (%) – % of precipitation available for evapotranspiration, while the remainder is direct runoff. It was calculated as a linear regression equation based on the quaternary's monthly precipitation as follows:

Eff Prec R20A = 80 – 0.09 × Prec R20A Equation 1

Eff Prec R20B = 95 – 0.03 × Prec R20B Equation 2

Eff Prec R20C = 95 – 0.09 × Prec R20C Equation 3

Eff Prec R20D = 100 – 0.03 × Prec R20D Equation 4

Eff Prec R20E = 100 – 0.05 × Prec R20E Equation 5

Eff Prec R20F = 95 – 0.03 × Prec R20F Equation 6

Eff Prec R20G = 95 – 0.03 × Prec R20G Equation 7

Eff Prec R30E = 95 – 0.05 × Prec R30E Equation 8

Eff Prec R30F = 95 – 0.05 × Prec R30F Equation 9

The equations were determined to match the present day simulated flows with observed flows at the stream gauges.

Precipitation – monthly rainfall data for quaternaries determined from WR2005 data (Middleton and Bailey, 2008).

ET_{ref} – monthly evapotranspiration (mm) for a reference land class was estimated from the annual S-pan evaporation for quaternaries (SPATSIM; Hughes et al*.,* 2000). Percentage monthly evapotranspiration was obtained from WR90 (see Figure E1).

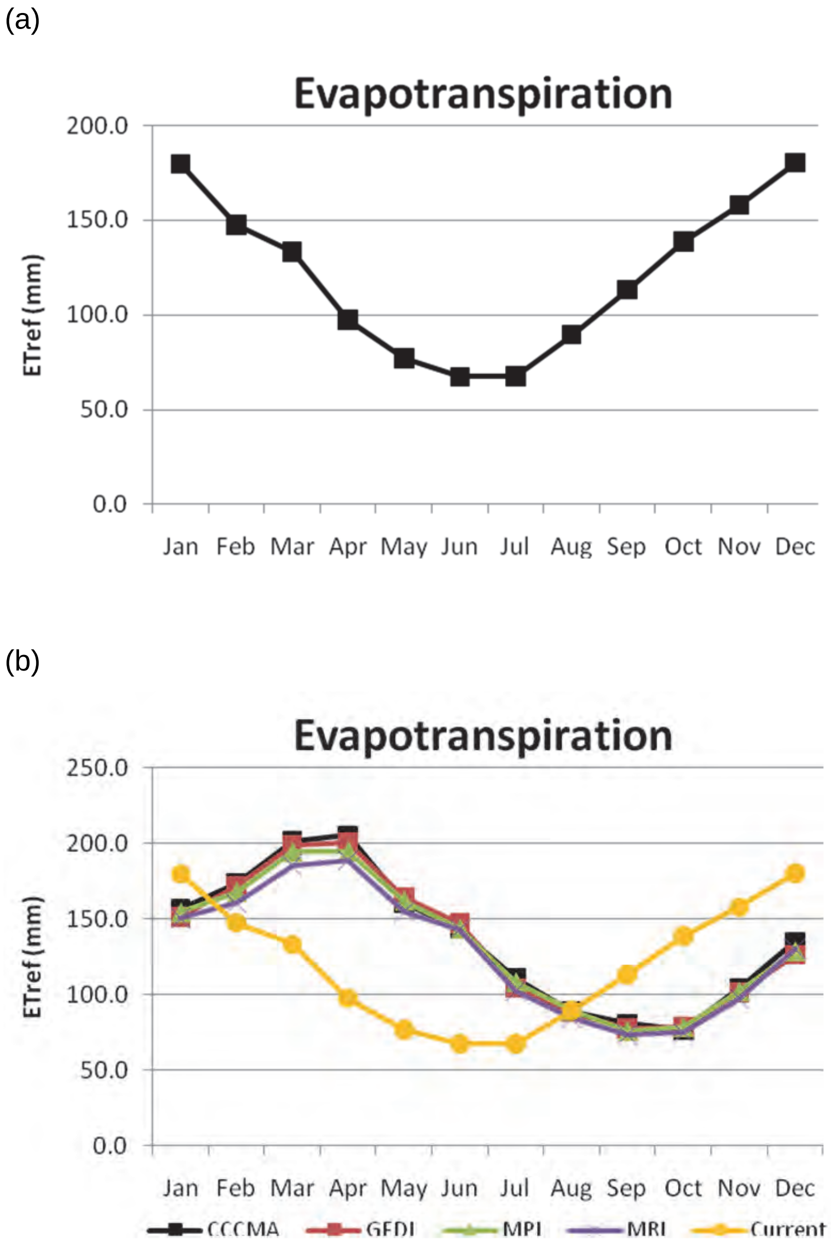


Figure E1 (a) Monthly distribution for current evapotranspiration (ETref) estimated for the WEAP model for R20 catchment quaternaries. (b) Comparison of average monthly evapotranspiration for current versus four other climate change scenarios for R20 catchment quaternaries.

E2 Reservoir data

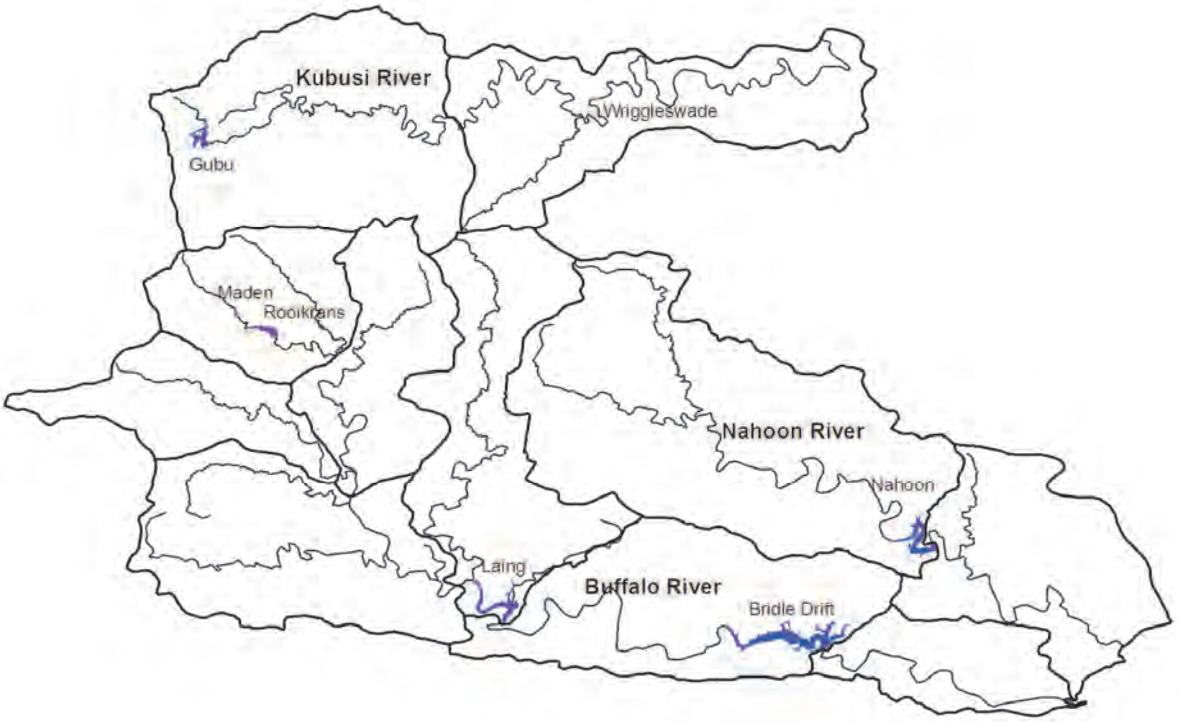


Figure E2 Location of the four reservoirs on the Buffalo River that were entered into the WEAP model.

The location of the reservoirs on the Amatole system is shown in Figure E2. Reservoirs are considered to be demand sites in terms of water storage. In the WEAP model, each demand site needs to be assigned a “priority level” that is defined by the user in order to prioritize allocation of river flow. The priority level for the reservoirs (shown in Figure E2) was set at priority level 5, which indicates that filling of the dams was secondary to supplying water to the demand sites that withdraw water from the reservoirs and that had a priority level of < 5.

The reservoir data are shown in Table E1a-b. The net capacity of reservoirs was entered into the model.

In the main model, the values without Environmental Water Requirements (EWR) have been used to determine the volume in the reservoirs that have historically not been available for allocation.

The simulated flows below dams in the WEAP model were noted to be higher than the flows recorded by the reservoir gauges (R2R001 below Laing Dam, R2R002 below Rooikrantz Dam). Thus, a buffer was defined below which reservoir releases are constrained in the WEAP model in order to match the recorded values more accurately.

The monthly net evaporation for the dams was set as in Figure E1 were obtained from WR2005 (Middleton and Bailey, 2008).

The simulated evaporative losses from the reservoirs in the WEAP model were determined from expected evaporative losses (that were estimated from the potential evaporation values in the Buffalo area obtained from SPATSIM [Hughes et al., 2000], and from the surface area of the reservoirs that were obtained from DWAF 2008: Appendix 3.2).

In order to match the expected evaporative losses, the volume-elevation curve values for the reservoirs were defined as in Table E1b.

Table E1a Reservoir parameters entered into WEAP model. Net capacity was obtained from AWB surveys of reservoirs conducted between 2005-2008. The 98% assurance of supply figures were obtained from DWAF (2008). Gubu and Wrigglewade reservoirs are not active in the current situation (with the exception of 1 or 2 transfers in the past) in terms of affecting water availability for the Buffalo River.

Reservoir name	**Location**	**Net Capacity (10^6 m^3 y^{-1})**	**98% assurance of supply without EWR (10^6 m^3 y^{-1})**	**98% assurance of supply with EWR (10^6 m^3 y^{-1})**
Maden	Buffalo River	0.48	0.48	0.48
Rooikrantz	Buffalo River	4.91	3.70	1.49
Laing	Buffalo River	18.9	18.27	12.54
Bridle Drift	Buffalo River	97.92	29.41	28.91
Nahoon	Nahoon River	19.25	8.41	3.45
Gubu	Kubusi River	8.5	2.87	2.11
Wriggleswade	Kubusi River	91.47	31.8	20.28

Table E1b Volume elevation curves for the reservoirs. Data used are: Amatola Water surveys, 2005-2008; Maden Dam: DWAF (2008: Appendix 3.2).

Reservoir name	**Volume (10^6 m^3)**	**Elevation (m)**
Maden	0.00	528.0
	0.14	528.8
	0.32	531.2
	0.48	534.0
Rooikrantz	0.00	497.8
	0.34	497.3
	1.00	499.9
	2.00	502.6
	3.00	504.6
	3.50	505.4
	4.00	506.2
	5.03	507.7
Laing	0.00	281.5
	0.62	287.1
	3.80	294.1
	7.00	298.0
	10.00	300.9
	15.00	304.5
	17.00	305.7
	18.91	306.6
Bridle Drift	0.00	90.0
	3.00	123.9
	5.00	124.4
	10.00	130.7
	30.00	139.0
	60.00	145.3
	90.00	145.0
	110.00	152.6
Nahoon Dam	0.00	112.0
	0.80	145.3
	5.00	155.0
	8.00	158.1
	12.00	161.0
	15.00	162.6
	18.00	164.1
	20.75	165.2
Gubu Dam	0.00	997.9
	0.28	999.8
	0.45	1 000.7
	1.00	1 002.7
	3.00	1 006.9
	5.00	1 009.7
	7.00	1 011.9
	9.25	1 014.1
Wriggleswade Dam	0.00	697.0
	3.00	700.3
	5.00	701.5
	10.00	703.8
	20.00	706.7
	40.00	710.6
	75.00	715.2
	93.00	717.2

E3 Demand sites: Population

The primary water demand categories are human settlements, industry, agricultural sites and alien vegetation (in some parts of the catchment). For simplification, the Amatole system has been divided into three demand areas – Upper, Middle and Lower Amatole as defined in Table E2.

Water requirements of the water users have been entered into the WEAP model as a stationary demand over the years. This was done in order to look at the effects of the varying hydrology in isolation instead of hydrological variation in combination with variation in water demand over the modelled years. The current water requirements that have been used are those for the year 2005 listed in DWAF (2008: Table 4.13) that are shown in Table E2.

These population water requirements were entered into the model as a population figure (Annual Activity Level) with an annual water use rate (m^3/cap) specified for each demand area (Table E2). Note that DWAF (2008) points out that the figures for water requirements are a composite of use by various socio-economic categories:

- Upper income 320 ℓ/c/d
- Middle income 200 ℓ/c/d
- Lower income formal 120 ℓ/c/d
- Lower income informal 25 ℓ/c/d
- Traditional 60 ℓ/c/d which includes allowance for limited gardening and livestock watering.

Population demand priority level was set at two, same as industry, in the WEAP model. The demand priority for irrigation users was set at three and for alien vegetation and WTWs as one.

Table E2 Population figures for the three areas on the Buffalo River that were given demand priority level of two in the WEAP model.

	Areas	**Population for year 2005 (DWAF 2008)**	**Annual water use rate per person ($m^3 y^{-1}$)**	**Water requirements ($10^6 m^3 y^{-1}$)**
Upper Amatole	King William's Town, Ginsberg, Breidbach, Frankfort, Tyutyu	90 465	54.83	4.96
Middle Amatole	Bhisho, Zwelitsha, Berlin, Ndevana, Potsdam	122 196	64.98	7.94
Lower Amatole	East London, Mdantsane, Newlands, Genubie	478 017	68.30	32.65
Total		690 678	---	45.55

E4 Demand sites: Industry

Industrial demands were estimated from DWAF (2008) as given in Table E3.

The priority for the delivery of industrial water requirements was set the same as population as these extract water from the same reservoirs and by setting a lower priority level for industry, the majority of the industrial water requirements are not met in the model. As this result is not a realistic scenario, the industrial priority was set the same as the population in WEAP.

Table E3 Water requirements (10^6 m^3 y^{-1}) for the industrial and agricultural sectors under the Current Scenario. Data source: DWAF (2008).

Scenario (Year)	**Upper Amatole**	**Middle Amatole**	**Lower Amatole**	**Total**
Industrial water requirement				
Current (2005)	2.48	1.23	10.61	14.32
Agriculture irrigation water requirement				
Current (2005)	1.24	1.9	1.26	4.4

E5 Demand sites: Irrigation

Irrigation water demands estimated from DWAF (2008) are given in Table E3. A monthly variation as indicated in Table E4 was entered based for irrigation water demands based on data from Schulze (2007). Irrigation was given a lower priority level (level 3) relative to industry and population (level 3). Irrigation users were supplied from dams as indicated in AWB (2010b). The Upper Amatole irrigation users were supplied from Rooikrantz Dam, Middle Amatole from Laing Dam and Lower Amatole from Nahoon Dam.

Table E4 Estimated percentage monthly irrigation demands for the Buffalo River catchment from Schulze (2007).

	Jan	**Feb**	**Mar**	**Apr**	**May**	**Jun**	**Jul**	**Aug**	**Sept**	**Oct**	**Nov**	**Dec**
%	10	10	8	6	6	5	5	8	10	10	11	11

E6 Demand sites: Invasive aliens

WR2005 (Middleton and Bailey, 2008) provides data for area covered by invasive aliens by quaternary. Water lost to invasive aliens was estimated from DWAF (2004b) to be approximately 3×10^6 m^3 per annum which was divided into the three demand areas as indicated in Table E5 with demand priority level of 1. It was assumed that 96% of the flow would be consumed by the alien vegetation.

Table E5 Invasive alien demands for the year 2000 estimated from DWAF (2004b).

	Invasive Alien Annual Water Use (10^6 m^3 y^{-1})	**Percentage inflow consumed (estimated as lost from system) by user**
Upper Amatole	1.59	96%
Middle Amatole	0.79	96%
Lower Amatole	0.62	96%

E7 Losses in the system

DWAF (2008) provides estimates of losses in the water provision system, as shown in Table E6 that were incorporated into the WEAP model. The losses in the WEAP model include evaporative, leakage and consumption losses and thus, those reported in Table E6 are higher than those listed in DWAF (2008).

Table E6 Water losses (as evaporative/leakage/consumption) in the Buffalo system.

Loss/water consumption	**Upper Amatole**	**Middle Amatole**	**Lower Amatole**	**Source of data**
Dams to Water treatment works (WTW) and through WTW	10%	4%	9%	DWAF (2008)
Demand site (population or industry)	20%	20%	20%	Estimated, including consumption and conveyance losses (DWAF, 2008)
Waste water treatment works (WWTW)	5%	5%	5%	DWAF (2008)
Return flow loss from demand site to WWTW	10%	10%	10%	Estimated from reticulation losses (DWAF, 2008)
Return flow loss from WWTW to river	10%	10%	10%	Estimated from reticulation losses (DWAF, 2008)
Total loss / consumption	44.6%	40.9%	44.0%	----

APPENDIX F. WEAP CALIBRATION RESULTS

F1 Water quantity calibration results (1980-2005)

The results for the simulation of hydrology from rainfall data by WEAP were matched against recorded data by stream gauges to assess how accurately the model was simulating water quantity. The gauges, whose data were compared with simulated reach data by WEAP, are shown in Table F1. The results for simulated and observed data for yearly flows and flow duration curves (FDC) are shown in Figures F1-6 for the reaches near the upstream gauges on the Buffalo River (R2H001, R2H006, R2H007, R2H008, R2H009 and R2H015). Simulated data for the Nahoon River could not be calibrated against measured flow data because the stream gauge R3H003 is located below the Nahoon dam. Overall, the model simulation matches the gauge data when comparing yearly and monthly flow figures.

Table F1 Gauge data used for calibrating the input hydrology for the Buffalo River tributaries using the rainfall-runoff model under WEAP.

Tributary name	Gauge on the tributary
Buffalo (upstream R20A)	R2H001
Qwengcwe (R20A)	R2H008
iZele (R20B)	R2H007
Mgqakwebe (R20C)	R2H006
Ngqokweni (R20D)	R2H009
Yellowwoods (R20E)	R2H015
Buffalo (midstream R20D)	R2H005
Buffalo (midstream R20D)	R2H010
Buffalo (downstream R20F)	R2H027

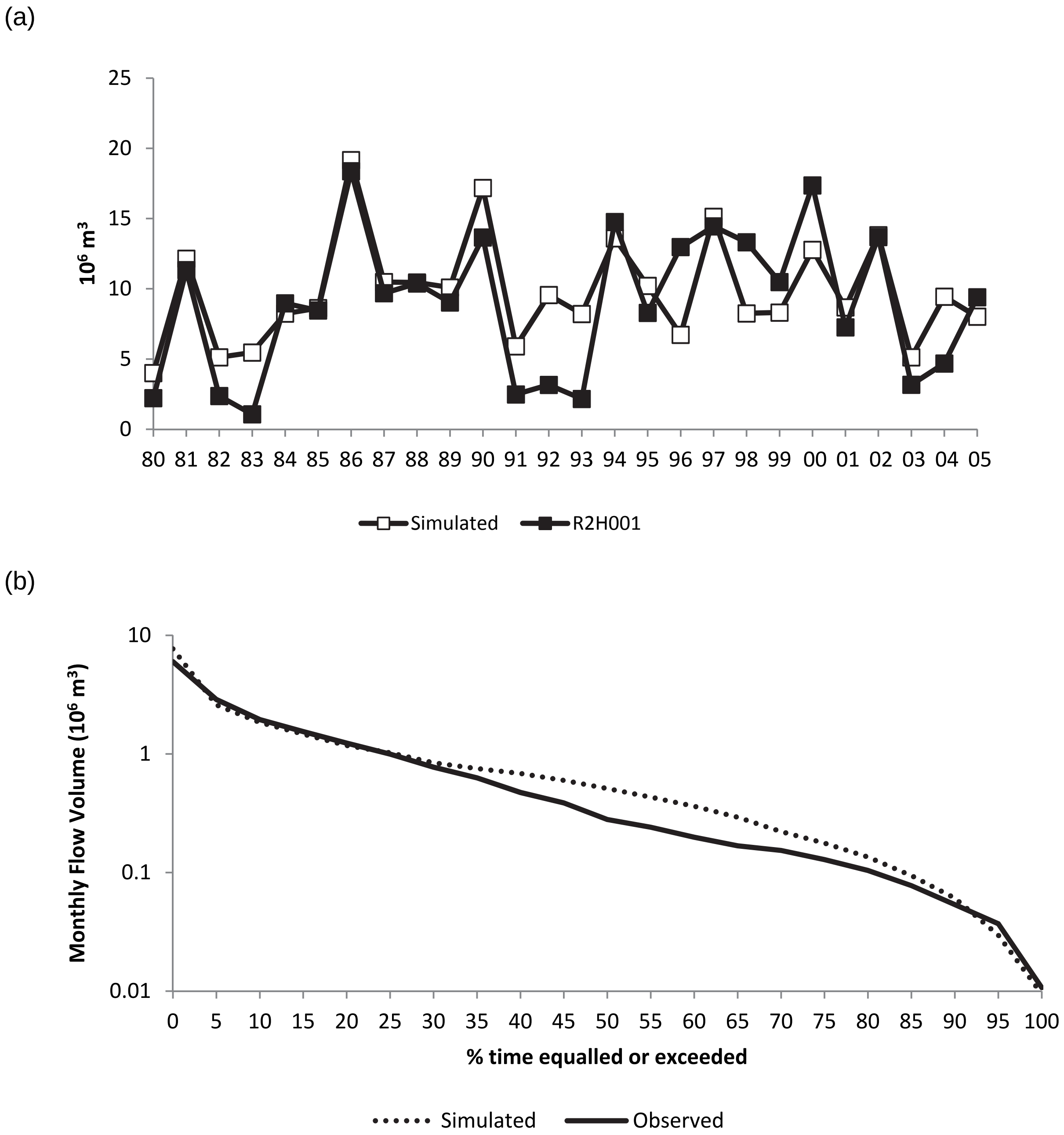


Figure F1 Simulated flow output of WEAP model relative to gauge data at R2H001 on the Buffalo River for the years 1980-2005 in quaternary R20A (a) yearly flow (b) flow duration curves.

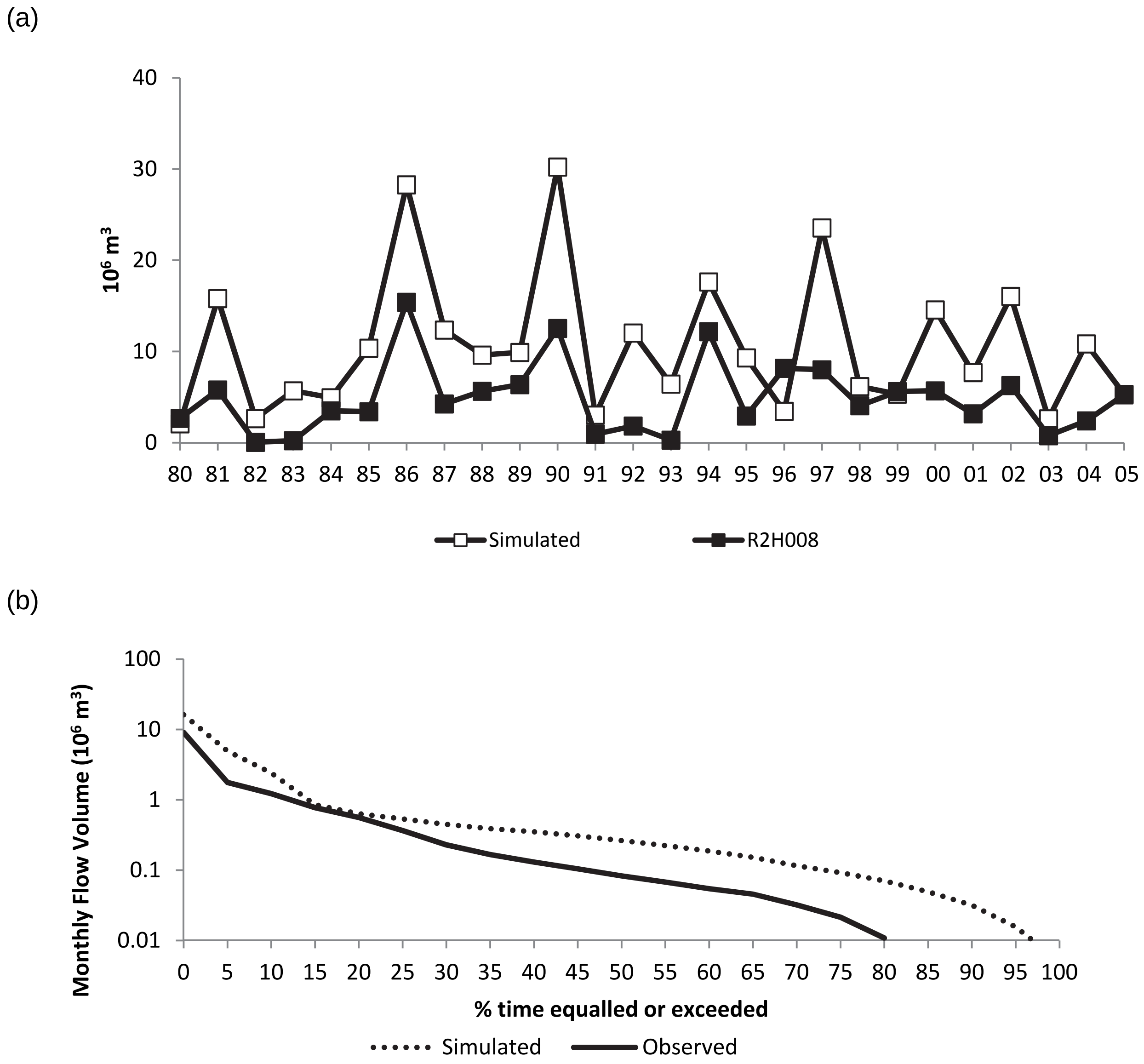
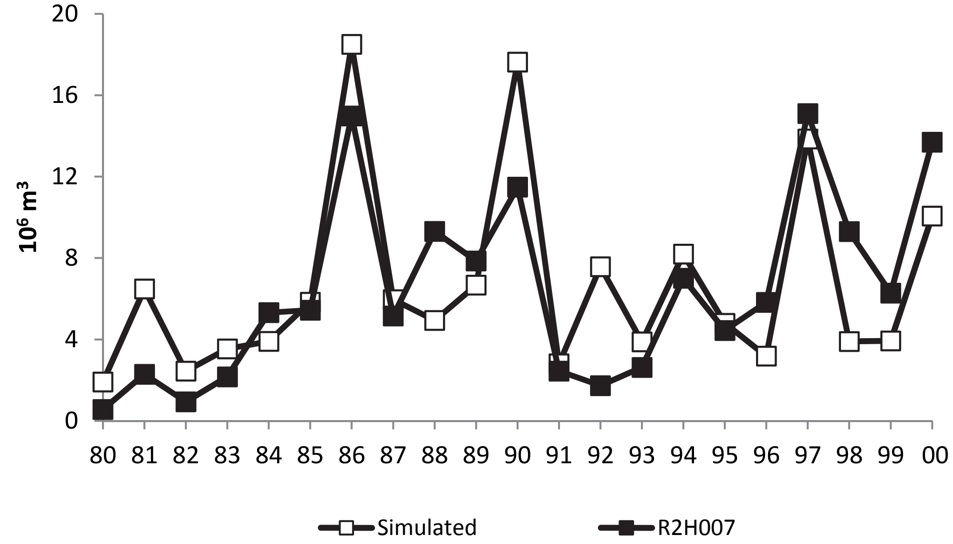


Figure F2 Simulated flow output of WEAP model relative to gauge data at R2H008 on the Qwengcwe River for the years 1980-2005 in quaternary R20A (a) yearly flow (b) flow duration curves.

(a)



(b)

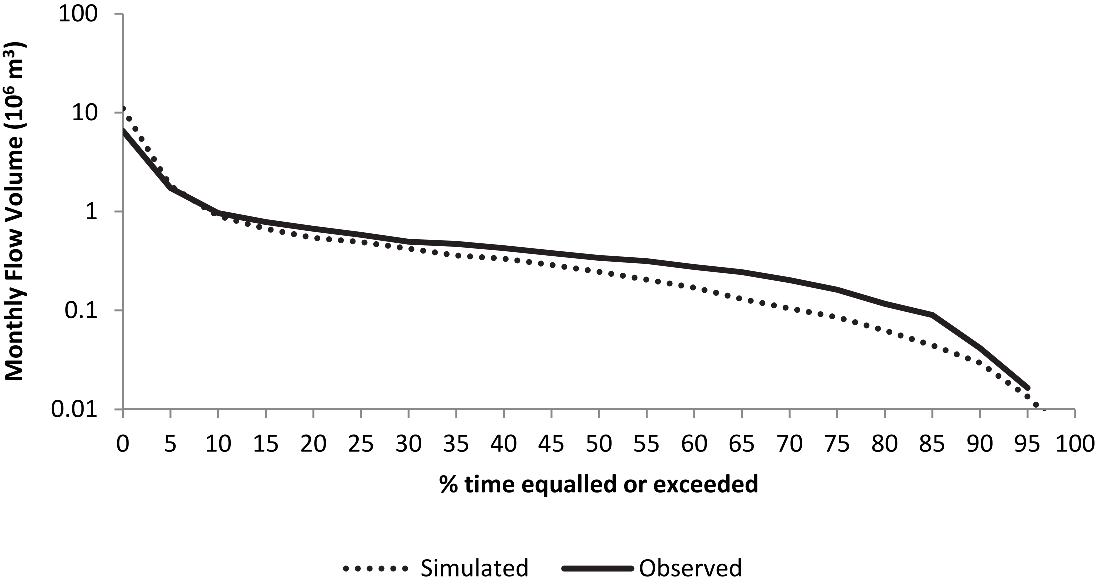


Figure F3 Simulated flow output of WEAP model relative to gauge data at R2H007 on the iZele River for the years 1980-2005 in quaternary R20B (a) yearly flow (b) flow duration curves.

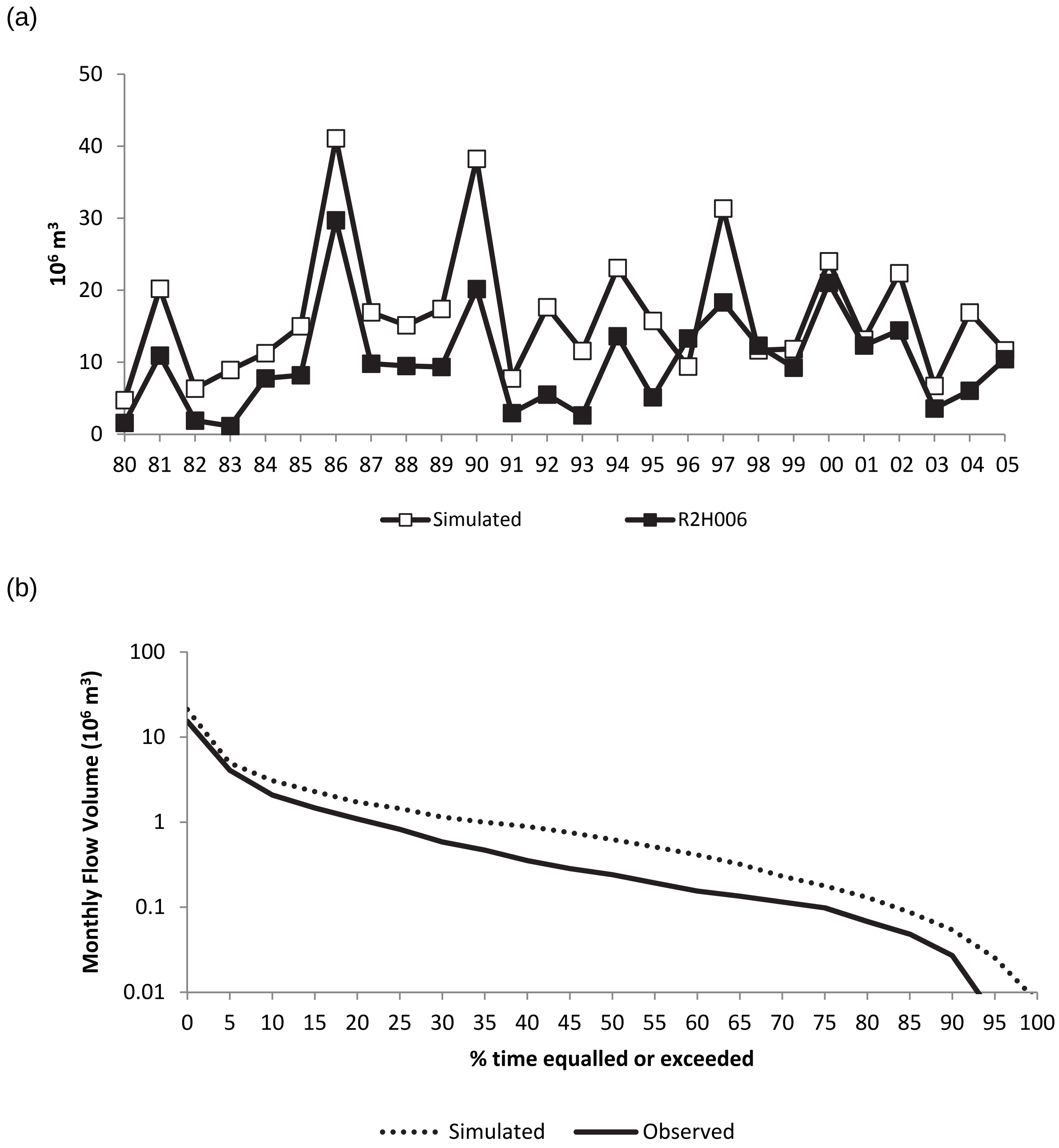


Figure F4 Simulated flow output of WEAP model relative to gauge data at R2H006 on the Mgqakwebe River for the years 1980-2005 in quaternary R20C (a) yearly flow (b) flow duration curves.

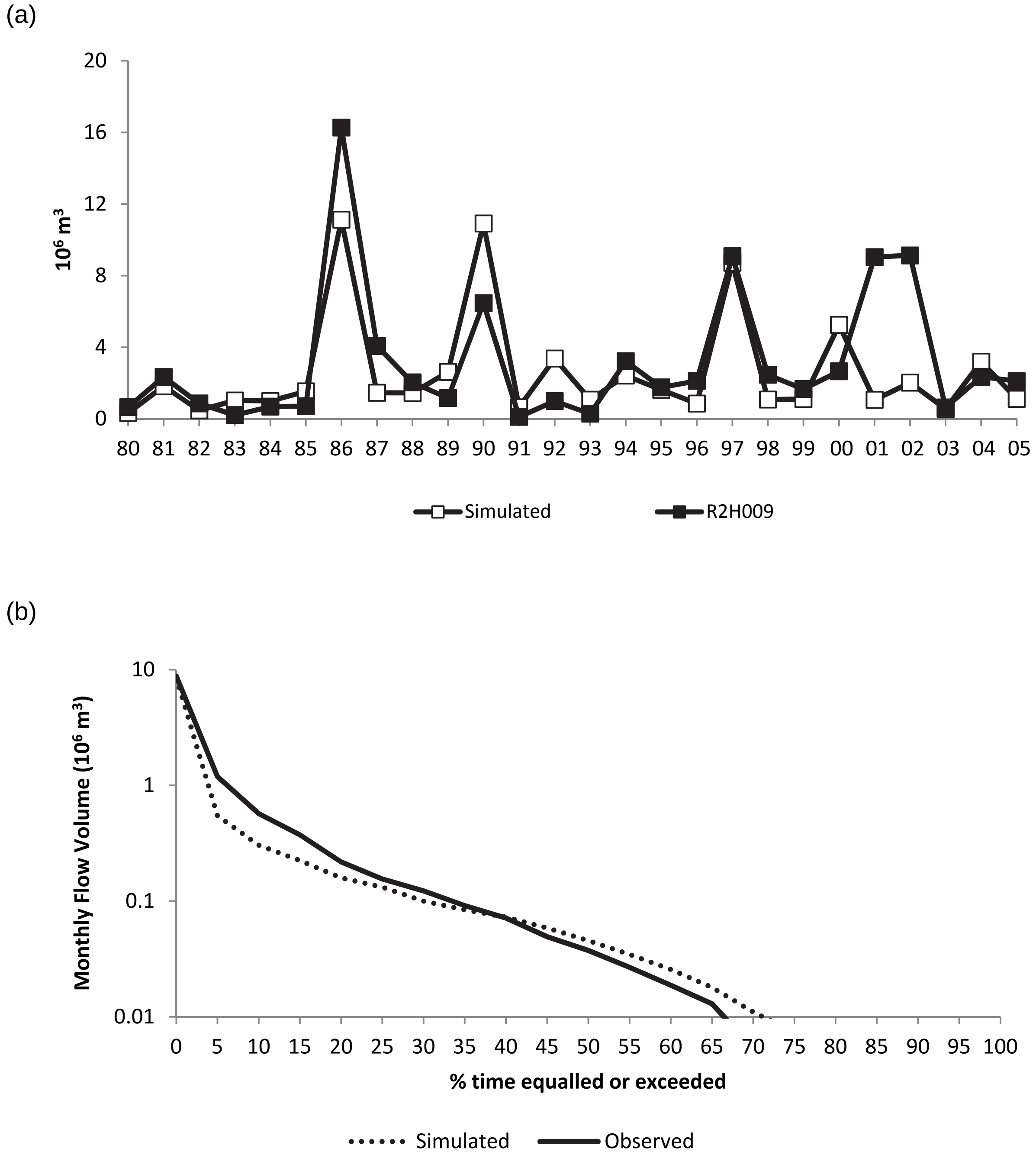


Figure F5 Simulated flow output of WEAP model relative to gauge data at R2H009 on the Ngqokweni River for the years 1980-2005 in quaternary R20D (a) yearly flow (b) flow duration curves.

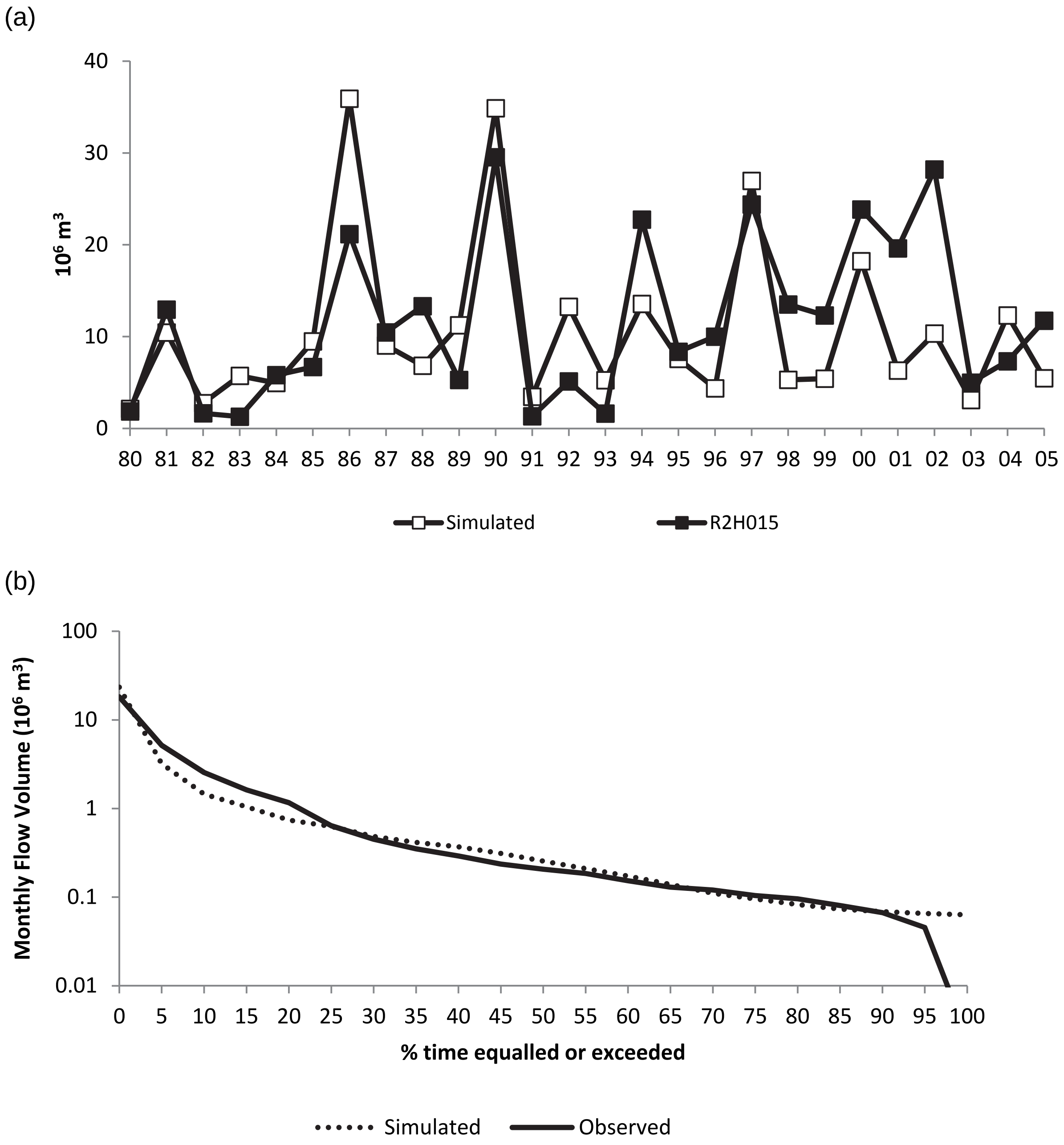
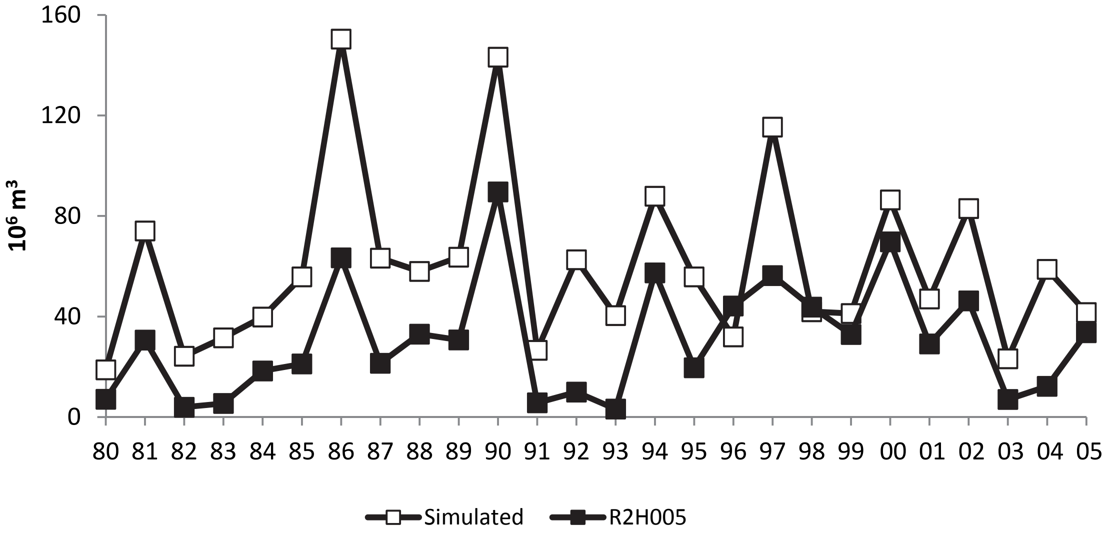


Figure F6 Simulated flow output of WEAP model relative to gauge data at R2H015 on the Yellowwoods River for the years 1980-2005 in quaternary R20E (a) yearly flow (b) flow duration curves.

Figures F7 and F8 show the simulated data relative to gauges on the Buffalo River at the inlet (R2H005) and the outlet (R2H010) of quaternary R20D. Figure F9 shows the simulated and observed data at gauge R2H027, for which data prior to October 1994 were not recorded by the gauge. The simulated data match the pattern of variation although they are slightly higher than actual flows. The reasons for the difference between simulated and actual flows could be due to uncertainty arising from various sources. These include uncertainty in the model structure, that in the observed flow data and uncertainty in the water user demands. Uncertainty may also arise from variation in actual water user demands over time whereas stationary demands were entered into the WEAP model.

(a)



(b)

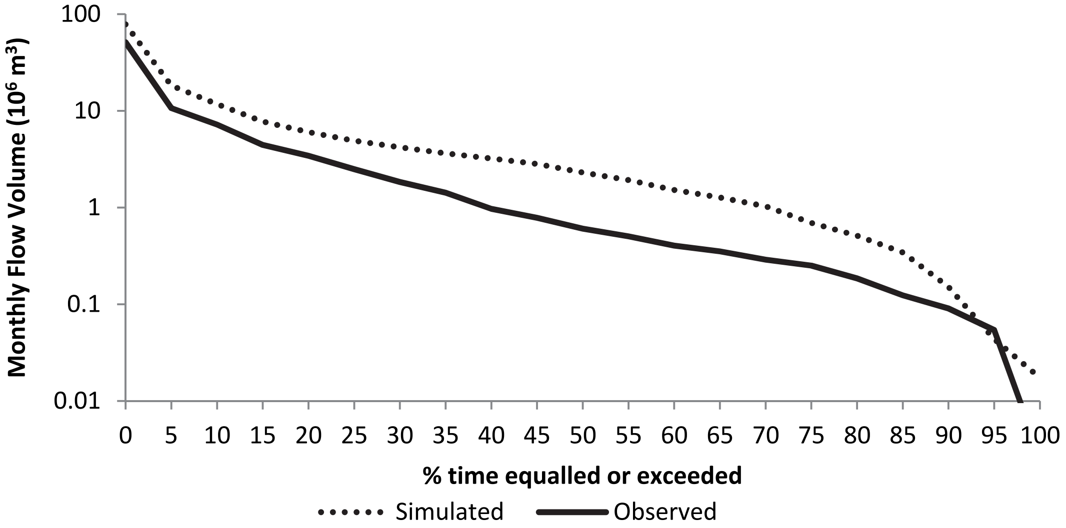


Figure F7 Simulated flow output of WEAP model relative to gauge data at R2H005 on the Buffalo River for the years 1980-2005 in quaternary R20D (a) yearly flow (b) flow duration curves.

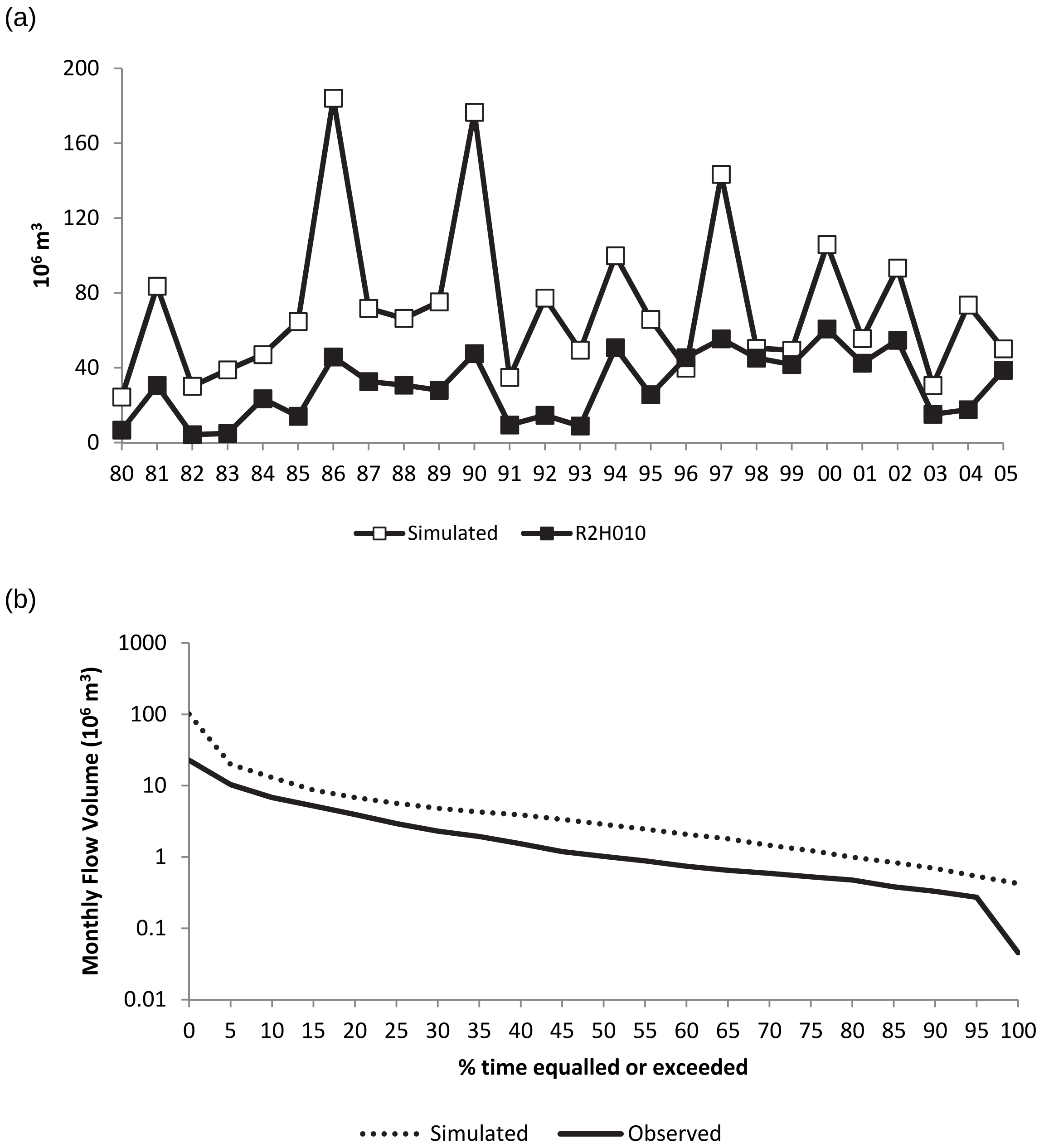


Figure F8 Simulated flow output of WEAP model relative to gauge data at R2H010 on the Buffalo River for the years 1980-2005 in quaternary R20D (a) yearly flow (b) flow duration curves.

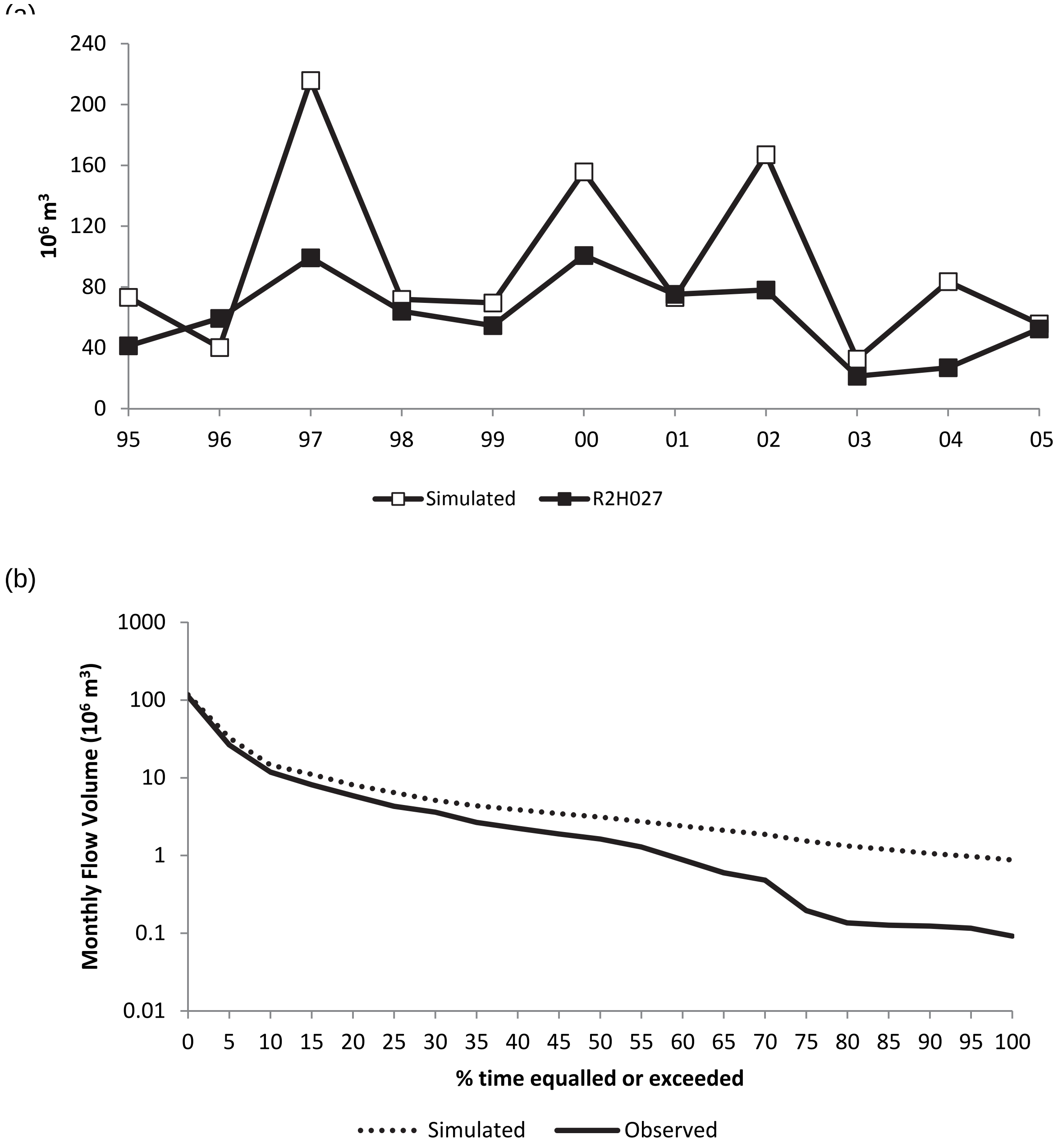


Figure F9 Simulated flow output of WEAP model relative to gauge data at R2H027 on the Buffalo River in quaternary R20F (a) yearly flow (b) flow duration curves. The gauge did not record data before October 1994 and therefore, only the available data years (1995-2005) are shown.

F2 Water quantity results for current water requirement situation under current climate variability (1921-2005)

To determine if the current water requirements can be met with the available infrastructure, the WEAP model was run for the full historical rainfall record for the years 1921-2005. The simulation was run over the 85 years as the full historical dataset represents the present extremes in hydrological conditions for the Amatole system.

Table F2 shows the supply requirements (including water lost in reticulation) for the various user groups under the Current Scenario. The results of the WEAP model indicate that the water user requirements were met 100% of the time for all users under the Current Scenario.

Table F2 Supply requirement (10^6 m^3; including water loss in reticulation system) of the three demand areas for population, industry, alien vegetation, and irrigation sectors for the Amatole system for the years 1921-2005 (Current Scenario).

	Oct	**Nov**	**Dec**	**Jan**	**Feb**	**Mar**	**Apr**	**May**	**Jun**	**Jul**	**Aug**	**Sep**	**Sum**
Upper Amatole													
Pop	0.42	0.41	0.42	0.42	0.38	0.42	0.41	0.42	0.41	0.42	0.42	0.41	4.96
Indus	0.21	0.20	0.21	0.21	0.19	0.21	0.20	0.21	0.20	0.21	0.21	0.20	2.48
Alien	0.14	0.13	0.14	0.14	0.12	0.14	0.13	0.14	0.13	0.14	0.14	0.13	1.59
Irrig	0.12	0.12	0.10	0.07	0.07	0.06	0.06	0.10	0.12	0.12	0.14	0.14	1.24
Middle Amatole													
Pop	0.67	0.65	0.67	0.67	0.61	0.67	0.65	0.67	0.65	0.67	0.67	0.65	7.94
Indus	0.10	0.10	0.10	0.10	0.09	0.10	0.10	0.10	0.10	0.10	0.10	0.10	1.23
Alien	0.07	0.06	0.07	0.07	0.06	0.07	0.06	0.07	0.06	0.07	0.07	0.06	0.79
Irrig	0.19	0.19	0.15	0.11	0.11	0.10	0.10	0.15	0.19	0.19	0.21	0.21	1.90
Lower Amatole													
Pop	2.77	2.68	2.77	2.77	2.50	2.77	2.68	2.77	2.68	2.77	2.77	2.68	32.65
Indus	0.90	0.87	0.90	0.90	0.81	0.90	0.87	0.90	0.87	0.90	0.90	0.87	10.61
Alien	0.05	0.05	0.05	0.05	0.05	0.05	0.05	0.05	0.05	0.05	0.05	0.05	0.62
Irrig	0.13	0.13	0.10	0.08	0.08	0.06	0.06	0.10	0.13	0.13	0.14	0.14	1.26

F3 Comparison of water quantity simulation with and without demands

The input hydrology of the Buffalo River tributaries was estimated using the FAO rainfall-runoff option in the WEAP model. In order to compare this with the hydrology simulated by the Pitman model (Chapter 2 results), the quaternary level simulated flows generated by the Pitman model were input into the WEAP model, and the results compared at gauge R2H005. Both these input hydrology flows were compared for WEAP model outputs with and without water user demands. Figures F10a-b show the outputs at a simulated reach in the WEAP model near the R2H005 gauge. The WEAP model outputs are shown with no user demands versus with user demands for comparison. The results indicate that the WEAP rainfall-runoff model provides an overall better simulation relative to the Pitman model.

Comparison of the Pitman simulation for the periods before and after the year 1980 indicates that there are very large differences in the low flow part of the flow duration curves. This may be a result of dramatic differences in water demands for the Upper Amatole. However, the project team's understanding of demands on the Rooikrantz Dam does not indicate a major change over the years. The alternative is that there are differences in the quality of the observed data record. A study of the rating curves for this gauging weir suggests that some changes were made to the weir during the period 1980-1988 when all the data are missing. Interpretation of the rating curves (and the photograph provided on the DWA website) suggests that a low flow control section was added (greater sensitivity of low flows to changes in weir pool depth). The implication is that the more recent data should provide more accurate low flow measurements but this issue needs to be further investigated in the future. If the more recent flow data are considered to be more accurate it will be necessary to re-examine the parameters used to simulate the natural hydrology of the upper reaches of the catchment (see Figures F10a and b).

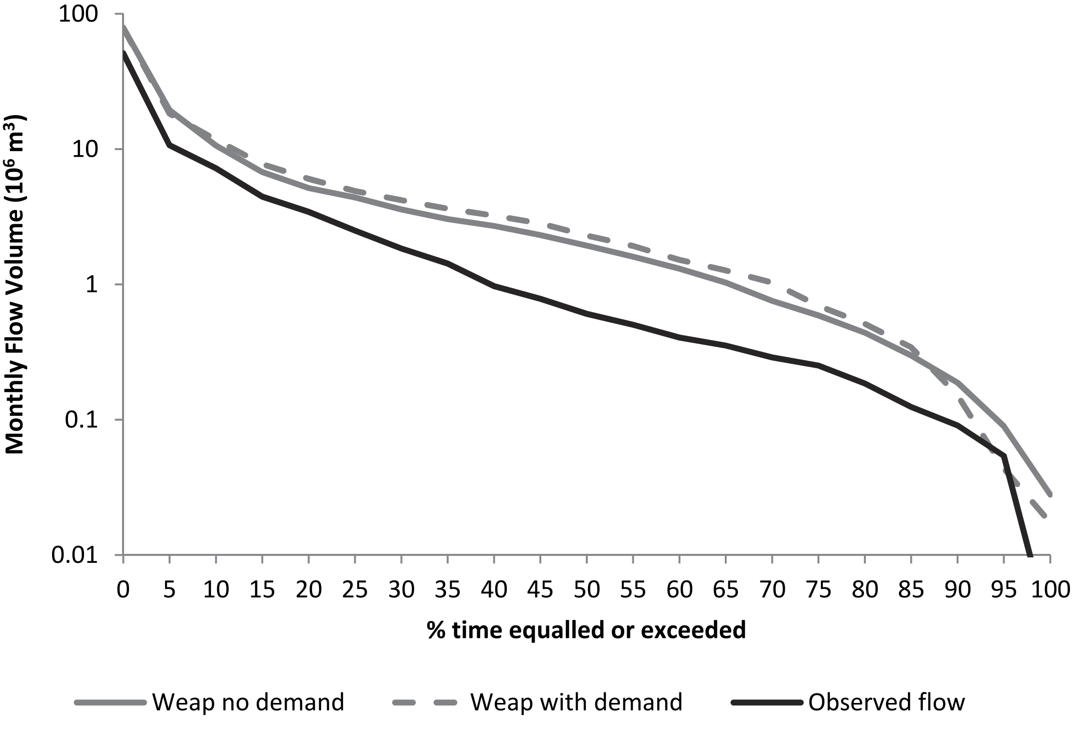


Figure F10a Simulated monthly flow output of WEAP model using the Rainfall-Runoff model included in the WEAP model. The WEAP model output is shown with and without water user demands at the reach near gauge R2H005 on the Buffalo River for the years 1980-2005.

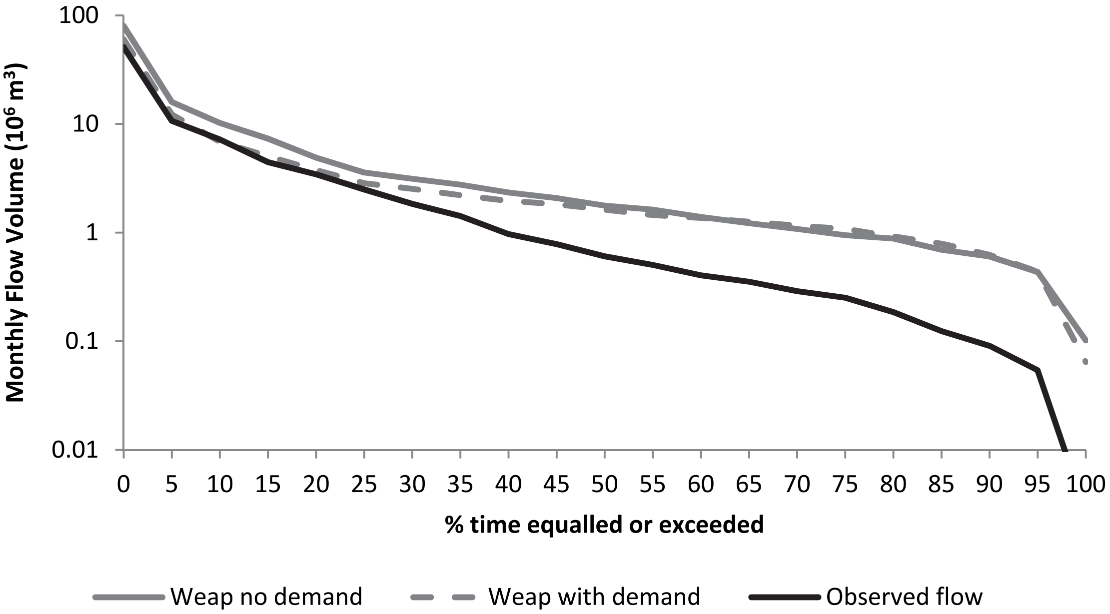


Figure F10b Simulated monthly flow output of WEAP model using the simulated quaternary flows output by the Pitman model as headflows. The WEAP model output is shown with and without water user demands at the reach near gauge R2H005 on the Buffalo River for the years 1980-2005.