IMPACT OF CLIMATE CHANGE ON SURFACE WATER AVAILABILITY IN THE UPPER VAAL RIVER BASIN

by

Huzefa Talibhusein Haji

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Supervisor: Prof F. A. O Otieno

Co-Supervisor: Dr G. M Ochieng'

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DECLARATION BY CANDIDATE

"I hereby declare that the thesis submitted for the degree Magister Technologiae in Civil Engineering, at the Tshwane University of Technology, is my own original work and has not previously been submitted to any other institution of higher education. I further declare that all the sources cited or quoted are indicated and acknowledged by means of a comprehensive list of references".

Huzefa Talibhusein Haji

This work is dedicated to my ‘Matashree’…

Who gave me strength even when she was weak,

Who put a smile on my face even when her own heart wept,

Who instilled the value of education even when she did not have one,

And who could not honour me with a chance to give back,

For she is now where all dreams come true.

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ABSTRACT

It is an established fact that South Africa is a water stressed nation, with its existing water resources under pressure to meet a growing demand. This vulnerability may further be exacerbated by possible changes in climate which will exert an additional layer of uncertainty on existing water resources. The Upper Vaal River Basin (UVRB) supports the economic heartland of South Africa and underpins the socio economic harmony of more than 12 million people.

The objective of this study was to investigate the UVRB's ability to sustain projected surface water abstractions under the impact of future climate change. In achieving this objective, the Water Evaluation And Planning (WEAP) model was used. The model incorporates different modules which can collectively describe the integrated nature of river basin management. This study has only set up the surface hydrology and water allocation modules of the model.

The approach used in this Study began by setting up the naturalised hydrology of the UVRB on a monthly time step over a 6 year period beginning in the water year 1999 to 2005. Thereafter, the present conditions in the basin relating to water abstraction, developed water infrastructure like dams and inter basin transfers were superimposed on the naturalised hydrology to validate the model. Climate change was simulated to the year 2030 using the ECHAM4 and CSIRO models under the SRES B2 emission scenario. These data were extracted from the TYN SC 2.03 dataset. Projected water demands to the year 2030 were adopted from a previous study.

The results indicate that the model can reasonably simulate the basin processes under naturalised conditions in terms of stream flows with overall basin R^2 and E efficiency criteria ranging from 0.674 – 0.843 respectively. As for the present conditions, the same efficiency criteria ranged between 0.68 – 0.69 respectively.

Climate change simulation indicates a wetter future with an increasing trend in stream flow. On one hand, the magnitude of mean monthly stream flow decreases while the maximum monthly stream flow increases when compared to the characteristics of monthly historical flows. Water abstractions by Rand Water and Industries are fully met. However, irrigation demands experience a small deficit (10-13%) during the dry season only. In addition, the Instream Flow Requirements are also met for all key points except for Klip River throughout the simulation period.

The above results are however heavily dependent on the continued increasing trend in inter basin transfer of water from the Lesotho Highlands Water Project (LHWP). If this transfer is in any manner constrained, despite the wetter future climate, the basin will experience deficits in meeting its water demand obligations. Furthermore, the period between years 2016 – 2024 indicates a dry period in which significant reservoir draw downs are observed. However, water demands will continue being met within this period.

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ABBREVIATIONS

CN	Curve Number
DSS	Decision Support System
DWEA	Department of Water & Environmental Affairs
DUL	Drained Upper Limit
ESKOM	Electricity Supply Commision
ET_O	Reference Evapotranspiration
ET_c	Evapotranspiration under Standard Conditions
GCM	General Circulation Model
GHG	Green House Gas
GIS	Geographic Information System
IFR	Instream Flow Requirement
IPCC	Inter governmental Panel on Climate Change
IWRM	Integrated Water Resource Management
K_c	Crop Coefficient
LHWP	Lesotho Highlands Water Project
MAE	Mean Annual Evaporation
MAP	Mean Annual Precipitation
MAT	Mean Annual Temperature
PFD	Preferred Flow Direction
PWP	Permanent Wilting Point
QC	Quaternary Catchment
RC	Runoff Coefficient
RCM	Regional Climate Model
RMS	Root Mean Square
RRF	Runoff Resistence Factor
SAWS	South African Weather Service
SCS	Soil Conservation Service
SASOL	South African Coal, Oil & Gas Corporation
SRES	Special Report on Emission Scenarios
URFM	Urban Return Flow Model
UVRB	Upper Vaal River Basin
VRESAP	Vaal River Eastern Sub system Augmentation Project

VRES	Vaal River Eastern Sub system
VRS	Vaal River System
WEAP	Water Evaluation and Planning
WHC	Water Holding Capacity
WMA	Water Management Area
WMO	World Meteorological Organisation
WSAM	Water Situation Assessment Model

CHAPTER ONE

INTRODUCTION

"Man has forgotten his origins and is blind even to his most essential needs for survival, water…has become the victim of his indifference."
Rachel Carson, *The Silent Spring*

1.1. The State of our Water Resources

Our water resources, with varied spatiotemporal distribution, are under continuous pressure due to major factors such as population growth and increased demand (UNESCO, 2006) and climate change (Bates *et al.*, 2008). Despite the fact that less than 1% of the world's fresh water (or about 0.007% of all water on earth) is readily accessible for direct human use, depletion of this invaluable resource continues without regard for the future. As a consequence of continued failures by governments in safe guarding water resources, coupled with increasing poverty and inequality, 1.1 billion people (approximately one in six people on earth) lack access to an improved water supply (UNDP, 2006). Over the last century, water use has grown at twice the rate of population growth. UN-WATER (2006) predicts approximately 1,800 million people will be living in countries or regions with absolute water scarcity, and two-thirds of the world population could be under water stress conditions by Year 2025.

On a continental scale, approximately 25% of the African population is currently experiencing water stress (Bates *et al.*, 2008). This is verified by the Climate Moisture Index (CMI) for Africa, a measure of potential water availability imposed by the climate, which is below -0.75 (whereas the global range is -0.10 to -0.25). This is indicative of the drier conditions across the continent (Vörösmarty *et al.*, 2005). Ashton (2002) projects approximately 65% of the African population will be at risk of water stress by the year 2025.

Sixty five (65) percent of South Africa's land mass is categorised as semi arid. With the country mean annual precipitation (MAP) of about 495mm (Aquastat, 2005), this is approximately 58% of the global annual average. Therefore, the country's water resources are, in global terms, scarce and extremely limited (New, 2002; DWAF, 2004). Water availability in South Africa is projected to fall below $1000m^3$ $capita^{-1}$ $annum^{-1}$ by the year 2025 (Bates *et al.*, 2008). The widely accepted threshold is $1{,}700m^3$ $capita^{-1}$ $annum^{-1}$ below which different levels of water stress are introduced (Falkenmark, 1989). Furthermore, the above estimate of water availability is solely based on population growth rates and does not consider the implications of climate change on the water resources.

To facilitate the management of water resources in South Africa, the country has been divided into nineteen catchment-based Water Management Areas (WMAs). Currently eleven of the nineteen Water Management Areas in the country are facing a water deficit where the requirements of water exceed its availability. Despite taking into consideration the planned future augmentation of the country's water infrastructure, deficits in other WMAs are nonetheless expected by the Department of Water Affairs (DWA) formerly known as Department of Water Affairs and Forestry (Otieno and Ochieng, 2004).

The Vaal River Basin constitutes three WMAs namely Upper, Middle and Lower Vaal. Water resources in this basin are highly developed and regulated with numerous inter basin transfers from adjacent catchments to supplement the natural supply. Therefore, marginal potential for further development remains. However, increase in population coupled with increased human activities in this basin in the future (DWAF, 2006) will require additional supply, resulting in greater pressure on the already strained existing resources.

The above facts bear witness that the current and future situation regarding our water resources from global to regional scale is dire. Future water scarcity is a viable threat to the Upper Vaal River basin and the country as a whole, despite the fact that surface water resources are highly developed and managed.

1.2. Climate Change and its Effect on our Water Resources

Climate change is now a scientifically established fact (UNDP, 2008) and the Intergovernmental Panel on Climate Change (IPCC) has accepted it as a threat to sustainable development (in UNESCO, 2006). It is defined as a trend or persistent change in the state of the climate that includes amongst others properties such as temperature, precipitation, humidity and wind speed. The change in state of climate can be identified (for example using statistical tests) by changes in the mean and/or the variability of its properties (Miller and Yates, 2005; Hegerl et al., 2007).

The atmosphere, oceans, ice and land surface characteristics describe the climate system. Solar radiation, natural (such as volcanic activity) and anthropogenic activities are the key elements in causing any change in climate. The climate system remains in balance when the energy from the Sun is balanced by radiation from the Earth's surface back into the space. The greenhouse gases, water vapour, carbon dioxide, methane, nitrous oxide and other man made compounds radiate some of this energy back to the Earth's surface. Aerosols on the other hand, composed of organic and black carbon, sulphates and nitrates and dust, have a cooling effect on the system by reflecting off solar radiation. Therefore, an increase in concentration of greenhouse gases for example, 'flips' this balance, redirecting larger amounts of radiated energy back to Earth's surface. Conversely, increase in aerosol concentration would lead to a cooling effect because of reflection of solar energy back to space. Due to the time scale involved with climate processes, the balance may take centuries to restore.

According to the latest report released by the IPCC (IPCC, 2007), the mean global temperature has risen by more than 0.76^{o}C over the last century. It claims with high certainty that the observed climate change could not have been possible from natural causes alone. Furthermore, an increase of 0.2^{o}C per decade has been projected even if the future emissions were mitigated. In fact, if the concentration of greenhouse gases were to be capped at year 2000 levels, an increase of 0.1^{o}C per decade would still be inevitable.

Assessment of future impacts of continued global warming is based upon projections from General Circulation Models (GCMs). These are numerical models representing physical processes in the atmosphere, ocean and land surface. However, GCMs have a lower spatial resolution (250 - 600 kilometres) hence adequate for global scale prediction of climate change. At regional scales however, climate variability[1] is much more amplified thus making it difficult to assess the effect of climate change using the GCMs at such low spatial resolution. Therefore, downscaling methods need to be applied to the GCMs so that they can be applied in regional impact analysis (Nijssen *et al.*, 2001; IPCC-TGICA, 2007).

Climate change is having a significant impact on weather patterns, precipitation and the hydrological cycle, affecting surface water availability, as well as soil moisture and groundwater recharge (UNESCO, 2006). IPCC (2007) describes a future where snow cover and sea ice will drastically reduce and more frequent occurrences of extreme temperatures and precipitation events. It has been predicted with high confidence (scale of confidence of 8 out of 10) that climate change will exacerbate the water stress situation in some countries, while introducing water stress to countries that currently do not experience it (Boko *et al.*, 2007).

[1] *Climate variability* refers to "variations in the mean state and other statistics (e.g. standard deviations, the occurrence of extremes) of the climate on all temporal and spatial scales beyond that of weather events" (Sposito, 2006). The time scale is therefore shorter (months to years).

Muller (2007), Schulze (2005) and EDRC (2003) agree that effects of climate change are amplified by the hydrological cycle. For example, average stream flows can increase and decrease by 10-40% and 10-30% respectively for a relatively small temperature change of a 1 - 3 degrees Centigrade (Muller, 2007) . This poses a high risk for societies that are vulnerable due to their inability to adapt to such a change.

Southern Africa is at more risk from climate change than many other regions of the world because of its already high variability in climate, higher level of water scarcity in many areas which is further compounded by poverty (Schulze, 2005). Modelling of climate change for Southern Africa (Engelbrecht, 2005) indicates an increase in temperature ranging between 2-3^{o}C assuming doubling of carbon dioxide (CO_2) concentrations over the next 100 years. Regarding precipitation, a 20 – 40% decrease in winter rainfall (June, July and August) was simulated over the western and southern coastal regions of South Africa for the same period. Conversely, an increase in precipitation of about 10 – 20% was simulated over the eastern interior of South Africa in future. Therefore, a varied effect of climate change in the country is apparent. Whereas a general increase in temperature across the whole country is expected, a reduction in precipitation is foreseen from the northeastern to the southwestern coast of the country.

The specific study of climate change and its impacts on surface water availability in the Upper Vaal River Basin has not been carried out. However, from the results of country wide climate change modeling, increased temperatures and precipitation in the region are expected. This will most likely alter the hydrology of the basin, thus having a 'domino' effect on the future socioeconomic development within. In addition, future augmentation of the existing water infrastructure and supply in the Basin has already been ear marked albeit solely on consideration of socioeconomic growth (DWAF, 2006). Therefore, climate change is now an additional source of uncertainty, thus necessitating a paradigm shift from conventional approaches to water resource planning and management in the Basin, which normally assumed a static climate.

1.3. Why study the Upper Vaal River Basin?

The Vaal River, known as the 'workhorse of South Africa's water resources' (Vuuren, 2008) meanders its way through the region termed as the 'economic powerhouse' of the country to meet the Orange River just upstream of Douglas Town. The three WMAs combined contribute approximately 24% to the country's Gross Domestic Product (GDP)(DWAF, 2004), evidence of its pivotal role in the country's economy. The Upper Vaal River Basin is responsible for water release to downstream Middle and Lower Vaal WMAs, thus making its role crucial in management of water resources of the Vaal River.

Extensive development in mining, power generation and agriculture makes this Basin an important lifeline to the country. Apart from the economy, the Basin supports a population of more than 6 million people, which is 13% of the National population. In addition, there are numerous inter-basin transfers of water into and out of the Upper Vaal River Basin making it a sensitive water resource system. As it stands, Vuuren (2008) infers the surface water resources of the Vaal River Basin have been fully exploited more than three decades ago.

However, due to further economic and population growth, water demand is projected to increase (DWAF, 2006) despite the constrained supply. In view of this, options for augmentation of existing supply are already being investigated. Furthermore, introduction of the 'Reserve'[2] by the National Water Act, 1998 (Act No. 36 of 1998) has placed additional pressure on the water availability.

[2] The Reserve is composed of two parts: the Basic Human Needs Reserve (BHNR) and the Ecological Reserve (ER). The BHNR provides for the essential needs of individuals served by the water resource in question and includes water for drinking, for food preparation and for personal hygiene. The ER on the other hand relates to the water required to protect the aquatic ecosystems of the water resource (Republic of South Africa, 1998).

It is therefore apparent that the situation in the UVRB is hanging on a balance. The combined supply is just adequate to meet the present water demands and of the near future. Therefore, an additional uncertainty of climate change has the strong potential to upset this balance, and cause for the reassessment of the planning measures already put in place.

1.4. Research Objective

The purpose of this research is to investigate the effects of future climate change on meeting the water demands of different consumers in the Upper Vaal River Basin using the Water Evaluation And Planning (WEAP) model.

1.4.1. Specific Objectives:

1. Set up the Upper Vaal River Basin naturalised hydrology in WEAP using historical hydro-meteorological data.
2. Superimpose the existing water infrastructure and present water demands in the basin on the natural hydrology based on the water demand data presented in the DWAF Report No P RSA C000/00/4405/07: Vaal River System: Large Bulk Water Supply Reconciliation Strategy.
3. Assess the effect of future climate change on meeting projected water demands in the Upper Vaal River Basin.

1.5. Outline of Dissertation

Chapter Two presents the concept of modelling and various types of models available. Previous research carried out regarding the impacts of climate change on water resources in South Africa is also given together with use of the Water Evaluation And Planning (WEAP) model in similar studies in South Africa and around the globe.

Chapter Three introduces the hydro-climatological characteristics and socio-economic development of the Upper Vaal River Basin.

Chapter Four outlines the modelling of the Upper Vaal River Basin naturalised hydrology in WEAP and its calibration to simulate historical hydro-climatological characteristics.

Chapter Five describes the setting up of the WEAP model to simulate the existing situation incorporating developed water storage infrastructure, inter basin transfers and the different water demands in the basin.

Chapter Six sets out the concept of climate change and the theory and justifications behind the General Circulation Model (GCM) adopted for this study. Demand projections are explained together with the assumptions made for this Study. Lastly, an analysis of the results from the simulation is presented here.

Chapter Seven summarises the conclusions of this Study and recommendations for further work.

CHAPTER TWO

LITERATURE REVIEW

"The danger posed by war to all of humanity - and to our planet - is at least matched by the climate crisis and global warming. I believe that the world has reached a critical stage in its efforts to exercise responsible environmental stewardship"
UN Secretary General Ban Ki-Moon

2.1. What is Climate and Climate Change?

A statistical description of weather of a region in terms of its mean and variability of the parameters for example temperature and precipitation over a long period, typically 30 years (defined by the World Meteorological Organisation(WMO)) is defined as the climate of that region (Harvey *et al.*, 1997). The climate system on the other hand is defined as being composed of the atmosphere, hydrosphere, cryosphere, land surface and biosphere. The collective interaction between the different components of the climate system determines the seasonal and geographical distribution of the global climate (Miller and Yates, 2005). This is further illustrated in Figure 2.1.

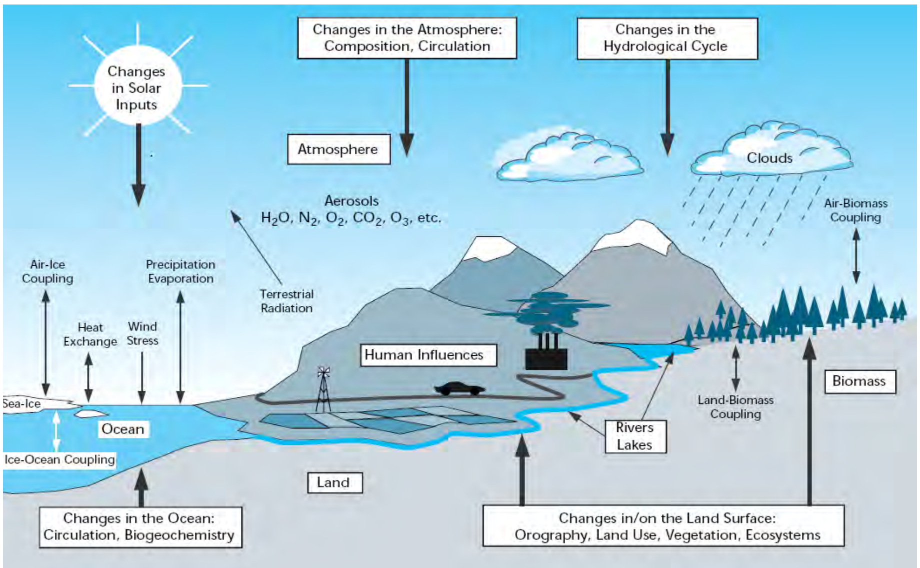


Figure 2.1: Schematic Representation of the Components of the Climate System (from Miller and Yates, 2005)

The energy from the Sun is the main driver of the climate system. The total solar radiation has to be offset by an equal magnitude of radiation back into space to maintain a transient balance between the incident and reflected solar radiation. However, this balance can be distorted by perturbations to the climate system. These can be categorised into two processes namely external forcings and/ or internal processes (Henderson-Sellers and McGuffie, 1987; IPCC, 2007).

- External forces occur naturally and outside the climate system for example Milankovitch variations, solar radiation and collisions of comets with Earth and contribute to the total natural variability in the climate system.
- Internal processes occur within the climate system from natural processes like volcanic activity, atmospheric processes and coupled interactions between climatic components for example the El Niño Southern Oscillation (ENSO). These processes occur instantaneously (condensation of water vapour to form clouds) or may take years (inter-hemispheric exchange). However, recent concerns are the contribution of human activities like deforestation and desertification, which alter the land surface hence resulting in surface-albedo change. Unlike the longer time scales of the natural processes, anthropogenic contributions are on relatively shorter time scales hence their effects can be realised within the century.

Therefore, ‘climate change’ results when these perturbations persistently alter the mean and/ or variability of the climate properties for an extended period (in terms of decades)(Bates *et al.*, 2008). This definition includes any change either because of the natural variability of the climate system or anthropogenic activity. On the other hand, climate change as defined by the United Nations Framework Convention on Climate Change (UNFCCC) is the change observed over comparable periods in composition of the global atmosphere in addition to the natural variability. This change is mainly due to direct or indirect human activity.

The main greenhouse gases (GHGs) that are carbon dioxide, methane, nitrous oxide and water vapour naturally exist in the atmosphere and are responsible for keeping the Earth warm. These gases do not absorb the incoming short wave radiation from the Sun, but absorb part of the reflected long wave radiation from the Earth's surface and 'back-radiate' it. This is known as the greenhouse effect. However, the main cause of alarm is the rate at which human activities are releasing additional quantities of these gases including the more potent halocarbons into the atmosphere. Since these gases have long atmospheric life spans, it will be centuries before the climate system can recover from this damage(Miller and Yates, 2005).

Conversely, small particles also known as aerosols, have a cooling effect on the climate system. These particles are soil dust, small particles from combustion and volcanic activity (sulphur dioxide, black carbon and organic carbon) that reflect the inbound Sun's energy away from the Earth's surface. However, this cooling effect is temporary due to shorter life spans of these particles in the atmosphere.

Perturbations to any element of the climate system will trigger an adjustment via feedback mechanisms. These mechanisms can be categorised into positive and negative feedbacks. A positive feedback amplifies a perturbation whereas a negative feedback dampens it (Henderson-Sellers and McGuffie, 1987). An example of a positive feedback mechanism is the ice – albedo feedback mechanism. This mechanism comes into play when air temperatures increase due to increased solar input or green house effect. As a result, the ice sheets and snow would start melting, causing the resulting area of ice cover to reduce. The reflectance of snow is high; hence, the reduced area of snow coverage means a larger area of the earth's surface to be exposed instead. Since the earth's reflectance is low, more radiant energy would be absorbed by land thereby further warming the affected areas.

A negative feedback on the other hand is cloud formation. Increase in temperature causes the ocean temperatures to rise. This consequently increases the rate of evaporation thus supplying the atmosphere with more water vapour conducive to enhanced cloud formation. As clouds reflect incident radiation away from the Earth's surface, greater global cloud coverage would reduce radiative forcing and lead to lowering of the global temperature.

2.2. Observed Climate Change

The authoritative body responsible for assessment of scientific, technical and socio economic research relevant for understanding the causes, impacts and possible adaptation and mitigation strategies of climate change is the Intergovernmental Panel on Climate Change (IPCC)(IPCC-DDC, 2008). Since its inception in 1988 by the WMO and United Nations Environment Programme (UNEP), the IPCC has published four major assessments of climate change in 1990, 1995, 2001 with the latest in 2007 known as the Fourth Assessment Report (AR4).

According to IPCC (2007) on observed climate change:

- Global concentrations of carbon dioxide (CO_2), methane (CH_4) and nitrous oxide (N_2O) have increased significantly since 1750 with the former two gases exceeding the natural range over the past 650,000 years. This has been attributed to human activities like burning of fossil fuels, land use change and agricultural practises. Emission of CO_2 increased by more than 35% from pre-industrial period (circa 1750) to 2005 with highest decadal (1995 – 2005) growth recorded in the last 200 years.
- Similarly, CH_4 and N_2O concentrations increased by approximately 148% and 18% since 1750 to 2005.
- An increase in global surface temperature of $0.74 \pm 0.18^{o}C$ has been observed from 1906 to 2005, with the years' 1995 to 2005 ranking amongst the 12 warmest years in the instrumental record of global surface temperature since 1850.

- More than 80% of this heat is absorbed by the oceans resulting in the average global average sea level rise of 1.8±0.5mm per year from 1961 to 2003.
- Observed trends from 1900 to 2005 dictate a significant increase in precipitation over eastern parts of North and South America, northern Europe and northern and central Asia whilst drying has been observed in the Sahel, Mediterranean, southern Africa and parts of southern Asia.

Therefore, climate change is an established scientific fact and has already begun having unprecedented impacts on our climate system. As a means of developing a better understanding of the intricate interactions between the components of the climate system in an environment of continued impacts of human and natural drivers of climate change, a variety of scenarios have been developed from studies of past climate and from climate models (discussed in Section 2.3.1). These models simulate the processes and predict the effects of changes in one or many components of the climate system, hence giving a picture on future impact scenarios of climate change.

2.3. Modelling Climate Change

The climate system is a complex interaction between physico-chemical processes, understanding of which has continued to evolve since the 1950's with developments in technology and advances in understanding its science. The developed techniques of studying our climate are a simplified representation of the how the climate components interact with each other. However simple the modelling approach, it nonetheless presents a hurdle because the various interactions operate on different timescales ranging from hours to decades. To this effect, impacts and respective magnitudes of climate change are derived from scenarios, which have been developed from climate studies to predict possible changes in the future climate.

2.3.1. Climate Change Scenarios

Climate change scenarios are possible sequences and/ or combinations of plausible changes in future climate. They are used to assess the future consequences of climate change and assist the relevant authorities to formulate appropriate mitigation and prepare adaptive measures to accommodate these changes.

2.3.1.1. <u>Types of Climate Change Scenarios</u>

IPCC-TGICA (2007) classifies climate change scenarios into three main categories. These are:

a) Arbitrary or Synthetic Scenarios

This type of scenario tests the sensitivity of a climatic system by changing the key climatic variables based on expert judgement of their plausible changes envisaged in the future. In most cases, a combination of the key variables is used. An example scenario is considering an increase in temperature over a range of 1^{o}-3^{o}C combined with an increase, decrease or no change in precipitation of 10%. These scenarios can be efficient in portraying a future consequence only if adopted variations in the key variables are based on an expert opinion of the most likely scenario derived either from climatologists or from climate models.

b) Analogue scenarios

The past climate can be reconstructed from historical observed records or from measurements taken from ice cores (paleoclimate reconstruction). The observed records can give a good picture of the inter and intra decadal variations in climate and its regional distribution. However, this is dependent on quality of the observations and the number of observation stations covering a region. The paleoclimate reconstructions are on a larger time scale of hundreds to thousands of years ago and cover a more detailed variation in climate compared to the observed records. Therefore, future scenarios are developed based on the past behaviour of climate.

c) Climate Models

Climate models attempt to simulate the interaction of processes which define the climate. Models, which simulate the entire Earth's climate, are called global climate models. These have coarse spatial resolutions (up to 300km grids spacing, which translates to one theoretical value per 300km by 300km grid cell) and range from simple one-dimensional to complex three-dimensional models known as general circulation models (GCMs). GCMs can further be divided into oceanic GCMs (OGCM) and atmospheric GCMs (AGCM). These two models can be coupled to interactively simulate the oceans, atmosphere and land surface. These are called atmospheric-ocean GCMs (AOGCMs).

Climate models have been parameterised using four main emission scenarios of anthropogenic forcings published by the IPCC Special Report on Emission Scenarios (Nakićenović *et al.*, 2000) for use in climate change studies. These scenarios, defined according to four storylines namely A1, A2, B1 and B2, were constructed to explore future socio economic developments in terms of economies, population growth, and technological advancement. A detailed description of these scenarios is given in Figure 2.2.

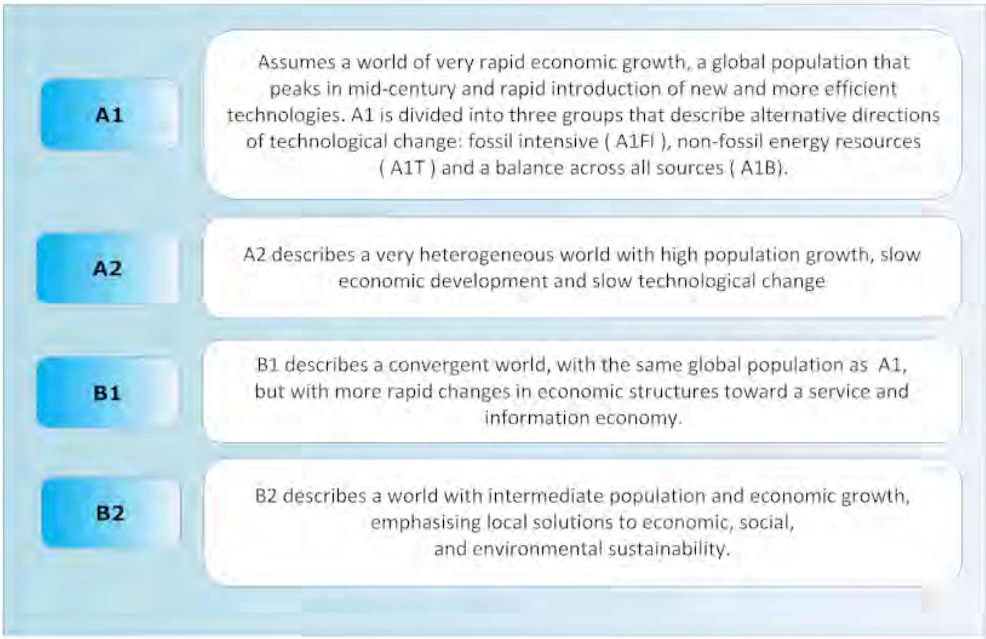


Figure 2.2: The Emission Scenarios of the IPCC Special Report on Emission Scenarios (SRES) (after Nakićenović *et al.*, 2000)

GCMs have been used to predict future changes in climate until the end of the 21st century by various institutions specialising in climate research. More information on these institutions, their models and analyses data can be obtained from the IPCC Data Distribution Centre at http://www.ipcc-data.org.

Presently, AOGCMs are the ideal tools for simulation of present and future climate (Hewitson *et al.*, 2005). However, due to their low spatial resolutions, they have to be downscaled to be of use in regional impact studies, which require higher resolutions ranging from 10 – 100km. Therefore, downscaling procedures are required to obtain regional scale detail from the AOGCM simulations (Engelbrecht, 2005). The three main techniques, according to (Mearns *et al.*, 2003), applied in downscaling are:

a) *Variable resolution time-slice GCM experiments*: Simulation of climate at higher grid resolutions ranging in the order of 100km globally and 50km locally is feasible over shorter time scales of several decades. The 'time-slices' of interest are identified and modelled in finer spatial detail.

b) *Nested regional climate models*: this modelling approach uses a high resolution regional climate model (RCM) within the lower resolution GCM. This is known as 'nesting' the RCM within the GCM. The input to the nested RCM is the output from the GCM at its nesting boundary. These models are also known as limited area models (LAMs).

c) *Empirical/ statistical interpolation*: Statistical downscaling involves modelling the relationship between the large-scale variables from GCMs (predictors) to the regional or local variables (predictands). Thereafter, the GCM predictors are input into the statistical model to estimate the corresponding local or regional predictands.

A more detailed description of the above methods of downscaling can be obtained from Mearns *et. al*. (2003) and Wilby *et. al*. (2004).

2.4. Climate Change in South Africa

A comprehensive study on climate change in Southern Africa, funded by the Water Research Commision, was carried out in year 2002 by a consortium of four South African universities. According to this study, a plausible future climate change scenario has been developed using a variable resolution model. The conformal-cubic atmospheric model (C-CAM), developed by the Commonwealth Scientific and Industrial Research Organisation (CSIRO) in Australia, was used for this purpose and has a relatively high spatial resolution, results of which are ideal for impact studies (Engelbrecht, 2005).

This model was nested in the CSIRO's Mk3 AOGCM with both models simulated for present day climate (1961 – 2000) using observed GHG concentrations. However, only the A2 SRES scenario was used for the future climate prediction (2001 – 2100). The dataset of simulated observed climate for the period (1961 – 1990) from the Climate Research Unit (CRU) was used to validate the present day simulation results from the C-CAM model and there was a consensus between the results and dataset in terms of rainfall and temperature with some uncertainties intrinsic to using such models.

Simulated January and July temperatures are set to rise in the future over the southern African subcontinent by $1^{o}C$ – $3^{o}C$ with the western sub continent being warmer than the east. The rainfall simulation was split into monthly clusters and expressed as a percentage of present-day monthly rainfall. Starting with the months of June, July and August (JJA), rainfall is predicted to decrease by 20 – 40% over the western and southern coastal regions of South Africa. However, in September, October and November (SON), an increase of up to 40% is predicted over the same regions. Moving to December and January, the central and eastern parts of the country are simulated to receive increased precipitation up to 20%. The western interior will see a rainfall increase in February to April of about 10 – 20% of the present day monthly rainfall.

Therefore, a clear message is portrayed that South Africa will have a warmer climate in the future with a varied quantitative distribution of precipitation. However, the results obtained from the model should be interpreted with caution because only one SRES scenario instead of an ensemble of different scenarios. Furthermore, as much as the models are the best tools available for climate prediction, the uncertainties in model performance should be borne in mind and the results construed as indicative rather than definitive.

2.5. What is Hydrological Modelling and Why?

Hydrological modelling, according to Schulze (2000), is the "quantitative expression of observation, analysis and prediction of the interactions of the various hydrological processes which vary in time and over space, i.e. rainfall, infiltration, evaporation or stream flow."

Modelling gives us a better understanding of the hydrologic processes and can be used to predict possible outcomes of present and future scenarios, hence assist in developing solutions to real world problems with a detail unattainable with conventional pen and paper analysis. In addition, it is essential in hydrology because it is difficult and impractical to ascertain physically the above-mentioned interactions at a sufficiently representative number of points in the catchment. Furthermore, any possible modifications to the hydrological system, for example, due to human activities need to be determined much earlier so that mitigation measures can be put into place in appropriate time. Therefore, modelling is the only way to ‘peek’ into the future and determine what will happen if present conditions remain constant, improve or worsen.

2.5.1. Classification of Hydrologic Models

Hydrologic models can be categorised based on the following (Hughes, 2004 & Fu, 2005)

a) *Purpose of the model*

   The objective of the modelling application determines the type of model to be used. For example, single event models are used for modelling short period events like floods, whereas continuous models are more suited to simulate longer sequences of occurrences. For water resource management, models which combine the simulation of hydrology and the effects of storage, abstraction and return flows are preferred. Some models are basically used to understand system processes in real time.

b) *Model Structure*

   Hydrologic modelling attempts to define the response of various outputs (stream flow, ground water and soil moisture) in response to climate inputs in the hydrological processes. The complexity of a model is therefore determined by the extent of this definition. Simple models use few parameters hence do not achieve a detailed representation. More complex models attempt to define all the input and output processes although requiring larger number of parameters.

c) *Spatial complexity*

There are two main modelling techniques, the first considering the area as a homogenous entity with generalised parameters. The flow processes are described for the area as a whole. The second method disaggregates the total area into sub-areas based on natural drainage or on geometric shapes. The flow processes are described at each point within the total area. The selection of which method to use largely depends on the quality of data available for the area.

d) *Temporal complexity*

This is defined by the time step the model uses to define the hydrological processes. The time steps vary from minutes to a year or can vary within the model run to capture special events like extreme rainfall or flood.

2.5.2. Types of Hydrologic Models

It is very difficult to distinguish between the different types of hydrological models because every model is a collection of modules, which compute the different components of the hydrologic process and each module can conform to a certain type of model based on the objective of the model and the quality of available raw data (Ochieng, 2007).

A brief hierarchical outline and definition of each type of model collated from Linsley Jr. *et al.* (1982), Olsson and Pilesjö (2002), Skidmore (2002), Ochieng (2007), Ragunath (2006)and Refsgaard (2007) has been presented for completeness. Models can generally be grouped according to two logical approaches:

Deductive models: These models form a specific conclusion based on general truths or known reasons based on physical laws, which are well understood.

Inductive models: These models use a series of facts to derive or prove a conclusion. The relationship between the fact and conclusion is observed but the exact mechanism may not be understood. This logical approach results in discovery of patterns from observed data.

Depending on the logical approach used, the following types of models emerge:

***Stochastic models*:** These models, as defined by Ragunath (2006), introduce the concept of probability because they are based on the chance of occurrence of input data or the parameters of the model itself. Therefore, the output will also vary.

***Deterministic models*:** These are models, which describe the catchment processes in terms of mathematical relations based on physical laws and not on probabilities of occurrence. These models operate within a set of initial and boundary conditions. Deterministic models are further grouped into the following:

a) *Empirical models*: Also known as 'black box' models, they are driven by equations derived from regression and correlation results from statistical analyses of observed time series data and do not attempt to understand the physical processes in the catchment.

b) *Process driven models*: These models use mathematical relationships to describe the processes and are largely deductive in nature. These models are also known as 'white box' models and can be divided into *conceptual models*, which mainly rely on theories to interpret natural phenomena rather than the physical processes, and *physical models*, which are based on detailed description of the processes in the catchment and require measurable input data.

Some models have both empirical and physical components. These are known as semi-empirical or 'grey box' models.

A further classification of the above can be based on how the catchment characteristics have been considered. This is as follows:

a) Lumped models**:** These models ignore the spatial variations in parameters and consider the catchment as a homogenous hydrological response unit (HRU).
b) Distributed models: These models on the other hand provide a description of catchment processes at geo-referenced computational grid points within the catchment. They break down the catchment into different HRUs based on their characteristics.
c) Semi – distributed models: These are hybrids of the lumped and distributed models. In this case, the descriptions of the hydrologic processes are based on semi – empirical equations. Some kind of distribution is implied, either in sub-catchments or in HRUs, where areas with the same key characteristics are aggregated to sub-units.

Figure 2.3 describes the different types of models. The arrows represent the possible combinations of the different types in modelling applications.

It would therefore be important to highlight the intertwined nature of the types of models explained in Section 2.5.2. For example, a conceptual or empirical model can be either deterministic or stochastic or a combination of both. This is illustrated by models for sediment transport, which have both deterministic and stochastic components. An example of deterministic conceptual models is propagation of flood waves and Nash models. Models based on synthetic unit hydrographs define the deterministic empirical combination(Ragunath, 2006).

Therefore, this classification serves only to give the main foundation of model types; the modeller defines its actual application.

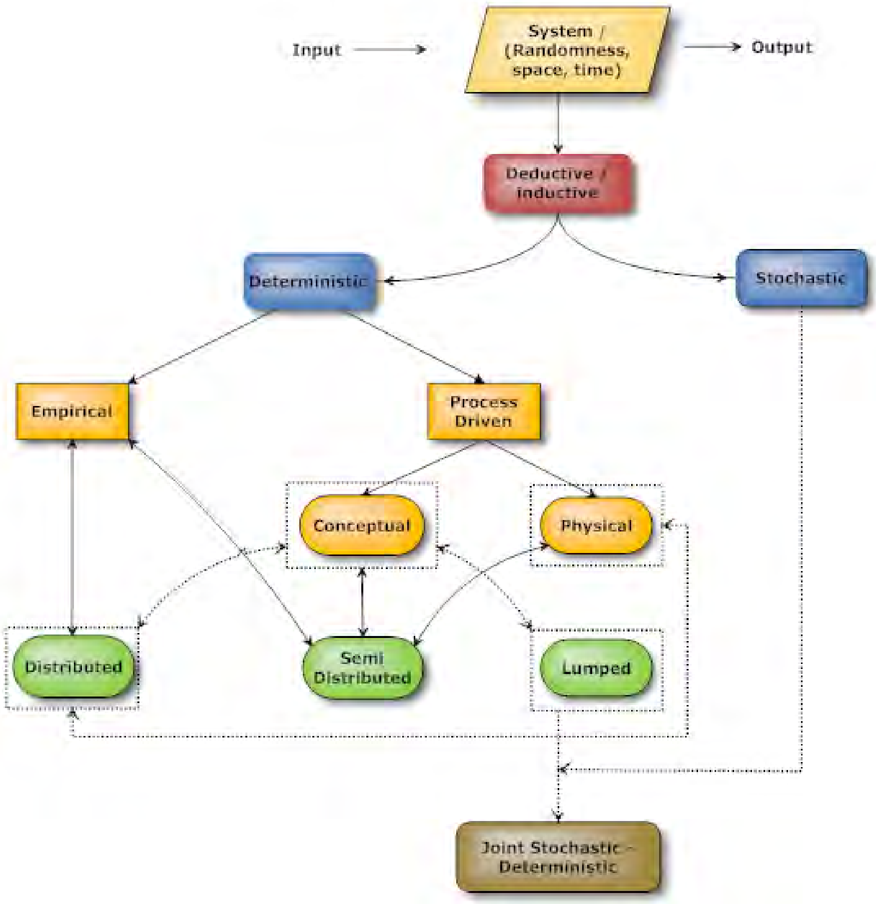


Figure 2.3: Basic Classification of Models
(Collated from literature)

2.6. The Concept of Integrated Water Resource Management (IWRM)

The current accepted definition of IWRM by the Global Water Partnership (2000) is:

> "a process which promotes the co-ordinated development and management of water, land and related resources, in order to maximise the resultant economic and social welfare in an equitable manner without compromising the sustainability of vital ecosystems".

This concept is underpinned by the Dublin - Rio principles established in year 1992 which propagate amongst others, the finite nature and vulnerability of our fresh water resources and the necessity of a participatory approach to water development and management. Therefore, IWRM focuses on an integrated approach to managing the biophysical and the socio-economic management systems (Yates *et al.*, 2005). Factors related to the biophysical system are climate, land cover, topography, surface and groundwater hydrology, availability of water and its movement through the watershed, water quality and water for the environment. The socio-economic management system comprises the storage, allocation, regulation and delivery of water to the consumers and water demand management through pricing, providing incentives for water conservation and formulation of pro-environment legislation.

The integrated approach to management of water resources is often complex, involving juggling of diverse objectives to achieve a common goal to safe guard the sustainability of the system. In most cases, this is further complicated by the conflicting nature of these objectives, for example, minimising environmental and water quality impacts as well as the running costs. This has led to the development of IWRM models, interchangeably known as decision support systems (DSS), which make this task easier than conventional methods (running different models and integrating the results by hand) that had a rather disintegrated approach in river basin simulation.

The IWRM process consists of three steps (Georgakakos, 2007). These are 1) knowledge on which to base the planning and management, which can be input into 2) a DSS that can generate information based on the inputs for 3) the public policy actors who play a major role in decision making by having a shared vision for utilisation of the water resources. Figure 2.4 gives an overview of this process in more detail. Due to the intrinsic nature of constant changes in IWRM, it becomes necessary to monitor the process on a regular interval to assess the impacts of made decisions and improve them if required. The dashed arrows in the figure highlight this.

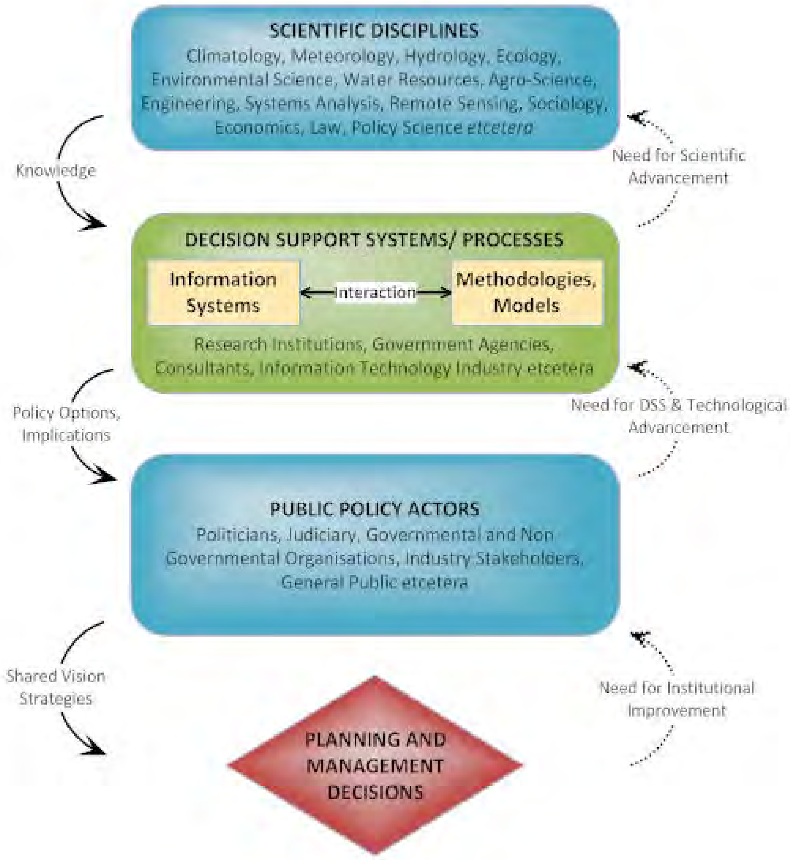


Figure 2.4 The IWRM Process
(after Georgakakos, 2007)

2.7. Climate Change and Water Resource Management

Africa is characterised by an unequal natural geographical distribution of rainfall and water bodies, water accessibility and poor sustainability in water use. This may be exacerbated by climate change, which has the potential to affect water availability and reliability, hence undermining the very existence of civilisation in terms of health, food security, energy and the environment. Furthermore, Bates *et al*.(2008) infers the current water resource management practises may not be adequately positioned to cope with the impacts of climate change. Therefore, information on current climate variability should also be incorporated in water resource management by developing mitigation strategies designed to address this issue in a wider context possibly including health and environment.

According to Schulze (2005a), water policy and related decision making in South Africa is yet to integrate the additional uncertainty due to climate change into the existing framework. Since response of the hydrological cycle is amplified by any change in climate (Muller, 2007), compounded by the fact that South Africa is already water stressed in some regions, presents a dire situation. Furthermore, the ability to adapt to these changes is weak, hence the urgency to integrate this threat into our present day policies.

2.7.1. How Will Climate Change Effect Water Resources?

Climate change will have a chain effect on the hydrologic cycle. The spatial distribution of precipitation coupled with its temporal occurrence will likely undergo alteration. Warmer temperatures will change the amount of precipitation, which will be converted to snow and affect the timing and proportion of ice melt. Evaporation will also increase leading to drier soils. Changing CO_2 concentrations will also affect the vegetation evapotranspiration thus potential increase in water loss. Longer droughts may result from drier soils, which will also alter the land cover thus affecting catchment run off response to precipitation. Furthermore, ground water recharge will also be affected thus changing the quantity of percolation. This change will consequently alter the base flow contribution of groundwater to stream flow.

In addition to water quantity, quality will also change. Extreme precipitation will result in increased run off thus washing away pollutants from urban areas and agricultural farms to the receiving water bodies. This will also pose a physical risk to water infrastructure like dams and water supply and wastewater treatment systems due to contaminant overload and difficulty in treatment. On the other hand, reduction in stream flows and water body volumes would result in increase of pollutant concentration. Furthermore, rising water temperatures would affect the ecology, which may be dependent on cooler environment.

The above is a brief of some of the consequences of climate change on our water resources. Reference is made to *inter alia* Arnell (1999)and Miller and Yates (2005) for further explanation of the impacts of climate change on water resources.

2.7.2. Climate Change Impact Studies in South Africa

The latest published research on climate change influences over southern Africa was commissioned by the Water Research Commission in year 2002 and carried out by a consortium of 4 local universities. The study is entitled “**Climate Change and Water Resources in South Africa: Potential Impacts of Climate Change and Mitigation Strategies”** (Schulze, 2005b).

The aforementioned study developed plausible climate change scenarios for southern Africa using the Conformal – Cubic Atmospheric Model (C-CAM) by simulating the period 2070 – 2100 compared to 1975 – 2005. It thereafter investigated potential impacts of climate change on hydrological responses and water resources and adaptation measures to cope with this change. The Thukela catchment was adopted as a case study.

2.8. Decision Support Systems

A decision support system (DSS) can be defined as an integrated, interactive computer system, consisting of analytical tools and information management capabilities, designed to arm decision makers with an informed systematic approach to analyses of different options in solving complex water management problems (Global Water Partnership, 2000).

A DSS is constructed of three main components. Firstly, the data required for carrying out the analyses needs to be acquired. This is done via various means, for example, hydro-meteorological from ground stations, through remote sensing technologies like radar and satellites or from surveys and literature.

Secondly, the data is collated into a database through the user interface, which provides easy access to the data and avails the data analysis tools and models. Visualisation and analysis from the data can be done using simple spreadsheets or GIS applications (spatial representation of geo-referenced data) and the built in models. Lastly, the results are extracted via the user interface and form the basis of decision-making. Figure 2.5 gives a schematic explanation of the DSS structure.

Therefore, due to the multi-faceted nature of IWRM, DSS's make it easier for policy makers and water managers to carry out 'what if' scenario analyses by simultaneously taking account of individual or a combination of causative factors *inter alia* climate change, land use and land cover change, population growth on the hydrology, water quality and economic relationships within the system. This gives a holistic response of the water resource system to these factors.

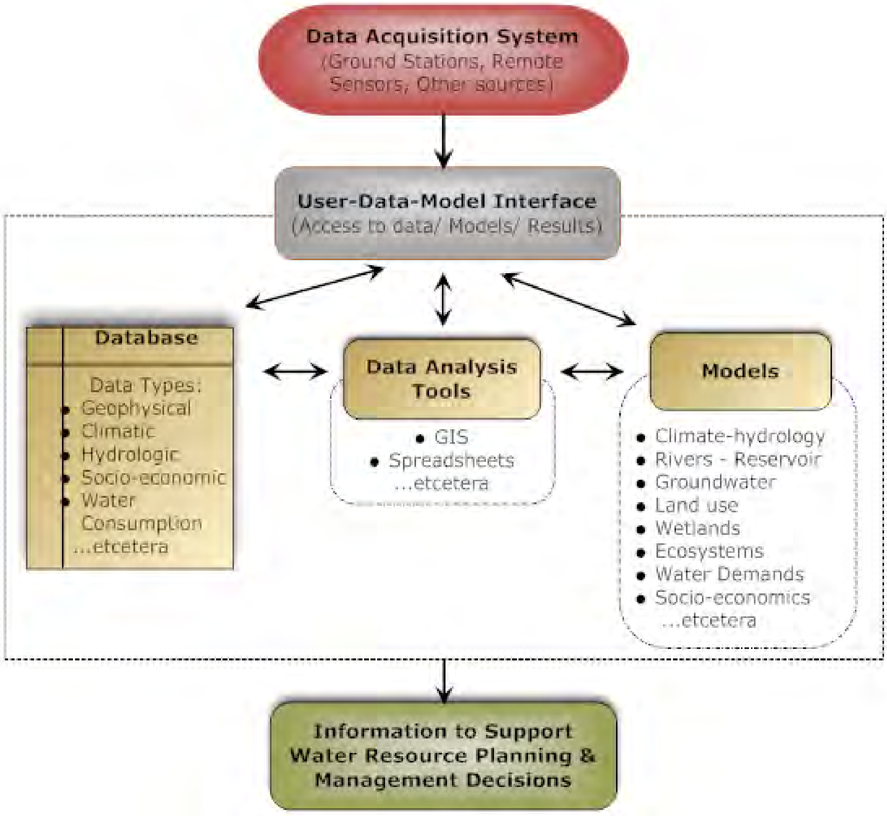


Figure 2.5: The DSS Structure (after Georgakakos, 2007)

There is a wide variety of DSS's, which have been implemented in river basins across the continents, thus making it impractical to mention all of them. Some examples of popular generic applications which have been applied to IWRM are given in Table 2.1.

Table 2.1: Generic Decision Support Systems

Model	Developed By
RIBASIM (River Basin Simulation Model)	Delft Hydraulics (Netherlands)
MIKE BASIN	DHI (Denmark)
MODSIM	Colorado State University (USA)
WBalMo (Water Balance Model)	WASY Ltd (Germany)
MULINO-DSS (Multi-sectoral Integrated & Operational Decision Support System)	A consortium under the European Union
WaterWare	
WEAP (Water Evaluation And Planning)	Stockholm Environment Institute (USA)

This study has used the WEAP model; therefore, more detail on the structure and capabilities of this model is presented.

2.9. The Water Evaluation and Planning (WEAP) Model

WEAP is a desktop tool for integrated water resource planning which has been developed by the Stockholm Environment Institute's (SEI) Boston Center. Over the past fifteen years since its first application by Raskin and Zhu (1992) in the Aral Sea region, the model has undergone major improvements such as a user-friendly graphical user interface (GUI), a more robust water allocation algorithm and the integration of hydrologic sub-modules that include a conceptual rainfall-runoff, a groundwater and stream water quality model. Furthermore, additional coupling options to external models such as Modular Three Dimensional Groundwater Flow Model (MODFLOW) and QUAL2E water quality model is also available in case the modeller finds the built-in sub-modules inadequate.

The WEAP model is a user-friendly tool that incorporates an integrated approach to water resource management, which over the last decade, has placed more emphasis on demand side management, water quality and ecosystem preservation and protection. The model integrates simulation of both the natural and engineered components of a water resource system by placing demand side issues such as water use patterns, equipment efficiency, re-use strategies, costs and water allocation schemes on an equal footing with supply-side resources such as available surface and groundwater, reservoir storage and inter-basin transfers. This gives the water manager the freedom of a more comprehensive view of the consequences of various decisions on the system.

The literature presented herewith on the WEAP model has largely been drawn from the accompanying user guide prepared by SEI.

2.9.1. Approach of the WEAP Model

Operating on the basic principle of water balance accounting, WEAP is applicable to municipal and agricultural systems, single sub-basins or complex river systems. Moreover, WEAP can address a wide range of issues, for example, sectoral demand analysis, water conservation, water rights and allocation priorities, rainfall-runoff and base flow, groundwater and stream flow simulation, reservoir operations, hydropower generation, water quality, ecosystem demands and project benefit-cost analysis (SEI, 2007).

The water system is represented in terms of its various supply sources, withdrawal, transmission and wastewater treatment facilities, ecosystem requirements, water demands and pollution generation. The data structure and level of detail are customisable (for example by combining demand sites) to correspond to the requirements of a particular analysis and constraints imposed by limited data.

WEAP applications generally include several steps. The study definition sets up the time frame, spatial boundary, system components and problem configuration. A baseline year is defined, known as the ‘current accounts’ in the model for which the actual data of confident quality is available. Alternative sets of future assumptions are then developed based on for example policies, costs, water demands, pollution, supply and hydrology. Thereafter, scenarios are constructed using either a single or a combination of these sets of assumptions and evaluated with regard to water sufficiency, costs and benefits, compatibility with environmental targets and sensitivity to uncertainty in key variables.

The study area can either be characterised as homogenous or sub-divided into sub-catchments (SC) depending on terrain or available data. The study area is fractionally sub divided according to the different land use/ land cover classes, which govern the runoff and infiltration. A one-dimensional, 2-store, conceptual water balance model calculates the hydrologic response of the area and partitions water into different components; evapotranspiration, surface runoff, interflow, and base flow. The sum of each fractional area represents its hydrologic response, with the runoff components linked to a river element, deep percolation to a groundwater element where prescribed, and evapotranspiration lost from the system.

Important time varying parameters of the water balance module include climate data (precipitation, temperature, relative humidity and wind speed), crop coefficients (k_c) and the run off coefficient, which is a function of Leaf and Stem Area Index (LAI), and slope. The time invariant parameters include upper and lower store water holding capacities, hydraulic conductivities, and a unit less parameter, *f* with a range between 0 and 1, which partitions water to move vertically as percolation to the second store or horizontally as interflow to the stream network. Stream-aquifer interactions can be represented by eliminating the lower store in the 2-store water balance by introducing a simplified groundwater element that has a hydraulic connection to associated river reaches.

At each time step, WEAP first computes the hydrologic response of the study area, which is then transferred to the respective river and groundwater components. The network allocation is then processed for the given time step, based on different priorities assigned to reservoirs, water distribution network, environmental flows *etcetera*. As in reality, all flows in the model occur instantaneously, thus a demand site can withdraw water from the river, consume some, optionally return the remainder to a wastewater treatment plant and then return it to the river in the same time step. The simulation time steps in the model can vary from daily, to weekly, to monthly or even seasonally with a time horizon from as short as a single year to more than 100 years (Yates *et al.*, 2005).

For more detail on the model, reference should be made to the WEAP User Guide prepared by SEI.

2.9.2. Applications of the WEAP model

Since its development, WEAP has been widely applied around the world in various IWRM projects with diverse objectives. Some examples are as follows:

International Projects:

- The first project involved the analysis of water accounts and evaluating water management strategies in the Aral Sea region in former U.S.S.R (Raskin and Zhu, 1992).
- WEAP has been used in the United States of America (U.S.A) for hydrological modelling (Amato *et al.*, 2006), water use and allocation studies (Yates *et al.*, 2008) and effects of climate change on agriculture (Purkey *et al.*, 2008). Furthermore, the Hydrologic Engineering Center (HEC) of the U.S Army Corps of Engineers has used WEAP in similar water resource planning studies in many basins in the Unites States of America.

- Has been applied in the Mideast to establish alternative water development and allocation scenarios involving both Palestinian and Israeli participants. In addition, Assaf and Saadeh (2008) used it to develop and assess water quality management plans to mitigate the discharge of untreated wastewater into the Upper Litani Basin in Lebanon.
- Used in the Beijing - Hebei Eco Region Programme to provide the basis for achieving co-operation on water-related issues, involving upstream and downstream stakeholders in 14 and 6 Counties respectively of Hebei Province in Beijing. The model was also used in conjunction with other solid waste models to develop the Beijing Environmental Master Plan Application System for the Beijing Municipal Environmental Planning Bureau.

On the *African continent*, WEAP has been applied:

- In Kenya for modelling water resource management in Lake Naivasha by Alfarra (2004) and for water allocation studies in Kitui under the WatManSup Project (Droogers and van Loon, 2006) and under the Green Water Credits Program in the Tana Basin (Hoff *et al.*, 2007)
- By Haagan (2007) to model the impacts of small reservoirs in an arid and semi arid region in Ghana.

In *South Africa:*

- Lévite *et al*. (2003) applied the WEAP model to the Steelpoort sub-basin in the Olifants River basin to assess the ability of Steelpoort River to concurrently meet the water demands of different consumers as well as the ecological reserve. Furthermore, different water demand management scenarios were also analysed. However, the hydrology of the basin was setup using calculated monthly stream flows from a previous study, hence was not simulated using the different climatic and non-climatic parameters in the hydrology module of WEAP.
- In another study focusing on the whole of Olifants catchment, Arranz and McCartney (2007) applied WEAP to evaluate the impacts of three water demand growth scenarios (up to Year

2025), implementation of environmental reserve (ER), international agreements (IA's) and water conservation and demand management (WC & DM) strategies on the water resource. The hydrology of the basin was simulated using rainfall and naturalised stream flows only. Calibration of the model was done by changing assumptions about the pattern of historic demand, altering demand priorities and altering the operating rules of water storage dams to improve the fit between simulated and observed stream flows at five gauging stations on the Olifants River. The impacts of climate, changes in water demand, water resource development and land use were considered to be inherently integrated in the observed stream flow data, that is, these impacts would manifest themselves in either increased or reduced stream flows. However, determination of these impacts either independently or in different combinations on the hydrology is difficult under this model configuration.

- Based on the above model configuration, McCartney and Arranz (2007) carried out another study to assess the historic scenario of water resource development in the Olifants catchment from 1920 to 1989 giving a picture on how the water infrastructure developed in context of increasing water demand. This was followed by evaluation of the impacts of previously developed plausible future scenarios for water demand (Arranz and McCartney, 2007), WC & DM policies and water infrastructure development. This study excluded the impact of future IA.

CHAPTER THREE

THE UPPER VAAL RIVER BASIN

"A river is more than an amenity, it is a treasure"
Justice Oliver Wendell Holmes

3.1. Introduction

This Chapter introduces the geographical characteristics of the Upper Vaal River Basin in terms of its climate, topography, geology, land use and land cover and specific water infrastructure developments existent in the area. A dissection of the available hydro-climatic data is also presented.

3.2. The Study Locale

South Africa is divided into 19 water management areas (WMAs) mainly to ease its water resource management. However, these WMAs do not necessarily comprise an exact hydrological response unit (HRU). Therefore, the country is also divided into 22 Primary catchments, which are further partitioned into Secondary, Tertiary and Quaternary catchments. These sub divisions serve as representations of HRUs in converging spatial detail. Quaternary catchments (QC) form a good basis for any hydrological representation of a catchment since they have been demarcated in such a way as to have similar runoff volumes. This demarcation was carried out under the Surface Water Resources of South Africa 1990 (WR90) study (Midgley *et al.*, 1994). This study has recently been updated to the year 2005 (WR2005). The Upper Vaal River Basin (UVRB) is a primary catchment, with 3 secondary, 9 tertiary and 91 quaternary catchments.

The UVRB is geographically located between longitudes 26° 55’ and 30° 20’ East and latitudes 25° 48’ and 28° 50’ South. It covers an approximate catchment area of 196,300 km^2 which is 16% of South Africa’s total land mass. Figure 3.1 gives the location of the study area.

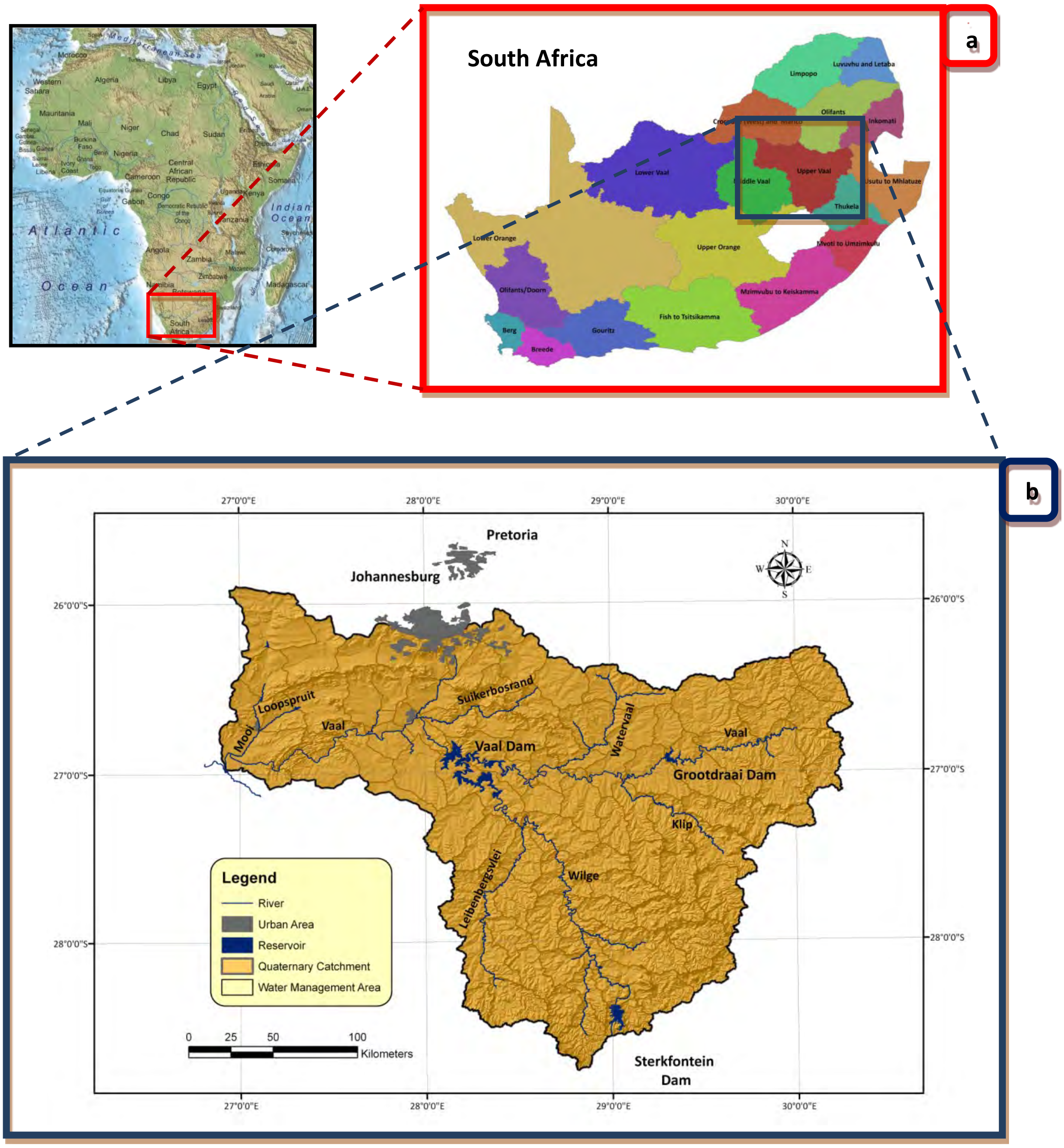


Figure 3.1: Location Map
showing a) the Primary Catchments of South Africa b) the Upper Vaal River Basin with the Quaternary Catchments, Vaal River and its major tributaries, dams and major urban areas

The Vaal River originates from the western slopes of the Drakensberg range in Mpumalanga and flows for over 1,100 km to its confluence with the Orange River near Kimberley. It is the major tributary of the Orange River.

3.3. Topography

The Vaal River flows west in the upper catchment, then south west across the middle and lower Vaal catchment indicating the catchment slopes in the N - S and SE – NW directions. The stream density is high in the upper catchment as this region has the highest elevations. The highest elevation within the catchment, greater than 2,500 m, is at the extreme south of the upper catchment. However, this is just a localised occurrence due to Lesotho Highlands. The south eastern boundary of this part of the catchment also has high elevations due to the Drakensberg Range. In general, the catchment slopes gently from 1,850 m east of upper catchment to 970 m above mean sea level near the confluence with Orange River. The higher altitudes comprise of mountainous terrain with rolling hills. Figure 3.2 shows the elevation categories in the catchment. A 90 m grid Shuttle Radar Topography Mission (SRTM) digital elevation model was obtained from http://srtm.csi.cgiar.org which was used for all subsequent terrain analysis.

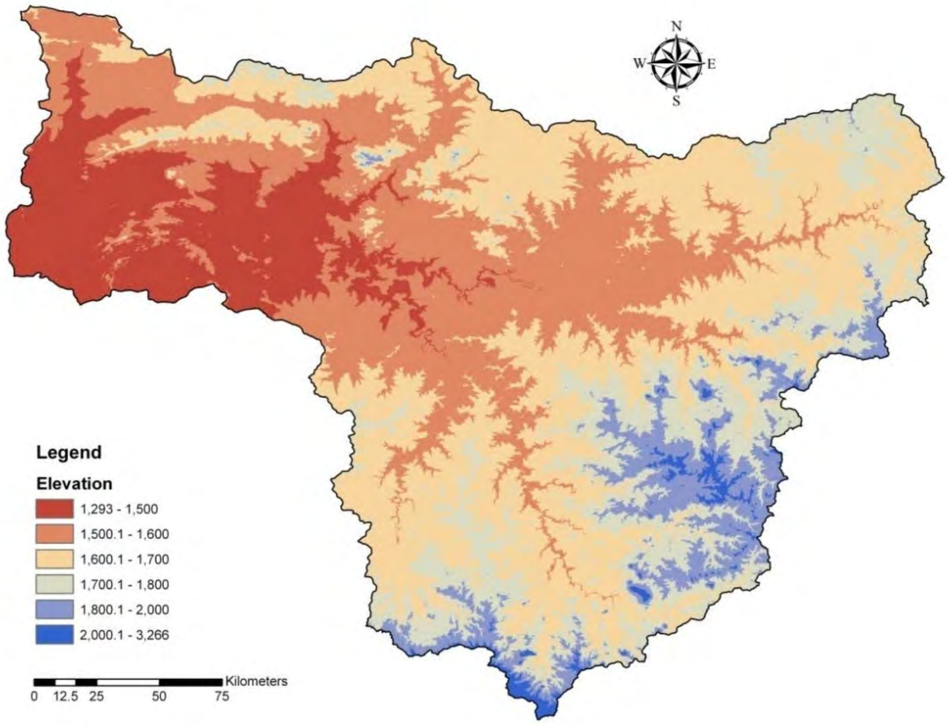


Figure 3.2: Elevation of the Vaal River Catchment
(derived from SRTM 90 m digital elevation data)

A slope analysis was carried out for the catchment using the ArcGIS Spatial Analyst. It can be observed that the extreme south and south east of the UVRB has steep slopes in the range of 25% due to the hilly landscape at the foot of the Drakensburg. The middle and lower parts of the basin is generally flat with slopes ranging from 0 to 7.5%. Figure 3.3 shows the slope categories within the basin.

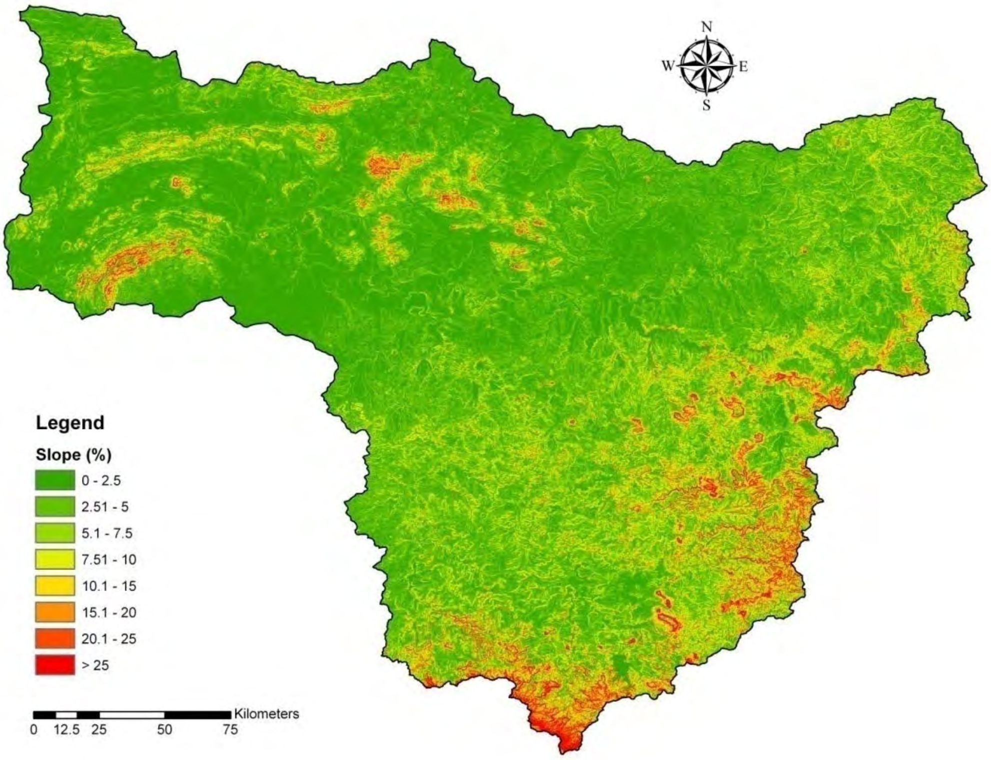


Figure 3.3: Slope Analysis for the Vaal Catchment
(derived from SRTM 90 m digital elevation data)

3.4. Geology

The UVRB is underlain by a mosaic of different geologic strata. Towards the south of the basin, fine sedimentary rocks (mudstone and arenite) of the Karoo system are predominant. The total area of the Karoo system represents about 80% of the UVRB. A 'strip' formation of shale runs across the basin. Adjacent to shale towards the north, following the same formation, is the mixed occurrence of sedimentary rock (dolerite and arenite respectively) with sparse igneous granite and andesite. Extensive dolomitic exposures can be observed at the extreme north of the basin. Towards the northwest, a large occurrence of andesite intermixed with sedimentary rocks is present. This region has extensive mineral deposits and also has the richest gold bearing ore in the world (DWAF, 2003). Sand and limestone dominate the extreme west of the catchment. Figure 3.4 gives the complete composition of the geology of UVRB.

The four main soil types within the catchment are sandy loam, clay loam, clay soil and sandy soil with soil depths ranging from moderate to deep with an undulating relief over the basin. The basin is also rich in minerals like gold, uranium, base metals, semi precious stones and coal.

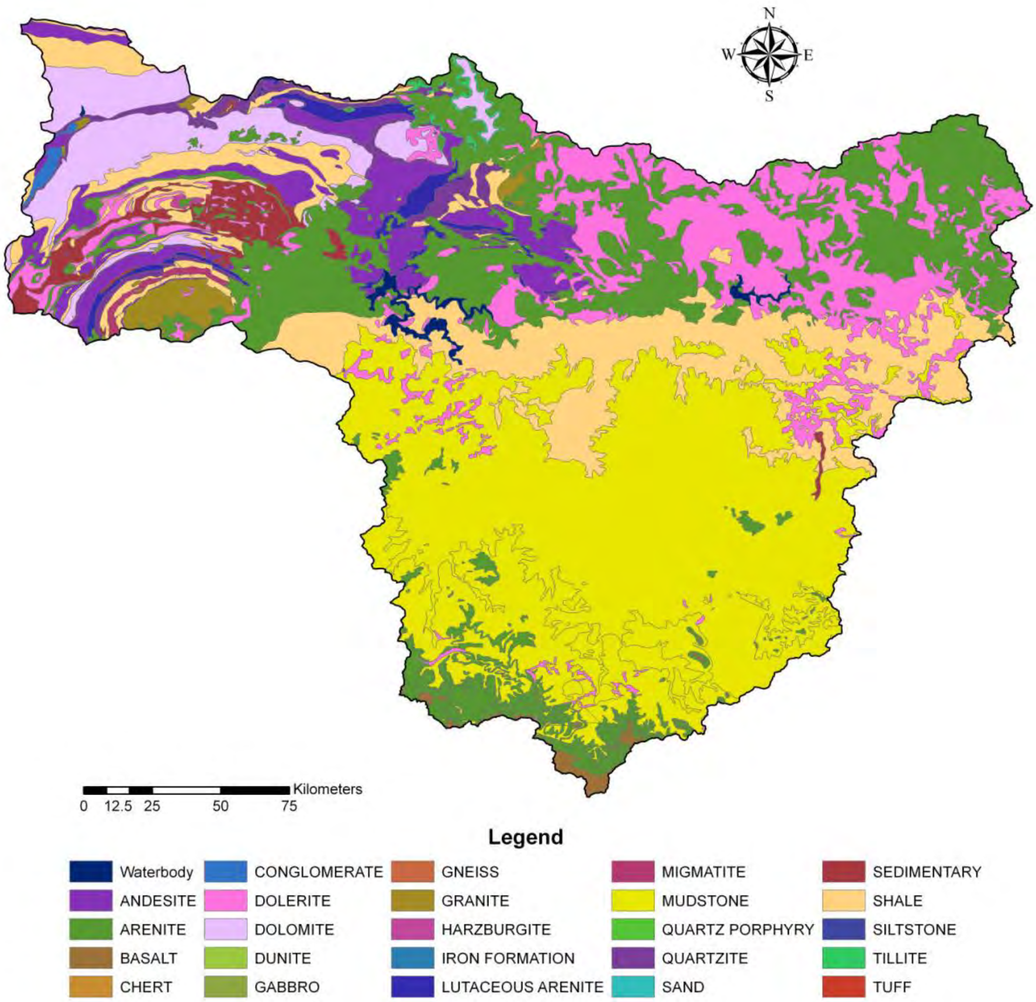


Figure 3.4: Geology of the Upper Vaal River Basin
Source: Water Resources of South Africa 2005 (WR2005)

3.5. Land use and Land Cover

By definition, land use refers to the modifications made on land by humans for the purpose of obtaining outputs in terms of products or benefits. On the other hand, land cover is the observed physical cover on the earth's surface as seen on the ground which includes vegetation (natural or planted), human constructions, water, ice, bare land and non-vegetated surfaces (Lesschen *et al.*, 2005).

Vegetation in the UVRB is mostly grassland with traces of savannah. Figure 3.5 gives the complete overview of the vegetation cover in the catchment.

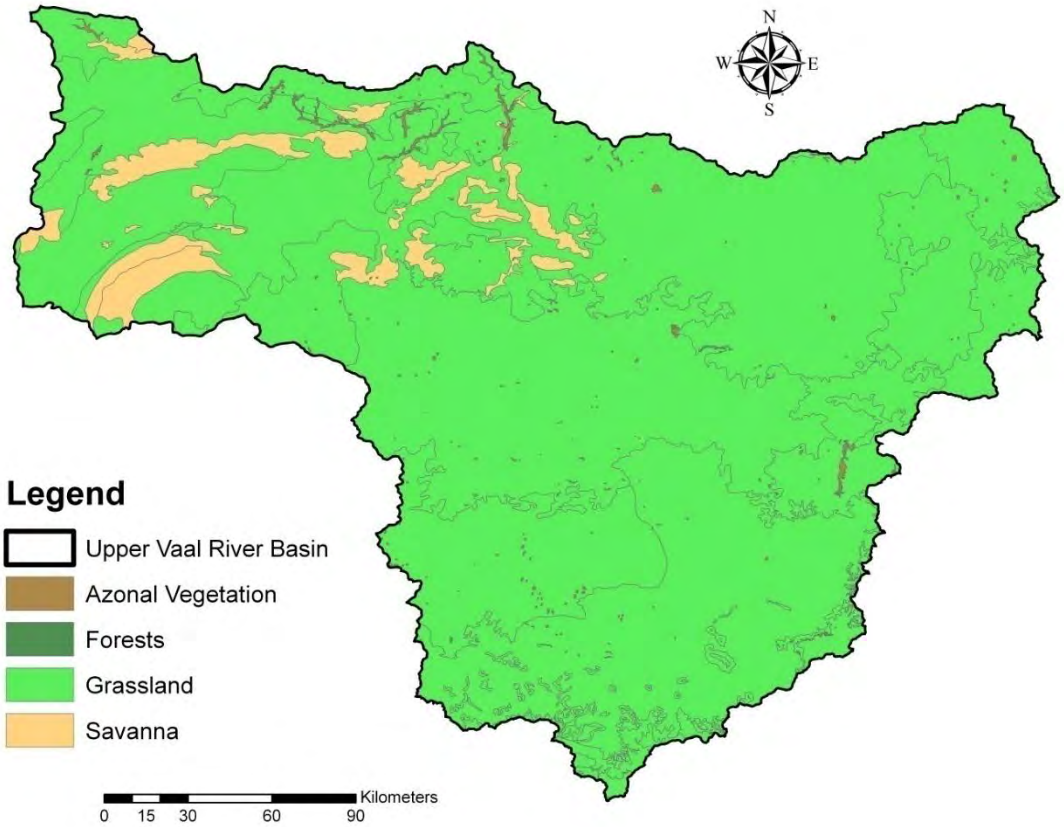


Figure 3.5: Vegetation Cover in the Catchment
Source: South African National Biomass Institute (SANBI)

The catchment has a varied land use, the major being agricultural cultivation which covers about 33% of the catchment area. There are six different categories of cultivation of which dry land commercial cultivation is the largest practise. Irrigation farming is widespread across the catchment but in small acreages. Urban/ built-up areas constitute of approximately 3.2% of the catchment area and are divided as well into four sub categories. Figure 3.6 gives a representation of the varied land use within the Vaal Catchment.

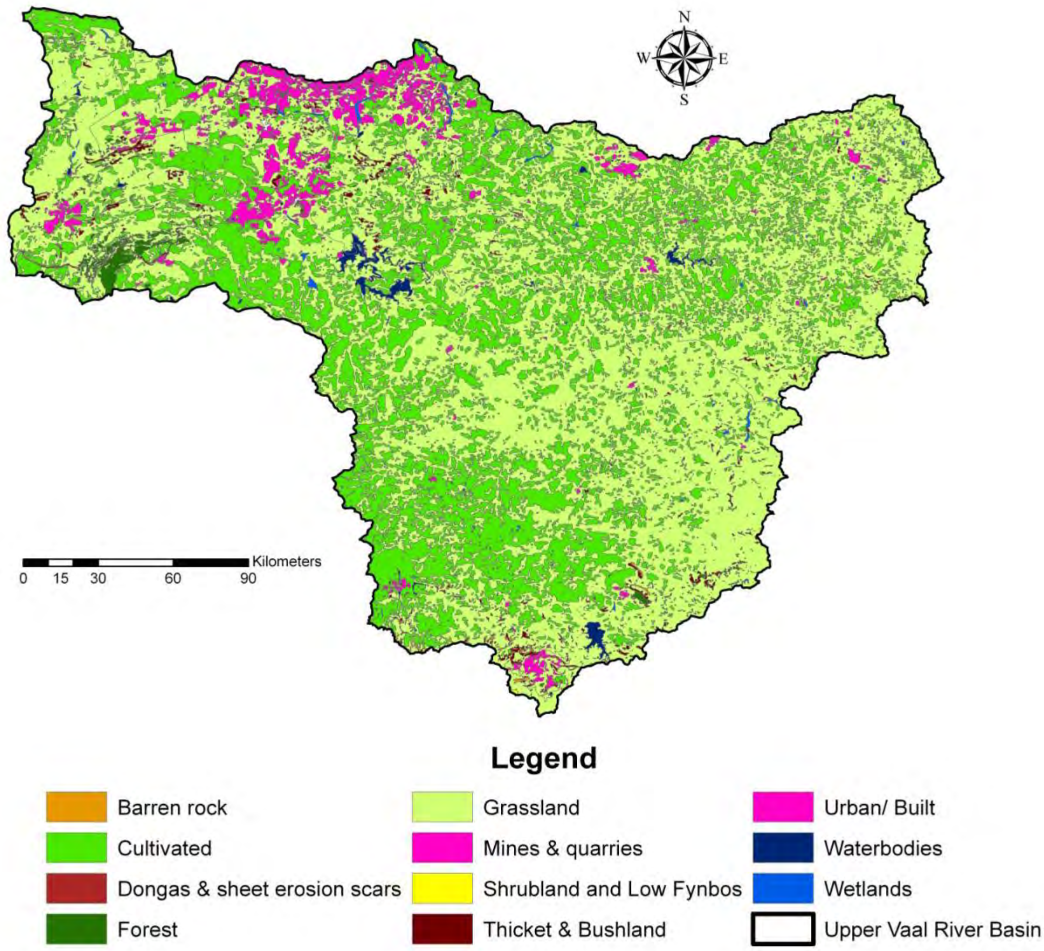


Figure 3.6: Land use within the Vaal Catchment
Source: CSIR 2003

For a clearer picture, the above land use categories were amalgamated into their main categories and have been presented in Figure 3.7 as a percentage of the total catchment area. The sub categories of the three main land uses are also indicated. Exposed rock surfaces do not exceed 0.1% of the catchment area.

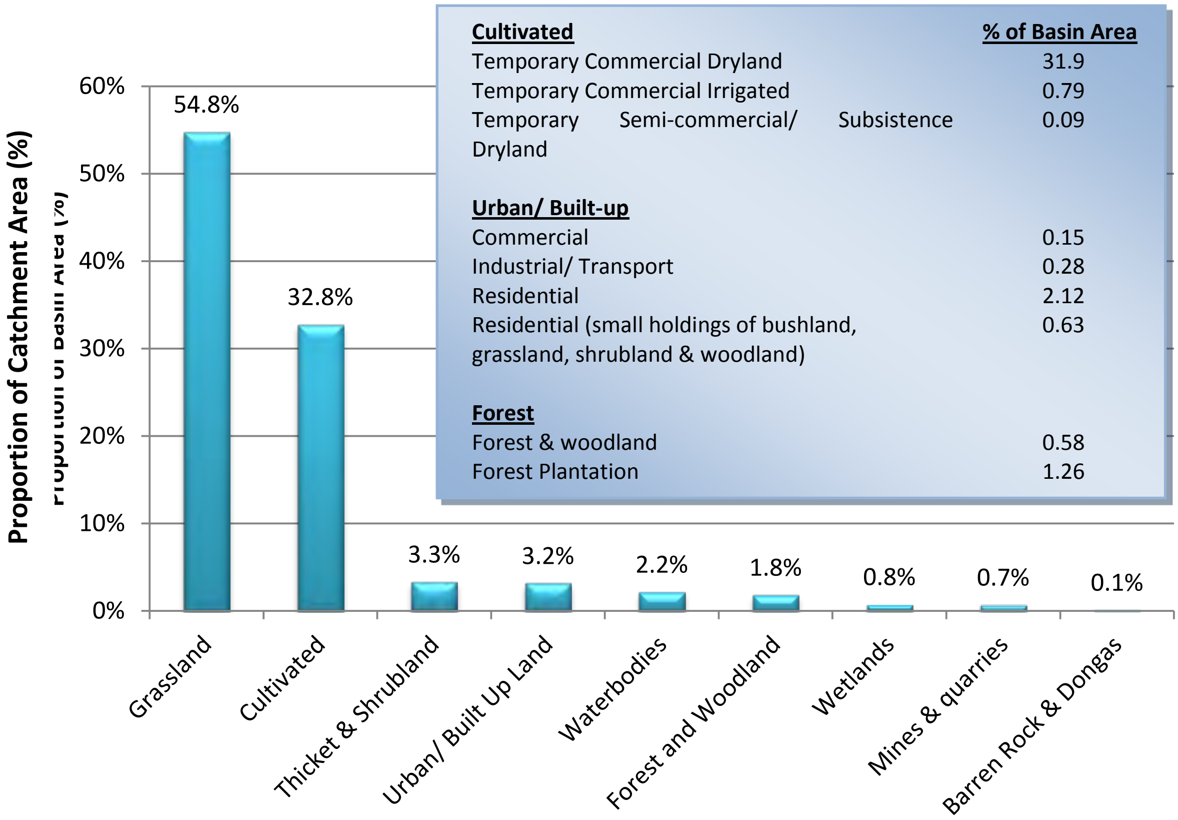


Figure 3.7: Land Use/ Land Cover Distribution Proportionate to Catchment Area (Derived from CSIR 2003 Data)

3.6. Climate and Hydrology

The DWA uses a hydrological year that begins on the 1st of October and ends on 30th September. This period captures the entire seasonal variation of rainfall and consequently the stream flow over a year. The hydrological year is named after the year in which the month of October falls. Therefore, for consistency, the same convention has been used in this study. Thus for example, the hydrological year 1961 extends from October 1961 to September 1962.

3.6.1. Precipitation

There are approximately 48 precipitation gauges within or very close to the UVRB boundary. These gauges are maintained by different organisations like the South African Weather Service

(SAWS) and DWA. However, for the purpose of this study, the rainfall data was obtained from the WR2005 Project which have consolidated the raw rainfall data for these gauges and ‘patched’ the missing data thus rendering a consistent dataset. The time period of the data varies for different stations, the longest being Year 1905 to 2004.

The UVRB is characterised by a mean annual precipitation (MAP) ranging between 600 mm to 900 mm. The slopes of the Drakensberg Range and near Lesotho Highlands experience the largest MAP. This can be attributed to the orographic rainfall in this region. In general, the UVRB experiences the highest rainfall and thus significantly contributes to the run off in the downstream regions. Figure 3.8 shows the MAP for the UVRB.

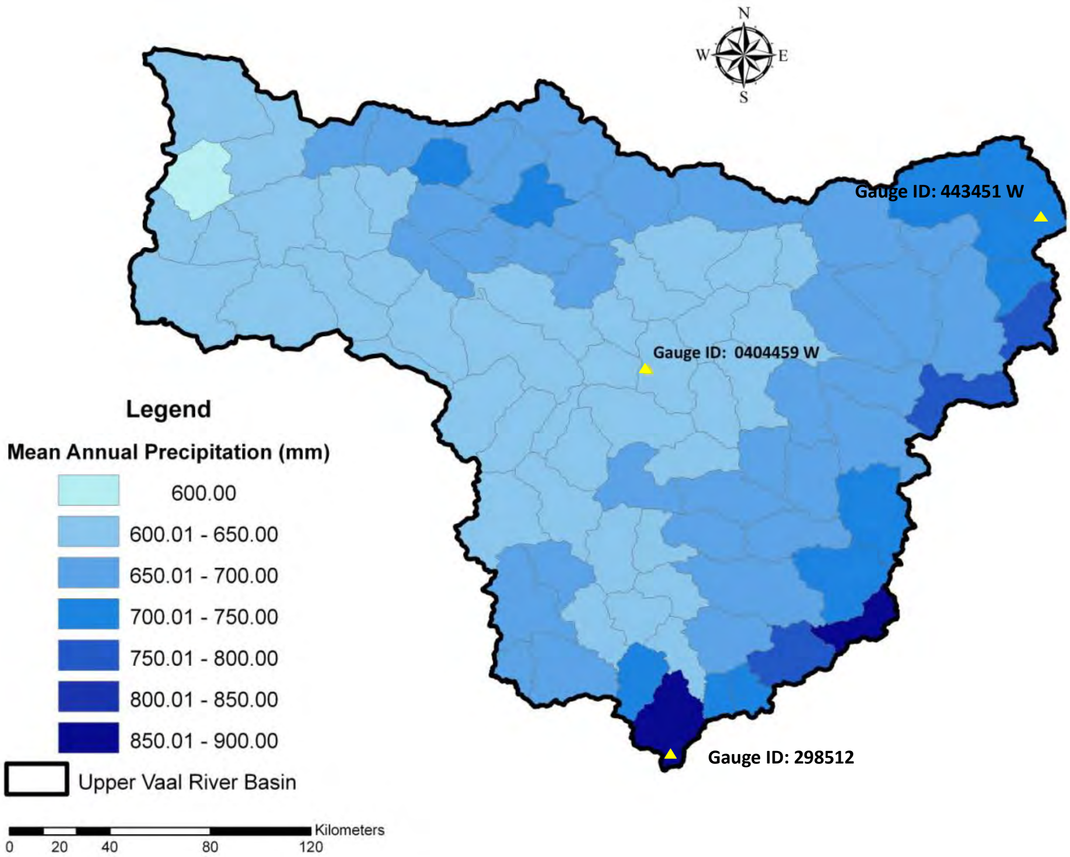


Figure 3.8: Mean Annual Precipitation (mm)
(Source: WR2005)

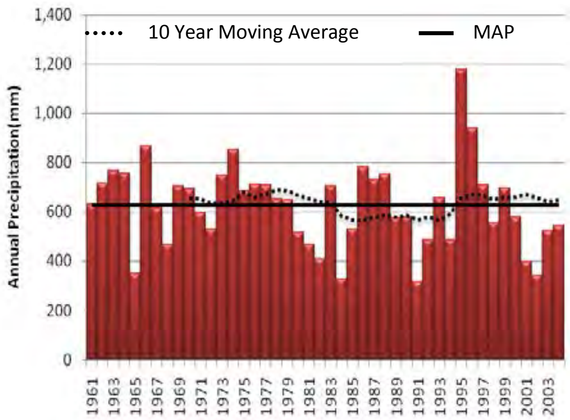
3.6.1.1. Inter - Annual Variation of Precipitation

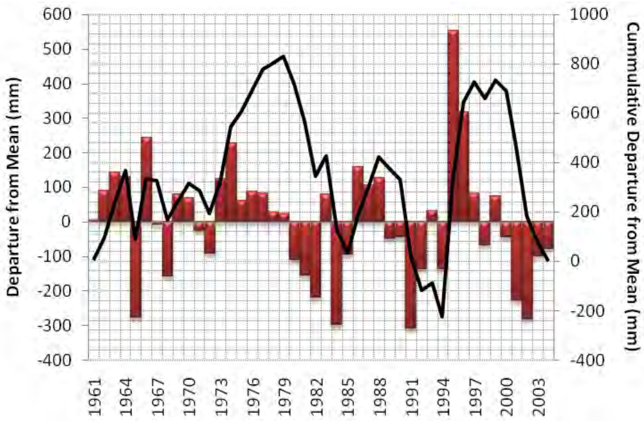
Rainfall gauges located within three zones in the basin were chosen as shown in Figure 3.8 for rainfall synthesis. The annual total precipitation was computed for the gauge over the 1961 – 2004 period. Arithmetic mean of the annual precipitation was thereafter computed and plotted against the time period. The variability of precipitation was assessed using the residual of annual total from MAP of 650mm (mid value of range for gauge in Figure 3.8). The analysis shows that the precipitation within the basin has significant inter - annual variability. Furthermore, there are many consecutive years when the rainfall was below the MAP. The 10-year moving averages also show the strong inter annual variation in precipitation. The results are given in Figure 3.9.

This methodology for precipitation analysis has largely been drawn from McCartney *et.al* (2004).

Total Annual Precipitation (mm)

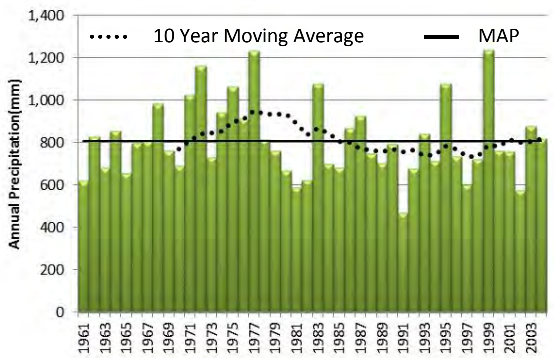
Departure from Mean Annual Precipitation (mm)

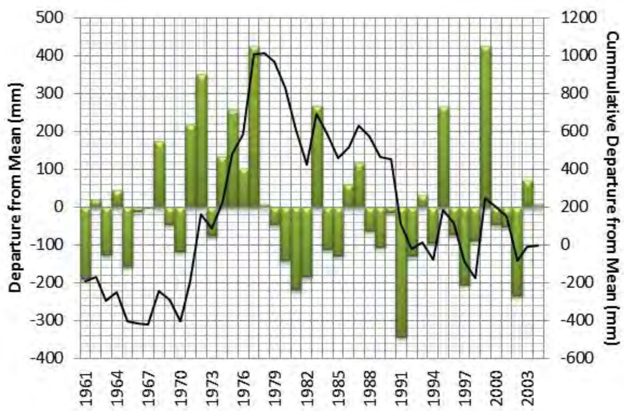




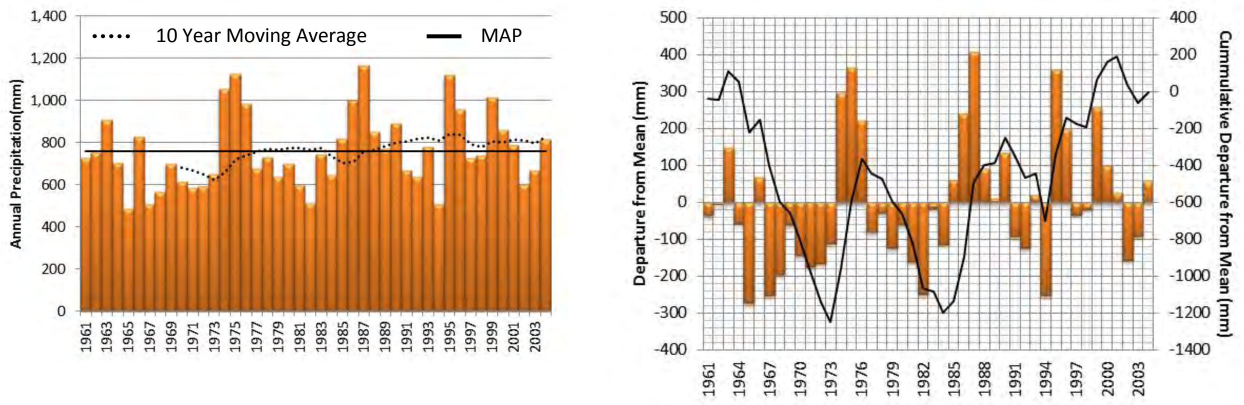
Gauge ID: 0404459W

Gauge ID: 0404459W





Total Annual Precipitation (mm) **Departure from Mean Annual Precipitation (mm)**



Gauge ID: 0298512W **Gauge ID: 0298512W**

Figure 3.9: Annual Total Precipitation and Departure from Mean for Gauge 0404459W
(Computed from WR2005 Rainfall Data)

3.6.1.2. Intra – Annual Variation of Precipitation

The intra annual variation of precipitation within the UVRB was determined using the median monthly values of precipitation computed at the chosen station. The result is presented in Figure 3.10. The basin mean of 662mm per annum was computed using station data as mentioned in Section 3.6.1.

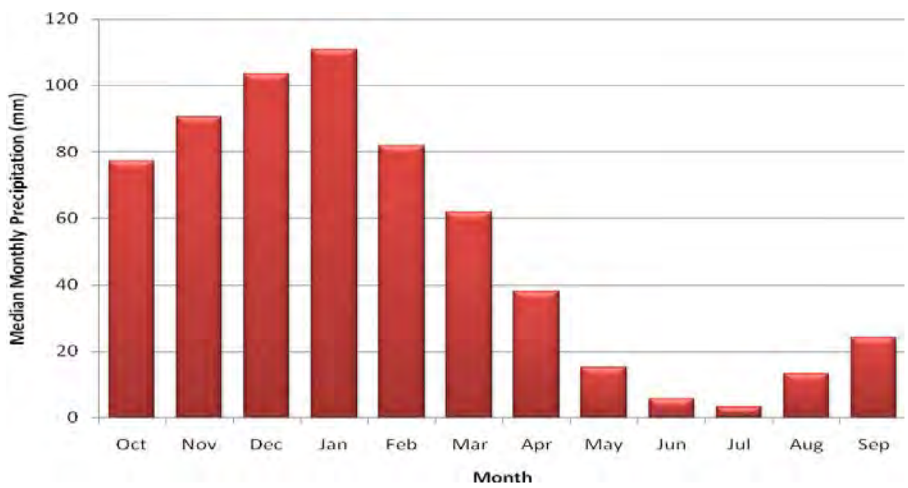


Figure 3.10: Median Monthly Precipitation (mm)
(Source: Computed from WR2005 Rainfall Data)

The monthly values show the seasonality of rainfall within the year. The wettest and driest months in the catchment are January and July respectively, with the wet season spanning October to April (summer) and the dry season being May to September (winter).

3.6.1.3. Correlation with Elevation

The MAP of 48 stations in the UVRB was computed and correlated with their respective elevations. It was found that the Station MAP was positively correlated with elevation as indicated by the scatter plot in Figure 3.11. A linear trend line gives the best R^2 coefficient of 0.635.

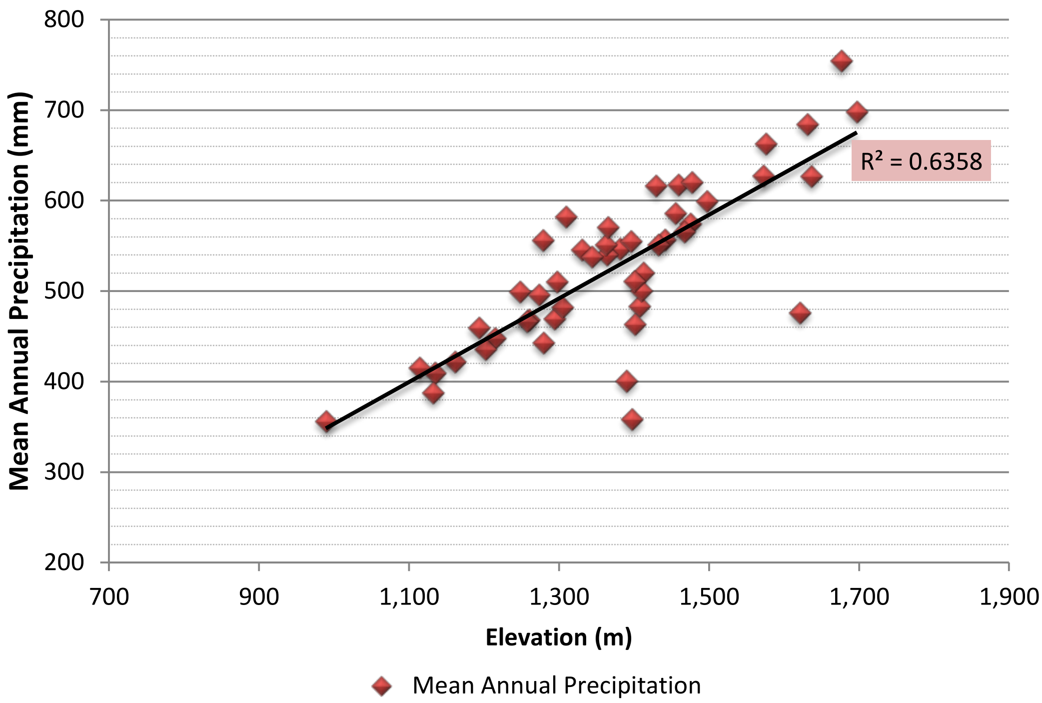


Figure 3.11: Correlation of Station Mean Annual Precipitation with Elevation
(Source: Computed from WR2005 Rainfall Data)

3.6.2. Temperature

The mean annual temperature in the UVRB is in the range of 14 – 18.5°C. Maximum and minimum temperatures are usually experienced in January and July respectively. For a synthesis of temperature for the basin, 13 gauges spread over the entire Vaal Basin were used. The Mean Annual Temperatures (MAT) were calculated for each gauge and extrapolated over the basin to obtain an idea of the spatial variation of temperature across the region. Figure 3.12 shows the MAT for UVRB and its spatial variance. The temperatures are lower in the eastern region and get higher towards the west.

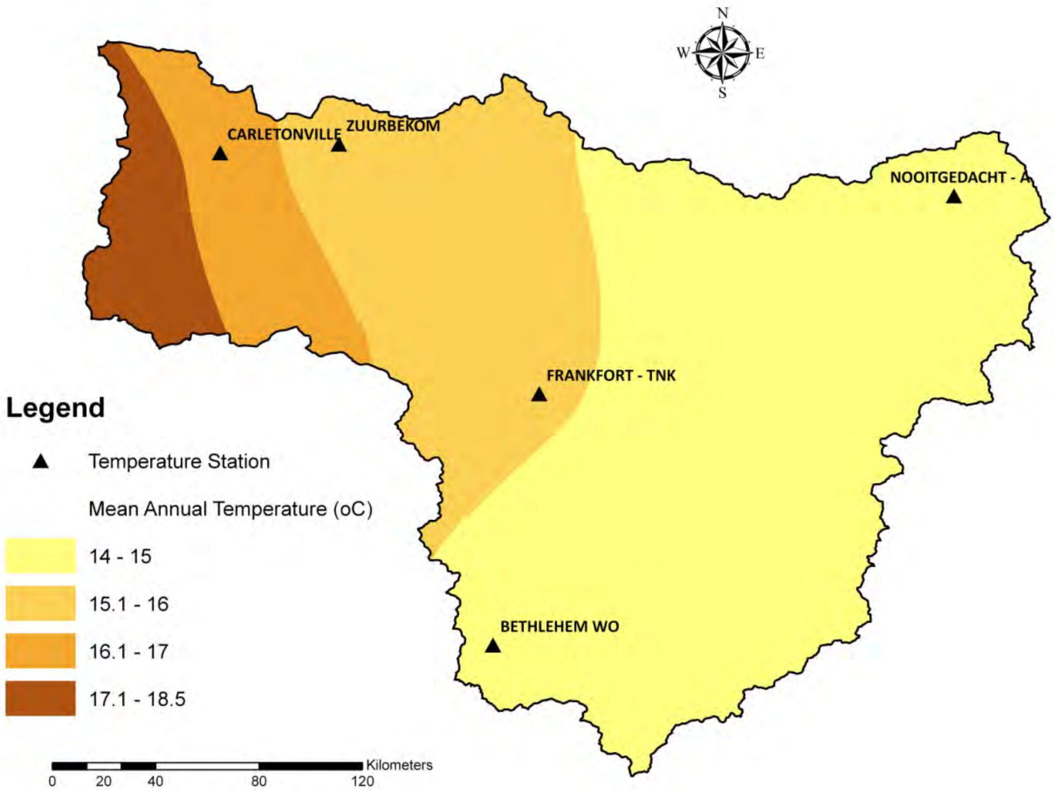


Figure 3.12: Mean Annual Temperature in the UVRB
(Source: Computed from SAWS Temperature Data)

The mean annual maximum temperatures for the basin range from 22.1 to 24.6^{o}C whereas mean annual minimum temperatures range from 6.3 – 9.8^{o}C. The station located centrally in the UVRB (Frankfort - TNK) was used to compute monthly statistics for temperature over a period of 40 years. Figure 3.13 shows the monthly maximum, minimum and mean for Frankfort TNK Station for the same period above.

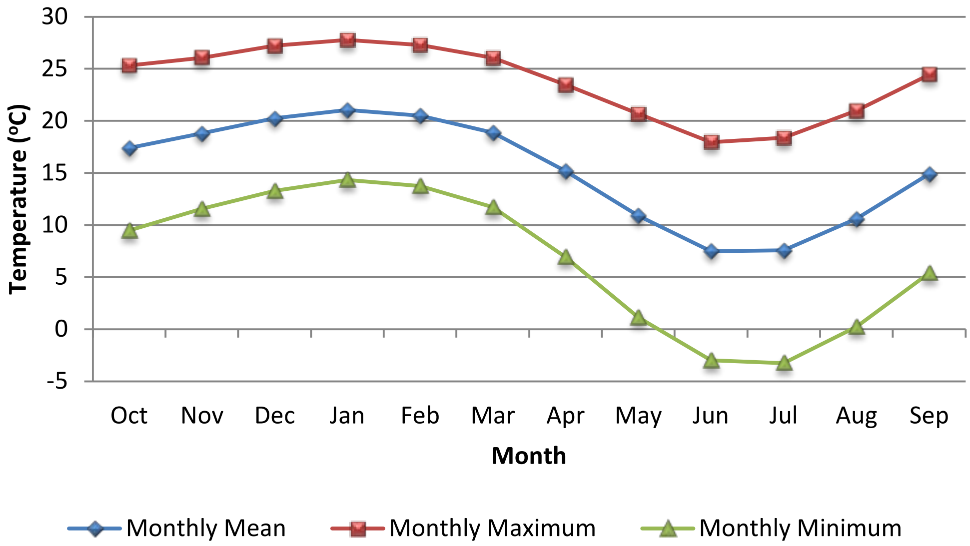


Figure 3.13: Monthly Statistics of Temperature for Frankfort Station
(Source: Computed from SAWS Gauge Data)

3.6.3. Evaporation

Mean Annual Evaporation (MAE) increases from less than 1,400 mm in the eastern basin to more than 2,000 mm in the west as measured using the Symon's Pan (S-Pan). The highest (142 mm to 248 mm) and lowest (54 mm to 89 mm) evaporation occurs in January and June respectively for the basin (DWAF, 2004a, 2004b). December is the month with highest evaporation (248 mm to 318mm) (DWAF, 2004c). It should be noted that the evaporation range values were converted from A-Pan (as quoted in the references) to S-Pan for consistency. Figure 3.14 shows the MAE for the UVRB.

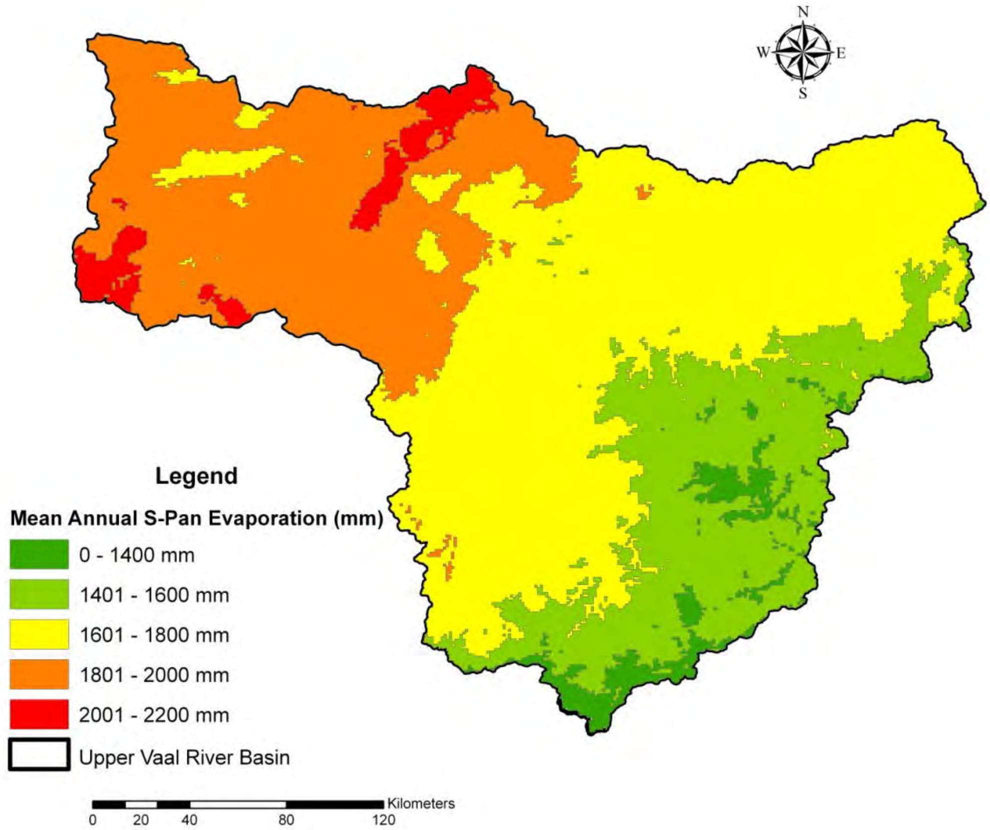


Figure 3.14: Mean Annual Evaporation (S-Pan)
(Source: WR2005)

3.6.4. Stream Flow

The river gauging station C2H018 located at the outlet of the UVRB was analysed for stream flow. The monthly hydrograph and variation of Mean Annual Flow from Mean Flow for the period between year 1960 to 2000 is given in Figure 3.15 and Figure 3.16 respectively.

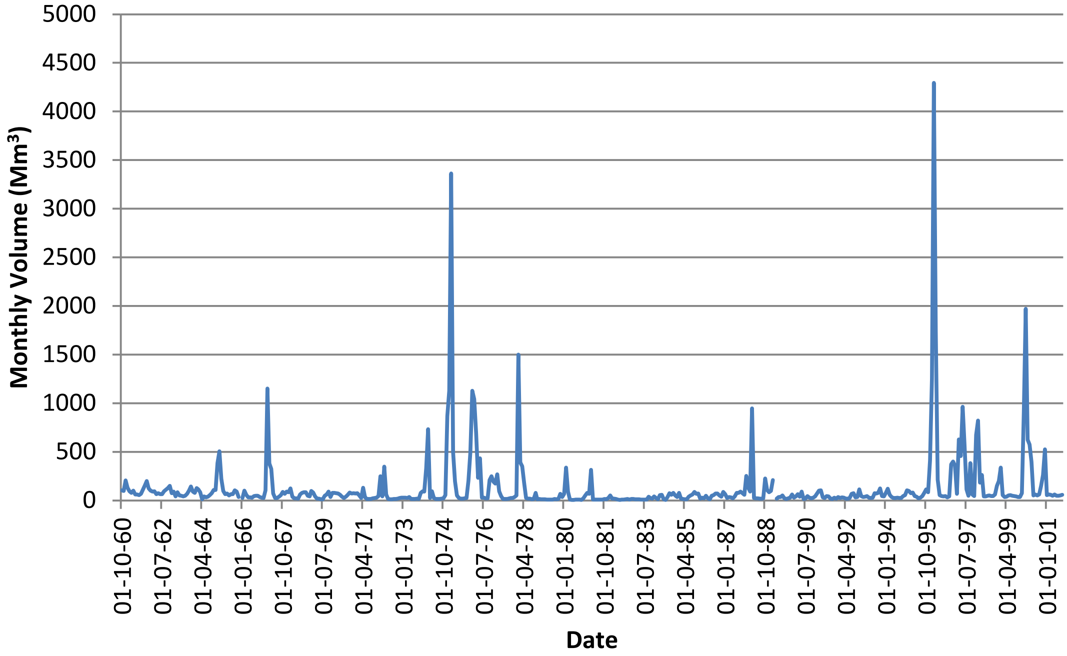


Figure 3.15: Monthly Stream Flow Hydrograph at C2H018
(Source: Computed from Data from DWA)

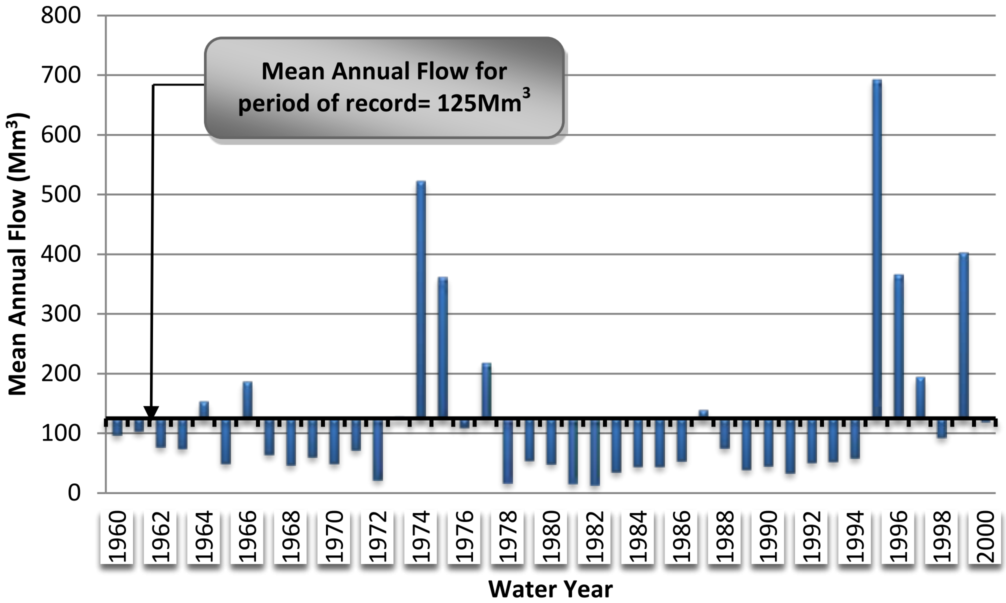


Figure 3.16: Variation of Mean Annual Flow Volume around Mean Flow Volume at C2H018
(Source: Computed from Data from DWA)

The periods between 1974 - 1975 and 1995 - 1996 represent wet years. The latter is representative of the El Nino phenomenon. However, the last 40 years have generally had stream flows below the mean annual volume. In addition to the heavy abstractions from the river, this may also be attributed to the highly regulated waters of the Vaal River due to the two main dams on it that is Vaal and Grootdraai dams.

3.7. Demography

The UVRB generally exhibits a clustered population residing near a water supply source, with the highest densities near Johannesburg and downstream of Vaal Dam. The basin is the most populous region in South Africa with a population estimated at 5.65 million in the year 1995, 97% of which is urbanised (DWAF, 2004a). Figure 3.17 shows the distribution of population density within the UVRB.

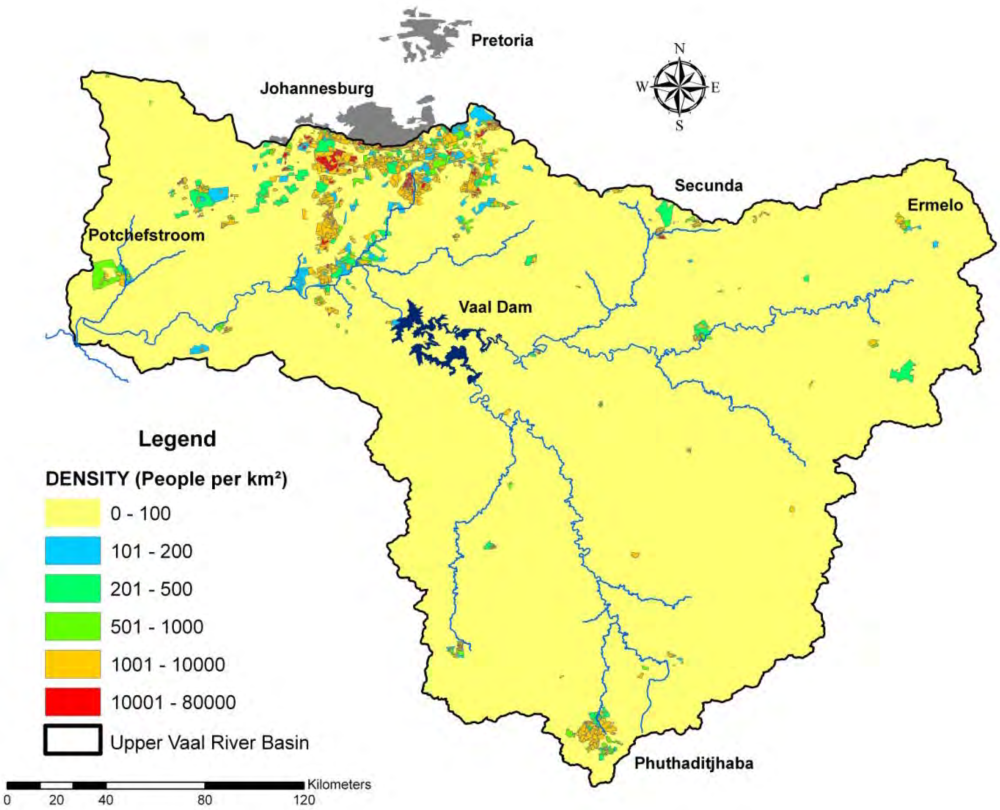


Figure 3.17: Population Densities in the Catchment
(Source: WR2005)

3.8. Water Resource Development

The Vaal River is the principal source of water supply to the Gauteng Province which is the industrial hub of South Africa. This has warranted an extensive water infrastructure to be put in place and a complex management of its water resources. According to the National Water Resource Strategy (DWAF, 2004d), approximately 2,057 million cubic meters of water was required per annum in year 2000 to meet local demand against a local reliable yield of 1,306 million m^3 a^{-1} in the Vaal Region. The deficit therefore is satisfied via numerous inter-basin water transfers in and out of the catchment. The net basin transfer for catchment use cumulates to 807 million m^3 a^{-1}. Therefore, the net balance of water resource available for the future is only 56 million m^3 a^{-1}.

3.8.1. Dams

According to the Dams Database of South Africa, there are a total of 11 dams in the UVRB catchment. The dams have been categorised as 'major' (> 2 million m^3 capacity) or 'minor' (<2 million m^3 capacity). All dams in the UVRB are classified as major.

The dams have been built to serve different purposes like irrigation, domestic water supply and recreation. Since cultivation is the largest land use practise in the catchment (Figure 3.7), 4 dams are used for irrigation water supply and 6 dams are used for domestic water supply. The Driekloof dam is the only dam used for hydro-electricity.

Figure 3.18 gives the individual storage capacities of the major dams together with the time progressive accumulation of storage capacity of the catchment of major dams. The capacities of the minor dams have been summed and added to the cumulative capacity of major dams to obtain the catchment total storage capacity.

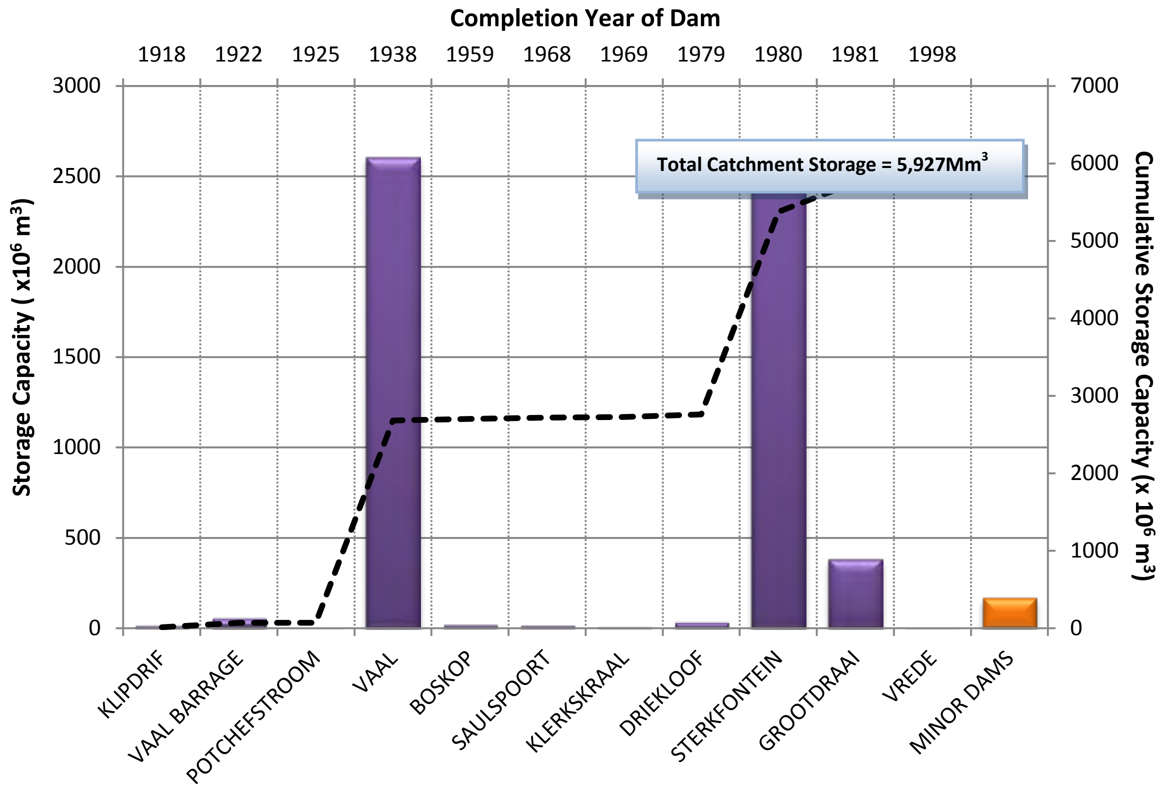


Figure 3.18: Major and Minor Dams in the UVRB
(Source: DWA Dams Database)

3.8.2. Ground water

Groundwater is reasonably utilised and impacted on within the catchment. Exploitable aquifers in the upper and middle catchment are found in four major geological supergroups namely the Karoo, Transvaal, Ventersdorp and the Witwatersrand. The most important aquifer is the Malmani dolomite which is also the most heavily utilised groundwater resource in South Africa (DWAF, 2004a). The main users of groundwater in the UVRB are the agricultural and domestic sectors, the former using it for irrigation and stock watering. Rand Water used this water resource (Zuurbekom Dolomitic Compartment) for domestic supply to urban areas of the Witwatersrand. It was after the potential of this compartment diminished that the Vaal River was chosen as the new source. However, approximately 12Ml/day continues to be abstracted from the compartment by Rand Water.

There are a total of 13,963 boreholes drilled within the Vaal catchment according to borehole data obtained from the DWA on August 2008. The data has been categorised *inter alia*, into:

a) status of borehole (in use, abandoned, destroyed, inaccessible and stand by),
b) purpose of the borehole (drainage, exploration, mine drainage, observation, production, recharge, stand by and waste disposal) and
c) potability of the pumped water (for animals only, very good, brackish, fresh, salty, good, marginal and unfit for human consumption)

The following conclusions have been derived from the borehole data:

1) Out of the total drilled boreholes, only 17% have data pertaining to their status. Out of this, only 69% are in use.
2) In the case of the purpose of borehole, 92% of the boreholes had missing data. Out of the remaining proportion, 46% of the boreholes were drilled for water supply production.
3) Regarding the potability of the pumped water, 82% of the boreholes had missing data. Out of the remaining proportion, 34% of the boreholes produced fresh water, 63% pumped out water fit for human consumption and only 0.3% produced 'very good' water. 3 boreholes produced water unfit for human or animal consumption.

3.8.3. Inter-basin transfers

The Upper Vaal WMA plays a polar role in the transfer of water from and to its adjacent WMAs. Due to the extensive urbanisation and industrialisation, its water resources are highly developed and utilised. DWAF (2004d) states that the total yield transferred into the WMA is more than 20% more than its total yield from local surface water resources, whilst a similar amount of water is again transferred out of the catchment.

The Middle and Lower Vaal WMAs depend on releases from the Upper Vaal WMA for their bulk water requirements (DWAF, 2004d).

Figure 3.19 gives a representation of the inter-basin transfers in place within the Vaal Catchment followed by Table 3.1 which shows the individual characteristics of the transfers.

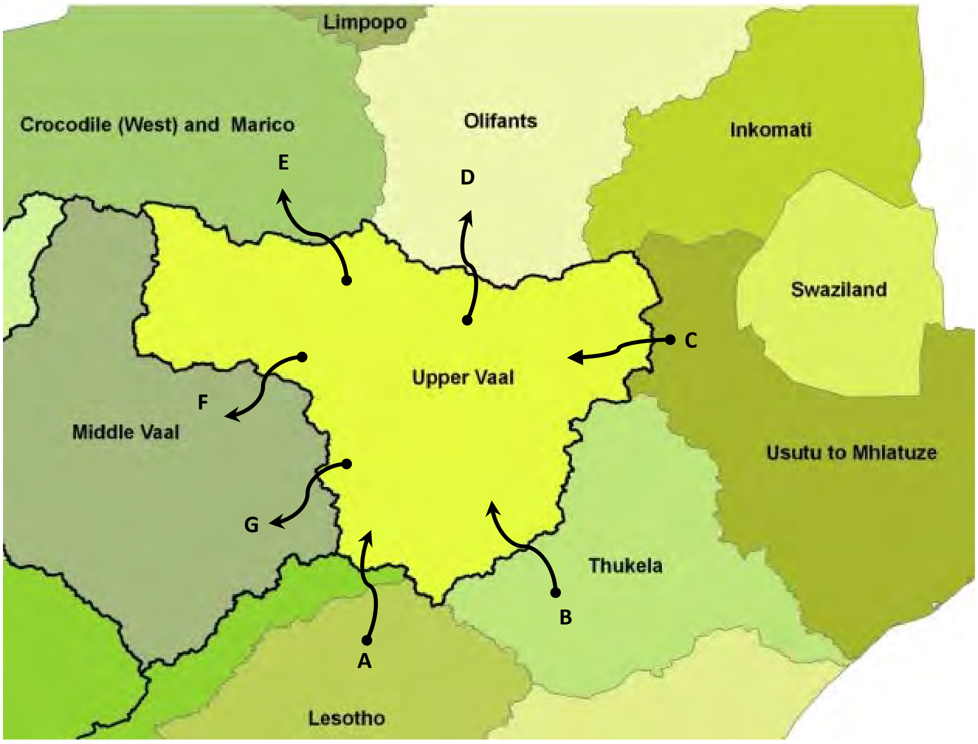


Figure 3.19: Inter-Basin Transfers between the Vaal Catchment and surrounding WMAs
Source: DWAF (2004d)

Table 3.1: Description of the various Inter-Basin Transfers

Transfer	Source	Destination	Existing Transfer (million $m^3\ a^{-1}$)	Future Augmentation Potential (million $m^3\ a^{-1}$)	Comment
A	Lesotho	Upper Vaal	491	835	After commissioning of Mohale Dam
B	Thukela	Upper Vaal	685[a]	475	Includes transfer from Buffalo River
C	Usutu to Mhlatuze	Upper Vaal	63	-	-
D	Upper Vaal	Olifants	36	38	-
E	Upper Vaal	Crocodile(West) & Marico	514	209	Rand Water Distribution
F	Upper Vaal	Middle & Lower Vaal	828	82	-
G	Upper Vaal	Middle Vaal	1	-	Domestic Supply to Heilbron

[a] – The actual transfer volume of 630 million $m^3\ a^{-1}$ excluding the volume from Buffalo River is equivalent to a yield benefit of 736 million $m^3\ a^{-1}$ in the receiving WMA.

CHAPTER FOUR

MODELLING THE UPPER VAAL BASIN NATURALISED HYDROLOGY

"What we observe is not nature itself, but nature exposed to our methods of questioning."
Walter Heisenberg

4.1. Introduction

This Chapter gives an overview of the WEAP hydrologic module, an outline of the different parameters required for successful simulation of the basin hydrology, the methods employed in parameter data preparation and the calibration procedure adopted. The results of the calibration are also presented.

4.2. The WEAP Hydrology module

The WEAP model offers a choice of three methods to simulate basin hydrological processes such as evapotranspiration, runoff, infiltration and irrigation demands (SEI, 2007). These are:

1) *Irrigation Demands Only method*

   This is the simplest method of the three which uses crop coefficients to calculate the potential evapotranspiration in the basin. The portion of evapotranspiration which cannot be met by precipitation is thereafter calculated, which will be therefore be supplied by irrigation. This method however does not simulate runoff or infiltration processes.

2) *Rainfall – Runoff method*

   This method also determines the evapotranspiration for irrigated and rainfed crops using crop coefficients. The portion of rainfall not used for evapotranspiration is then converted to runoff to a river and/ or groundwater.

3) *Soil moisture method*

This method is a one dimensional, two compartment soil moisture accounting scheme based on empirical functions describing evapotranspiration, surface and sub-surface runoff and deep percolation within the basin. Two options for routing the deep percolation are available, namely, as baseflow to a surface water body or directly to groundwater storage if a groundwater link is made. Furthermore, this method allows for a more robust simulation of land use changes as compared to the other two methods. This gives an advantage of a holistic approach to modelling a river basin and is the best attempt given the other options to simulate the hydrological processes as accurately as possible. Additional characteristics of change in a basin can also be incorporated in the model like land use and groundwater recharge.

As a consequence to the comprehensive analysis offered, this method requires an extensive soil and climate parameterisation for successful analysis.

Reference is made to the User Manual (SEI, 2007) for information on the mathematical background of the different hydrologic methods.

4.3. Basin Model Setup

WEAP is able to function as a distributed model at varying spatial scales depending on the modeller. For this Study, the model was setup at the Quaternary Catchment (QC) scale as defined in the WR2005 Study. Every QC in the model represents a catchment with its individual set of parameters. This translates to a total of 91 catchments subdividing the Upper Vaal River Basin (UVRB).

Some form of lumping is inevitable in modelling. Despite the finer scale of subdivision in the model, in real sense every QC still maintains its heterogeneous characteristics. However, it can be assumed that the heterogeneity within each QC is overshadowed by the larger spatial scale of the modelling exercise. Therefore, for this study, every QC has been assumed to be homogenous. The centroidal coordinates of the QC's have been taken as the representative points for the different land and climatic parameters which have been derived and input in the model.

Out of the three methods outlined in Section 4.2, the Soil – Moisture method was adopted because it captures the hydrological processes in greater detail than the other options and also because of availability of data for its successful setup.

The calibration of the model has been carried out for a period of 6 hydrological years (cf. Chapter 3 Section 3.6) starting from October 1999 to September 2005 using a monthly time step under 'pristine' land cover conditions. Pristine condition in this context means there has not been any anthropogenic influence in the Basin like change in land cover due to urbanisation and agriculture and no water infrastructure like dams have been built as yet. In other words, the Basin is still in its natural state before any change due to human activities began. The model simulation was assessed using naturalised flows for each QC obtained from the WR2005 Study.

Figure 4.1 gives a screenshot of the main WEAP Graphical User Interface (GUI) showing the UVRB with the Vaal River schematically represented together with catchment nodes symbolising every QC.

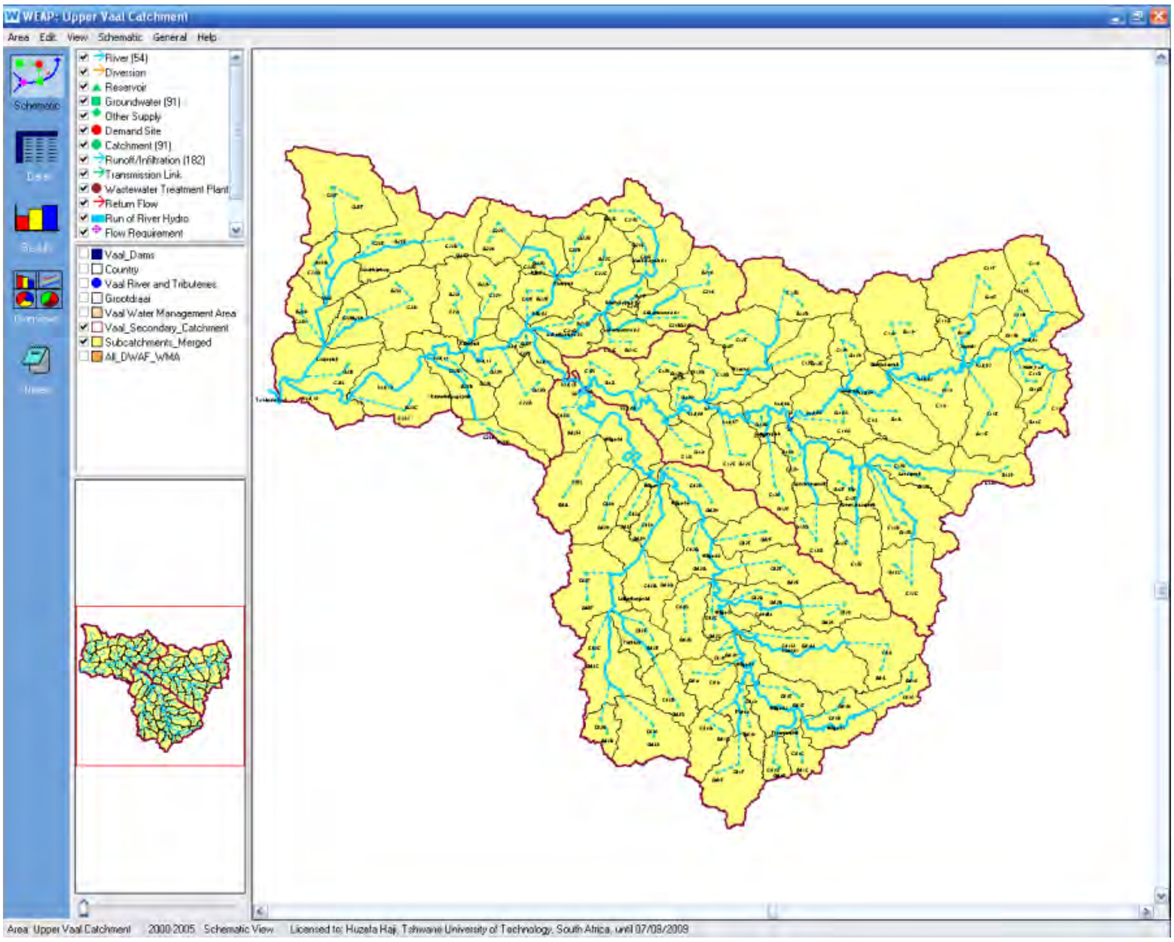


Figure 4.1: The WEAP Graphical User Interface

4.4. Derivation of Initial Parameter Values

The different parameters required by WEAP have been derived from various sources using different methods of analysis. However, GIS techniques have repeatedly been used as they offer a wide range of data analysis options with faster outputs. Furthermore, most of the data obtained has been in the shapefile (.shp) format which is easily utilised across a range of GIS softwares.

The setting up of Soil – Moisture method involves populating parameters for two main variables namely Climate and Land use. These two variables are further divided into respective sub variables, derivation of which is outlined in Sections 4.4.1 and 4.4.2.

4.4.1. Climate Parameters

This variable is further divided into 9 sub variables. These are:

4.4.1.1. <u>Precipitation</u>

Precipitation (P) is one of the most critical inputs in the model. For this reason, calibration was carried out using the WR2005 rainfall data which has been derived for the whole country at the QC scale. under the WR2005 Study, rainfall Zones have been determined which correspond to groups of QCs which share similar rainfall characteristics. The mean annual precipitation (MAP) was calculated for every Zone based on analysed and patched rainfall recordings of various rainfall stations with record lengths longer than 15 years. Approximately 161 rainfall stations located within the UVRB were used for the WR2005 study. Monthly P values from year 1920 to year 2005 for each QC have been expressed as a percentage of the respective MAPs for the Zone the QC falls in. Therefore, for the present Study the time series of P was constructed by multiplying the percentage of MAP for every QC for each month with the MAP of the zone the QC is part of.

This method was preferred to the conventional analysis of rainfall station recordings because the latter had missing values which would have required further analyses to patch the data. Furthermore, additional geostatistical analysis would have been necessary to determine the P values of every QC thus introducing errors in the final data whilst consuming more time. The WR2005 rainfall data has already been patched for missing values and spatial distribution using verified statistical techniques, thus simultaneously increasing its dependency and considerably reducing process time.

4.4.1.2. Temperature

Mean monthly temperature data in centigrade degrees was obtained from the South African Weather Service (SAWS). It was discovered that only 5 stations measuring temperature were located within the UVRB. For a meaningful geostatistical interpolation, a larger number of stations were required (minimum of 10 for ArcGIS Geostatistical Analyst). Therefore, the whole Vaal Region (includes Upper, Middle and Lower regions) was considered for analysis, from which results for Upper Vaal were extracted. A total of 25 temperature measuring stations exist in the region with varying records. Out of these, only 9 stations have a complete record spanning the calibration period. Therefore, to optimise the use of available data, all stations with record in any month were used for analysis rather than using only the stations with a complete record. This ensured data from a minimum of 19 stations being utilised for analysis for any particular month. Figure 4.2 shows the gauges used for analysis and their respective locations.

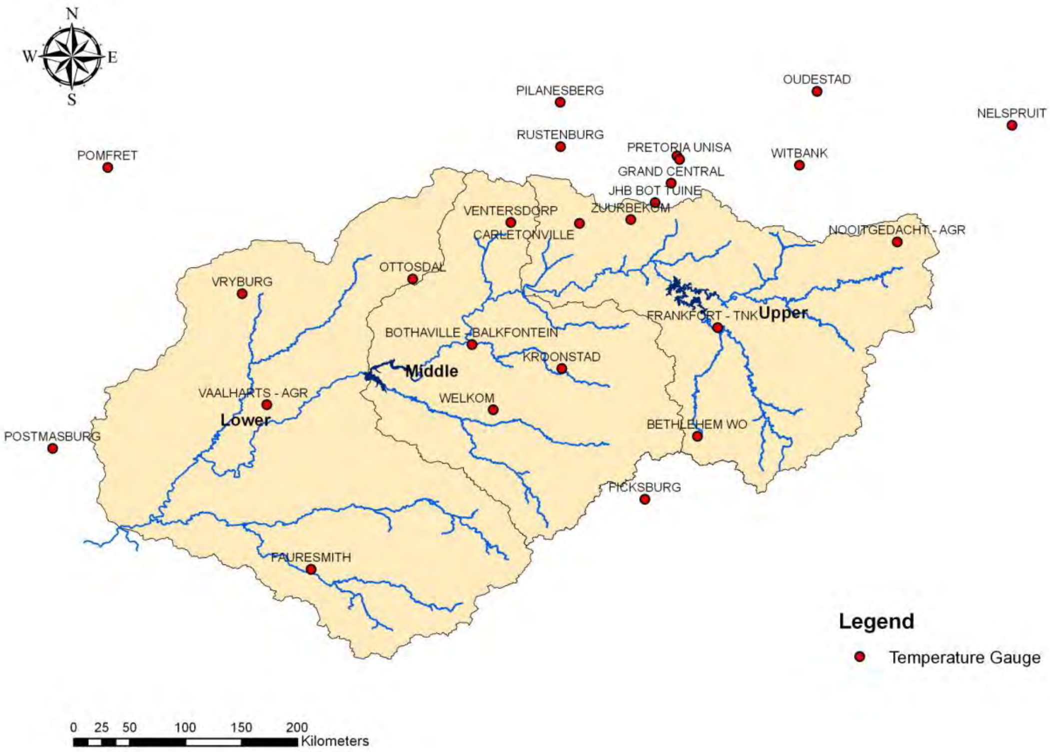


Figure 4.2: Temperature Gauges used for Analysis

Since the stations were fewer than the QC centroids and temperature values being required for each QC, a geostatistical analysis approach was adopted for interpolation at the centroids. The ArcGIS Geostatistical Analyst which contains a comprehensive set of tools for creating surfaces from measured sample points was used. Since temperature is correlated with elevation (Apaydin, Sonmez, and Yildirim, 2004), the station elevations were incorporated in the analysis using the Ordinary Co-kriging method. This method takes into account the spatial cross-correlation of two or more variables. Interpolation of the data was carried out for each month over the calibration period. For some months, the data had to be normalised before analysis using either the Log Transform or Box Cox methods built in the Geostatistical Analyst.

Trend surfaces are processes operating on a regional scale and can be described using one mathematical model (Rossiter, 2009). Some monthly data exhibited 1st or 2nd order trends which had to be removed prior to analysis. This is reasonable in view of the relationship of temperature with elevation. The elevation data had to be de-trended as well, constantly using the 2nd order polynomial which is expected of an undulating land topology.

Johnston *et al.*(2001) define the efficiency of a geostatistical analysis based on the different statistical parameters of the interpolation. These are the Standardised Mean Prediction Error, Average Standardised Error, Root Mean Square (RMS) Prediction Error and Standardised RMS Prediction Error. For the best interpolation, the following criteria should be met:

- Standardised Mean $\cong$ zero
- Smallest RMS Prediction Error
- The Average Standardised Error nearest to RMS Prediction Error
- Standardised RMS Prediction Error $\cong$ one

Table 4.1 gives the results of the geostatistical interpolation for the calibration period.

Table 4.1: Summary Statistics of the Interpolation Results for Temperature (HY1999 – HY2004)

Parameter	Minimum	Median	Maximum	Mean
Standardised Mean	-0.13	-0.06	0.06	-0.05
RMS Prediction Error	0.94	1.53	2.12[a]	1.49
Average Standard Error	0.85	1.44	1.95	1.44
Standardised RMS Prediction Error	0.85	1.01	1.3	1.04

[a] Only 2 instances out of a total of 72

From Table 4.1, it can be seen that the results are within acceptable range of the aforementioned criteria because 1) the mean of the interpolation is close to zero, 2) the Average Standard Error is within 3% of the RMS Prediction Error and 3) the Standard RMS Prediction Error is 4% greater than the preferred value of one. However, the mean RMS Prediction Error is modest at $\pm 1.49^{o}$C. Nonetheless, this result compares well with a study carried out by Apaydin *et al.*(2004) using the same interpolation technique on *inter alia* long term average (28 years) temperature using 27 stations which had an RMS error of $\pm 1.99^{o}$C.

After creating the interpolated surfaces for every month, the temperature values were extracted at the centroids using basic ArcGIS procedures.

4.4.1.3. *Relative Humidity*

Mean monthly relative humidity data in percentage units was obtained from the SAWS. Similar to the predicament with temperature, there was only one gauge within the UVRB measuring humidity. Therefore, nearby gauges had to be used to interpolate a surface across the study area. According to data from SAWS, only 12 gauges recorded this parameter within and around the Vaal region. Furthermore, none of the gauges had a complete record spanning the calibration period. For the months from September HY2000 to October HY2001, only 9 gauges had records. This created a problem because the Geostatistical Analyst requires a minimum of 10 gauges to run an analysis. Therefore, data for one station named ‘Witbank’ (elevation of 1,555 m above mean sea level) was patched using data from the nearest stations which shared similar elevations. The mean of one year data from stations named ‘Jhb Bot Tuine’ and ‘Pretoria Endracht’ located at 1,624 m and 1,310 m above mean sea level, was used to develop a regression equation which in turn was used to calculate the humidity values for Witbank for the missing months. For validation purpose, the regression equation was tested by calculating already observed values for the periods December HY1999 to July HY2000 and December HY2004 to December HY2005. These periods are the only ones having observed data. The correlation coefficient, R^2, of the observed and calculated values were 0.7 and 0.93 respectively which means the calculated missing values can be taken in high confidence.

Thereafter, the same methodology of surface generation used in temperature analysis was applied. This ensured a minimum of 10 stations being used in analysis of any particular month. Figure 4.3 shows the gauges used for geostatistical interpolation of relative humidity.

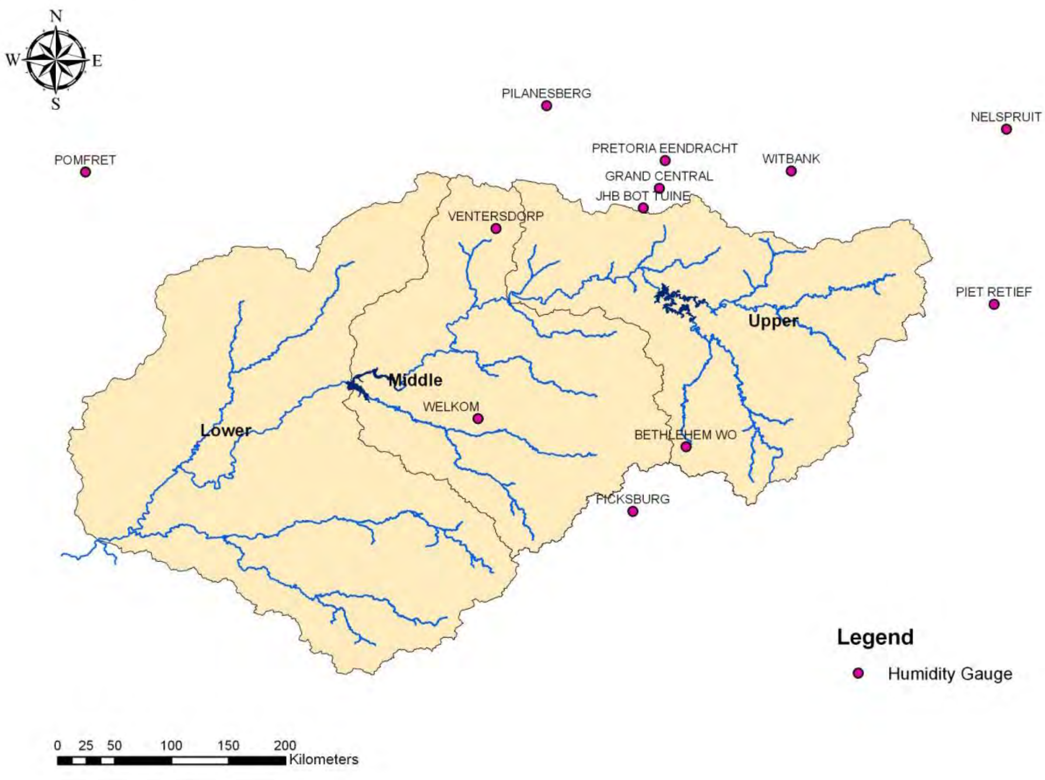


Figure 4.3 : Humidity Gauges used for Analysis

Apaydin et al.(2004) did not find a correlation between relative humidity and elevation in their study. Similarly no correlation existed in the UVRB. Using simple scatter plots of relative humidity-elevation for each month, low correlation coefficient (R^2) ranging from 0 to 0.5 only were obtained. Therefore, because of only one variable (RH) being predicted, the Ordinary Kriging technique was used instead of Ordinary Co-kriging to create the prediction surface. Table 4.2 outlines the results of the geostatistical interpolation for the calibration period.

Table 4.2: Summary Statistics of the Interpolation Results for Humidity (HY1999 – HY2004)

Parameter	Minimum	Median	Maximum	Mean
Standardised Mean	-0.16	-0.01	0.24	-0.01
RMS Prediction Error	4.22	9.4	16.1[a]	9.41
Average Standard Error	3.57	8.5	13.0	8.62
Standardised RMS Prediction Error	0.80	1.05	1.66	1.08

[a] Only 1 instance out of a total of 72

The results presented in Table 4.2 satisfy the criteria outlined in Section 4.4.1.2. However, the RMS prediction error is quite large at ±9.41%. This can be attributed to the small number of stations used for analysis. Apaydin *et al.*(2004) had an RMS prediction error of ±5.73% for the long term average (28 years) of relative humidity using 27 stations.

After creating the interpolated surfaces for each month, the humidity values were extracted at the centroids using basic ArcGIS procedures.

4.4.1.4. Wind Speed

Monthly wind speed data was obtained from SAWS in units of meters per second (m/s). As the case with temperature and relative humidity, only 11 wind speed measuring gauges were located around Vaal region with none in the UVRB. All the stations had an incomplete record over the calibration period and most of them were spatially biased towards the north. An initial attempt on using the Kriging technique yielded RMS prediction errors in the range of 100 to 200% of the observed value. This negated the use of geostatistical methods to analyse the data. Therefore, it was decided to adopt the Thiessen Polygon method instead. Figure 4.4 shows the locations of the wind speed measuring gauges in the region.

The same methodology of surface generation used in calculation of the previous parameters was applied thus ensuring at least 10 station records being used in any particular analysis. Thiessen polygons were derived for each month and the centroids falling in each polygon grouped and assigned the polygon value of wind speed.

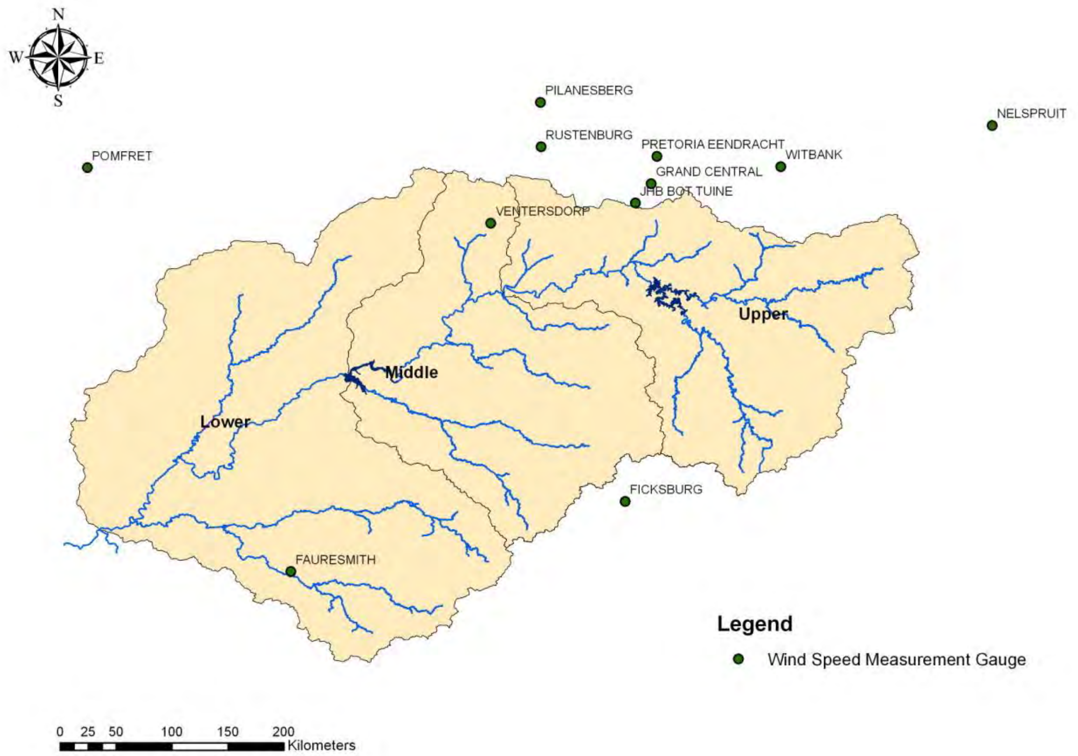


Figure 4.4 : Wind Speed Gauges used for Analysis

Unfortunately, the Thiessen method does not give any statistical result on the prediction efficiency, hence the result is assumed to be the best possible considering the quantity of data available.

4.4.1.5. Latitude

The centroidal latitude in decimal degrees was taken as the representative for each QC.

4.4.1.6. *Cloudiness Fraction, Initial Snow and Melting and Freezing Points*

Cloudiness Fraction is the fraction of daytime hours with no clouds. This parameter is required when modelling water temperature which was not part of this Study. Therefore the default value of 1, which means ‘no clouds’ was allowed.

Initial snow is the initial value of snow accumulation at the beginning of the first month of simulation. Since there is no occurrence of snow in the UVRB, the default value of zero was accepted. The former value represents the temperatures when snow would start melting and the latter value is the temperature at which water starts solidifying.

Melting and Freezing Points are the liquid water threshold for snow melt and solid water threshold for snow accumulation respectively. The default values of +5^{o}C for the former and -5^{o}C for the latter were adopted.

4.4.2. Land Use Parameters

This variable is further divided into 5 sub variables. These are:

4.4.2.1. *Catchment Area*

Catchment Area is an important parameter in any hydrological model. The areas were taken from the WR2005 Study database for each QC. The QC areas ranged from 195 km^2 to 1,324 km^2. The mean area of all the 91 QCs is 610.4 km^2.

4.4.2.2. Crop Coefficient (K_c)

The crop coefficient (K_c) is basically the ratio of the crop evapotranspiration under standard conditions (ET_c) to the reference evapotranspiration (ET_o) (FAO, 1998). Standard conditions refer to crops grown in large fields under excellent agronomic and soil water conditions. ET_o represents the evaporation potential offered by the atmosphere. There is a distinct difference between ET_c and ET_o as a result of four main physical characteristics namely crop height, albedo, canopy resistance and evaporation from soil. This difference is encapsulated in the K_c factor for the various crops.

The Acocks veld types (Acocks, 1988) have been used to describe the pristine conditions in the UVRB. This dataset was chosen because it is the most accurate status of vegetation available before major human influence began to take effect. Furthermore, it was used in the WR90 Study as well as its updated version, the WR2005 Study for the same purpose. The data in GIS format of the spatial distribution of the vegetation over whole of South Africa was downloaded from http://www.plantzafrica.com/vegetation/vegimages/acocksshape.zip and projected to the South African projection standard (Alber's Equal Area Conic). Thereafter, the areal coverage of vegetation within the UVRB was extracted for further use.

The QC boundaries were also available in GIS format and therefore superimposed on the vegetation map. Using the 'intersect' tool in ArcGIS, the areal coverage of different vegetation types falling within each QC was calculated and exported to a simple spreadsheet for analysis. Figure 4.5 shows the different vegetation types and their spatial coverage in the UVRB.

The monthly Crop Coefficients (K_c) for the Acocks veld types were obtained from the University of Kwa-Zulu Natal's website (http://www.beeh.unp.ac.za/acru/tips_and_tricks/Acocks.htm). Since many of the QCs have more than one type of vegetation, and only one representative monthly value of K_c is required per QC, an area weighted average of the different veld types was calculated. A simple arithmetic mean would not be appropriate in this case because the result would not consider the spatial contribution of the area covered by each vegetation type. Therefore, if an area is covered largely by vegetation of low K_c, and also has a small area with higher K_c value, a simple average would mean that the area generally has a larger K_c value which would significantly alter the evapotranspiration values. Equation 4.1 was used to calculate the area-weighted mean of K_c. The inset in Figure 4.5 gives an example of a QC with areas of different vegetation types used for calculating the area weighted averages.

$$K_{c(avg)} = \frac{\sum_{i=1}^{n} A_i K_{ci}}{\sum A} \qquad (4.\ 1)$$

Where

$K_{c(avg)}$ = Area Weighted value of K_c for QC

A_i = Area covered by Vegetation Type I in the QC

K_{ci} = K_c of Vegetation Type i

A = Total area of the QC

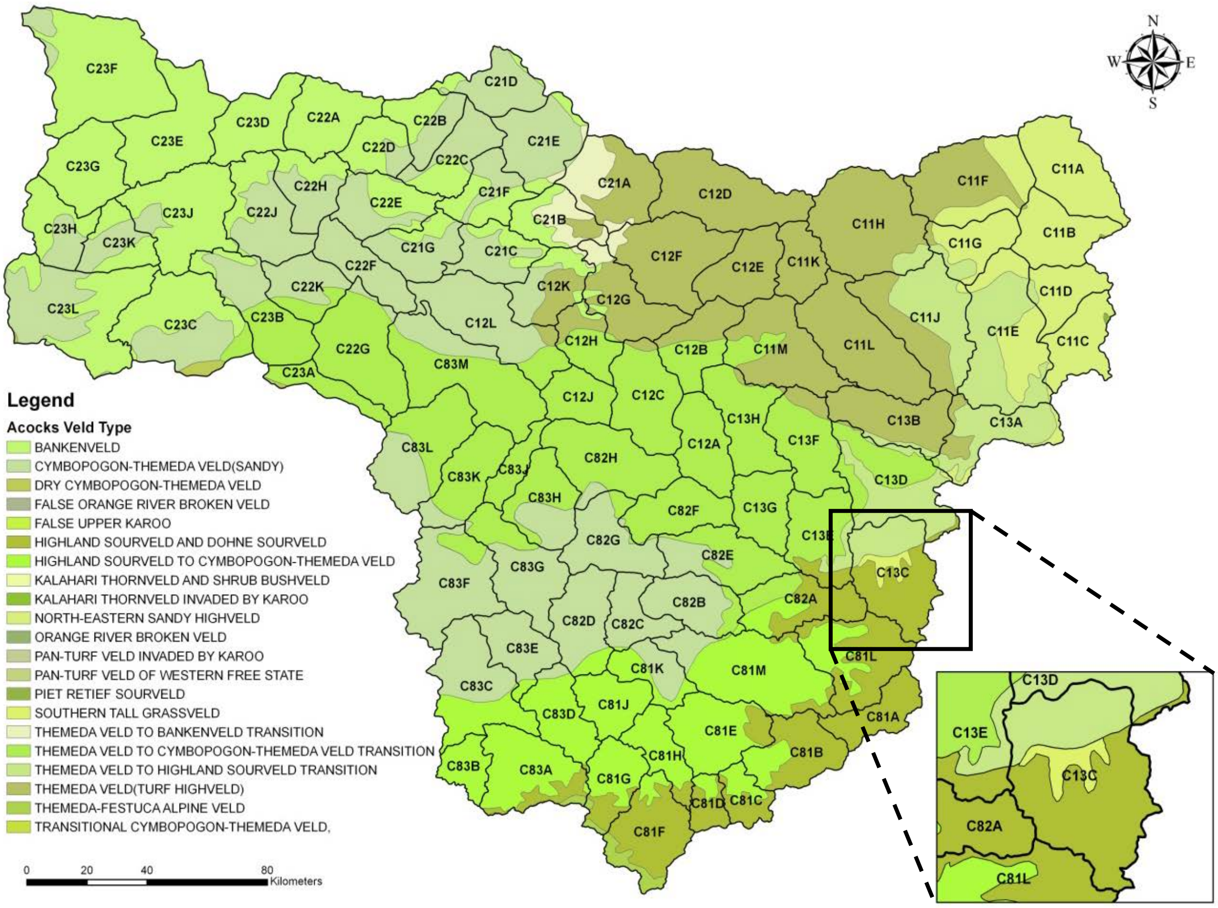


Figure 4.5 : Acocks Veld Types within Quaternary Catchments.

Inset: Coverage of Different Vegetation Types within same QC used for Area Weighting

4.4.2.3. Runoff Resistance Factor

The runoff resistance factor (RRF) is responsible for partitioning the precipitation into surface runoff and infiltration into the ground. This is a unit less parameter which ranges from 0.1 to 10. Initial estimates of this parameter could have been derived by calculating the runoff coefficient (RC) which is the ratio of flow to precipitation. However, simulations of future scenarios would not be possible as there would not be any flow data available hence the inability to derive this parameter. Therefore, a method which was dependent on an available parameter for its derivation was required to ensure the usage of the model for future scenarios. The curve number

(CN) method which is a function of precipitation and also land use was thereby adopted for runoff estimation. Thereafter, the RC was calculated and transformed into RRF for input in the model.
The CN method was originally developed by the Soil Conservation Service (SCS) which is now called the United States Department of Agriculture's Natural Resources Conservation Service (NRCS). It was initially developed for prevailing conditions in the United States of America (USA) but has been modified and applied under conditions found in other parts of the world. The CN is based on the region's hydrologic soil group, land use and antecedent runoff condition (Van Mullem *et al.*, S.a). It is generally applied to estimate the runoff depth from precipitation depth, given an index describing runoff response characteristics.

A monthly time step has been adopted for this study and bearing in mind that the CN method was originally developed for storm events which are in time steps of hours to days, an assumption was made that the same amount of initial abstraction would result if the rainfall was lumped over a month. The relationship of runoff with precipitation and initial abstraction is given in Equation 4.2.

$$Q=\frac{(P - I_a)^2}{P - I_a + S} \qquad (4.2)$$

Where
Q = Accumulated runoff depth (mm)
P = Accumulated rainfall depth (mm)
I_a = Initial abstraction (mm)
S = Potential maximum retention (mm)

I_a has been empirically determined to be 20% of S and thus replaced in Equation 4.2 to give Equation 4.3 which is valid only if rainfall depth exceeds 20% of runoff depth. If this is not the case, then there will be no runoff.

$$Q=\frac{(P - 0.2S)^2}{P+0.8S} \qquad \text{for } P > 0.2S \qquad (4.3)$$

The relationship of S and CN is given by Equation 4.4.

$$S = \frac{25400}{CN} - 254 \qquad (4.4)$$

The Acocks land cover was obtained in GIS format from DWA and was used as the basis for virgin conditions in the UVRB. The soil distribution in the UVRB was extracted from the soil map obtained from the WR2005 study. This data also had the SCS hydrological grouping of the different soils. Using basic GIS tools, the different veld categories and hydrological soil groups were extracted for each QC.

Since exact CN's corresponding to the different veld types were not available, approximations had to be made. Schulze, Schmidt and Smithers (1992) give an outline of CN for selected land cover and hydrological soil groups. The 'veld' category was assumed to have the same curve number**.** Table 4.3 gives the equivalent category used to derive the CN values for the Antecedent Moisture Condition (AMC) Class II for the three main hydrological soil groups in the UVRB.

Table 4.3: Equivalent CNs for Virgin Condition

Land Use Category		**Curve Number (AMC Class II) for Hydrological Soil Group**		
	Category Equivalent in Schulze *et.al* (1992)	**AB**	**BC**	**C**
All Acocks Veld Types	Veld/ pasture in good condition	51	68	73

Mean catchment slope (%) for each QC was extracted using GIS tools from the SRTM terrain model for the UVRB. The CN's presented in Table 4.3 were then adjusted for slope. Work carried out by Sprenger (1978) in East Africa on runoff determination using curve numbers developed adjusted CNs for a number of land uses, one of which was 'pasture or range in good hydrological condition'. This group was assumed to correspond to the 'veld/ pasture in good condition' in Schulze *et.al* (1992). Table 4.4 gives the curve numbers for the different hydrological soil groups and respective slopes (Sprenger, 1978).

Table 4.4: Curve Numbers for Different Slopes and Hydrological Soil Groups

			Hydrological Soil Group				
Land Use or Cover	**Slope**		**A**	**B**	**C**	**D**	**Adjustment Value**
Pasture or range in good hydrological condition'	I	< 1%	33	55	68	74	-6
	II	1-5%	39	61	74	80	Reference
	III	5-10%	42	64	77	83	3
	IV	10-20%	44	66	79	85	5
	V	> 20%	45	67	80	86	6

(after Sprenger, 1978)

A closer inspection will reveal that there is a constant difference between the CNs for different slopes across the hydrological soil groups. As an example, the difference between CN for group A slope II and group A slope III is 3. This difference is constant across all the soil groups for these two slope categories and between slope II and the other slopes. Therefore, these differences were assumed for this Study to represent the slope adjustment of the original CN's. The CN's given in Table 4.3 represent slope category II and thus was used as the reference category. Differences were computed between the other slope categories and the reference category and are given as adjustment values in the Table 4.4. Since an area-weighted approach was taken to calculate the CN for QC's with more than one soil group, the adjustment values were simply added to the weighted CN's to come to the final CN values to be used for runoff calculation.

Monthly time series of runoff depths were computed for each QC and the RC's calculated using the respective precipitation depths. The RRF in WEAP ranges from 0.1 to 10, with the latter representing zero run off. Therefore, RC's calculated using the CN method were transformed to RRF's as follows:

1) Convert the RC’s into percentages and divide by 10 since the RRF range in WEAP is the same as [1/10] – [100/10]
2) Since higher RRF’s represent lower runoff, unlike higher RC values which are indicative of higher run off, the RC’s are subtracted from 10 to invert their representation.

The above procedure outlines the method used to derive initial estimates of RRF. This data was then input in the model.

4.4.2.4. Preferred Flow Direction

The preferred flow direction (PFD) is responsible for partitioning the interflow in the ‘top bucket’ from deep percolation into groundwater. It is a unit less parameter which ranges from 0 – 1. Initial estimate of this parameter was derived from the interflow potential of each type of hydrological soil group given in Schulze (1995).

The taxonomy of South African soils is clearly explained in Schulze (1995). The soil distribution data obtained from WR2005 study is also classified based on this taxonomy. As a brief background, the soils are divided into soil forms which are further divided into soil series for ease of use by hydrologists. As previously outlined, the soil distribution was extracted at the QC level. Each QC either had a single series composition or a maximum of two different soil series of which the depth ranges and soil texture were available for each case. Soil texture can be defined as the composition of a soil in terms of its clay, silt and sand content.

The interflow potential of each soil form has been categorised into three types namely No Interflow, Moderate and High Interflow. However, a numerical value has not been assigned to these categories. Since the indication that a soil has high interflow potential does not necessarily mean that all moisture in the layer will be transmitted as interflow, it was assumed that a maximum of 50% of the infiltration can be converted to interflow. Therefore, as a starting point, a value of 0, 0.25 and 0.5 was assigned to the three categories respectively. These values lie within the WEAP range of the PFD parameter of 0 and 1, with the former and latter signifying only vertical and only horizontal flow respectively. In the case of two soil forms within a QC, the interflow potential value was assigned to each soil form and an average obtained.

4.4.2.5. <u>The Top 'Bucket'</u>

i) Root Zone Water Capacity

This is the effective water holding capacity (WHC) of the top layer of soil and is represented in mm. This parameter was calculated as the difference of the drained upper limit (DUL) and permanent wilting point (PWP) of the different soil textures composing each QC. Schulze (1995) defines DUL as the condition reached when water drains naturally from the soil layer and remaining water is retained by capillary forces great enough to resist gravity. He also defines PWP as the lower limit of the soil water available to plants that is, when the water cannot move to the plant roots.

The percentage of clay content and its vertical distribution within the soil profile significantly affects its water capacity. For that purpose, 5 clay distribution models have been developed for South Africa. Smithers and Schulze (1995) have provided a breakdown of the soil series and corresponding clay distribution models. They have further provided estimates of PWP and DUL for each clay model and soil series. Using a spreadsheet, the soil series for each QC were assigned their respective values of PWP and DUL corresponding to the clay distribution. For the case of a QC having more than one soil series, the WHC of each series was calculated and then averaged.

The unit of the WHC calculated from the aforementioned procedure is mm/m. Therefore, the soil depth (in metres) for respective QC's were then used to express the WHC in mm as required in WEAP.

ii) Root Zone Conductivity

Hydraulic conductivity is defined by Leap (2007) as "the volume of liquid flowing perpendicular to a unit area of porous medium per unit time under the influence of a hydraulic gradient of unity". It is expressed in units of mm/month in WEAP.

In many cases, the soil distribution within a QC was composed of 2 soil texture classes. For the case of hydraulic conductivity, an average of the 2 texture classes would distort the value. This is because the texture composition is higher with fine soil which has a low hydraulic conductivity (for example 1.2 - 4.3 $mmhr^{-1}$) as compared to a medium of coarse soil texture which has relatively large conductivity (26 - 61 $mmhr^{-1}$), therefore an average would result in a much larger conductivity signalling an overall medium/ coarse texture in contrast to the dominant fine texture. Therefore, in deriving the conductivities for the root zone layer, the dominating soil texture class was assumed to represent the distribution in the QC. For establishing confidence in this assumption, the compositions were checked and it was observed that in most cases, the dominant texture was greater than 70% of the total composition.

The respective hydraulic conductivities for the different dominant soil texture classes for each QC were extracted from Schulze (1995). Table 4.5 outlines the main soil texture classes found in the UVRB and their respective hydraulic conductivities.

Table 4.5: Soil Texture Classes found in the UVRB and Respective Hydraulic Conductivities

Soil Texture Class	Saturated Hydraulic Conductivity ($mmhr^{-1}$)
Loamy Sand	61
Sandy Loam	26
Sandy Clay Loam	4.3
Sandy Clay	1.2

iii) Initial Z_1

Initial Z_1 is the moisture content (%) of the top layer. This information was not available for the UVRB. Therefore based on the fact that the hydrological year begins in October following the dry season with higher evaporation, the soil moisture would be low. Therefore an initial estimate of 15% was adopted.

4.4.3. Groundwater Node Parameters

i) Hydraulic Conductivity

This is the conductivity of the aquifer having the same definition given in Section 4.4.2.5 (ii). The UVRB geology was also available in GIS format with the composition of different lithologies. These were extracted for each QC. For the reason explained in Section 4.4.2.5 (ii), the dominant lithology in every QC was taken as its representative. The unit is expressed in units of metres/ day in WEAP.

Conductivity values for different materials were taken from Schwartz and Zhang (2003) and Todd and Mays (2005). In some cases, none of the literature had values for certain materials for example 'arenite'. Therefore, its equivalent category in the aforementioned references was adopted based on the parent material characteristics. Therefore, since arenite is an igneous rock, its closest equivalent category was 'unfractured igneous' rock. The dominant geologies and their equivalent conductivity values are presented in Table 4.6.

Table 4.6: Hydraulic Conductivity Values for the Different Geological Materials in UVRB

Geology	Equivalent to	Hydraulic Conductivity (m/ day)
Andesite	Sandstone (Fine Grained)	0.2
Arenite	Unfractured Igneous	0.0001
Dolerite	Gabbro (Weathered)	0.2
Dolomite	-	0.001
Granite	Granite (Weathered)	1.4
Mudstone	Siltstone	0.0012
Sedimentary	Sand (Fine)	0.5184
Shale	-	0.00008

ii) Specific Yield

This parameter has been interchangeably used in WEAP with porosity. In fact, it has been defined as “the porosity of the aquifer represented as a fractional volume of the aquifer” (SEI, 2007). This parameter ranges from 0 to 1 in WEAP. Porosity values from Todd and Mays (2005) were adopted for the same geological groups outlined in Section 4.4.3 (i).

Table 4.7: Porosity Values for the Different Geological Materials in UVRB

Geology	Equivalent to	Porosity
Andesite	Sandstone (Fine Grained)	0.43
Arenite	Unfractured Igneous	0.37
Dolerite	Gabbro (Weathered)	0.43
Dolomite	-	0.26
Granite	Granite (Weathered)	0.45
Mudstone	Siltstone	0.33
Sedimentary	Sand (Fine)	0.33
Shale	-	0.06

iii) Reach Length, Horizontal Distance and Wetted Depth

The Reach Length (l_w) is the horizontal length of the interface between the reach and linked aquifer whereas the Horizontal Distance (h_d) is the length from the farthest edge of the aquifer to the river channel. The Wetted Depth (d_w) is the depth of the river channel in contact with the aquifer. All three parameters are expressed in units of metres.

Groundwater is represented as a wedge that is symmetrical about the river reach therefore the recharge and extraction from one side of the wedge will represent half the total rate. The total groundwater storage is estimated under the assumption that the water table is in equilibrium with the river level. Figure 4.6 shows the schematic of the WEAP groundwater conceptualisation.

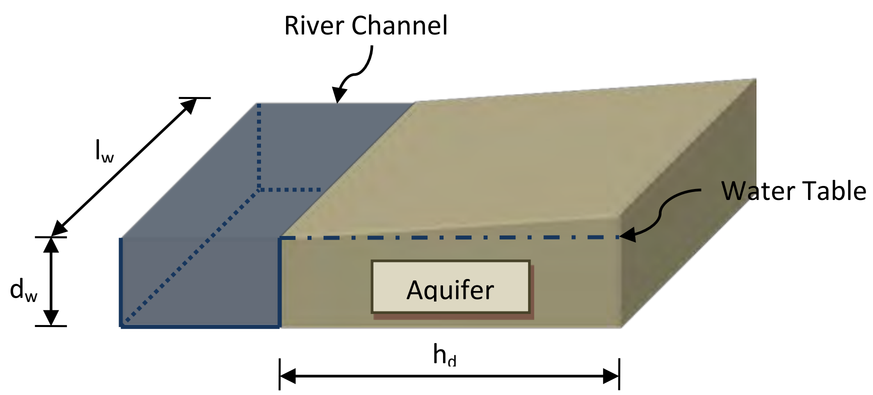


Figure 4.6: Conceptual Representation of Groundwater in WEAP

The reach lengths were estimated from the GIS map of the Vaal River and its tributaries as they traverse through the UVRB. The straight line horizontal distance of each main river/ tributary spanning the QC boundary in every QC was measured manually from the map and taken as the river reach. The straight line distance would be an underestimation of the actual distance but weighing the additional time it would take to calculate the exact lengths to the relatively larger benefits, it was considered uneconomical.

The horizontal distance was also calculated in the same manner outlined above. In many cases, the QC's were asymmetrical about the reach length. Therefore, average widths of the QC's were subjectively estimated and halved.

For the case of the wetted depth of the rivers, reliable data could not be obtained. Le Roy (2005) used an approximate of 3 m for a study he carried out in the Olifants Catchment using WEAP.

Therefore, this value was also adopted for the Vaal River. In addition, the smaller tributaries were given a lower depth value of 1.5 m to appreciate their size compared to the Vaal River.

4.5. Model Calibration

Calibration is the process of 'tuning' the model to derive the optimum input parameters by fitting the simulation of the model to observed measurements. This process is mainly guided by statistical analyses of the simulation to indicate the direction of the process. The following Sections discuss the different model efficiency criteria used for analysing the results of model calibration.

4.5.1. Model Performance Assessment Criteria

Efficiency criteria are normally applied to assess how well the model reproduces the observed measurements. There are a number of different 'goodness-of-fit' criteria available for this purpose such as the Nash – Sutcliffe efficiency, Index of Agreement and Coefficient of Determination. Even for the most experienced hydrologist, it is normally difficult to decide on which criteria to use and how to interpretation the results obtained (Krause, Boyle, and Bäse, 2005). Therefore, various criteria and their modified versions have been used in this study to reinforce the confidence in the results of the model simulation. The modifications to the original versions of the aforementioned criteria are described in detail by Krause *et al.* (2005). In addition, Ahnert *et al.*(2007) recommends the use of visual evaluation using the time series and scatter plots to supplement the results obtained from the 'goodness-of-fit' criteria.

The model performance was gauged using visual evaluation and the different statistical criteria (and their modified versions) outlined below:

i) Descriptive statistics: Mean, Standard Deviation and Coefficient of Variation (CV)

ii) Root Mean Square Error (RMSE) and Mean Absolute Error (MAE)

iii) Coefficient of Determination (R^2)

iv) Nash Sutcliffe Coefficient of Efficiency (E)

a. Modified with absolute values of residuals (E_j)

b. Modified by use of relative deviation (E_{rel})

v) Index of Agreement (d)

a. Modified with absolute values of residuals (d_j)

b. Modified by use of relative deviation (d_{rel})

4.5.1.1. Root Mean Square Error (RMSE) and Mean Absolute Error (MAE)

Root Mean Square Error (RMSE) and Mean Absolute Error (MAE) are popular goodness-of-fit criteria (Harmel and Smith, 2007) that describe the differences in measured and simulated values in the same units of measurement as the values. They are calculated using Equations 4.5 and 4.6.

$$\text{RMSE} = \sqrt{\frac{\sum_{i=1}^{n}(O_i - S_i)^2}{n}} \qquad (4.5)$$

$$\text{MAE} = \frac{\sum_{i=1}^{n}\left|O_i - S_i\right|}{n} \qquad (4.6)$$

Where O_i = Observed value, S_i = Simulated Value and n = Number of values

For a good agreement between observed and simulated values, the RMSE should be closest to zero.

4.5.1.2. Coefficient of Determination (R^2)

The Coefficient of Determination, R^2, can be defined by the following Bravais-Pearson equation:

$$R^2 = \left(\frac{\sum_{i=1}^{n}\left(O_i-\bar{O}\right)\left(S_i-\bar{S}\right)}{\sqrt{\sum_{i=1}^{n}\left(O_j-\bar{O}\right)^2}\sqrt{\sum_{i=1}^{n}\left(S_i-\bar{S}\right)^2}} \right)^2 \quad (4.7)$$

Where R^2 = Coefficient of Determination, O_i = Observed value, S_i = Simulated Value, $\bar{O}$, $\bar{S}$ = Mean of Observed and Simulated values respectively and n = Number of values.

R^2 ranges between 0 and 1 which is a description of how much of the dispersion about the observed value is explained by the simulation. A value of 0 signifies no correlation whereas 1 means the simulation is equal to the prediction.

A major disadvantage of this indicator is that only the dispersion is quantified. Therefore systematic (over) under prediction can still result in high values of R^2. Krause *et al.* (2005) therefore recommends to consider additional information such as the slope 'm' and y-intercept 'b' of the regression equation of the coefficient. This recommendation is reiterated by Ahnert *et al.* (2007) as well. For a good agreement, 'm' should be close to one and 'b' should be close to zero.

4.5.1.3. <u>Coefficient of Efficiency (E)</u>

This objective function, also referred to as the Nash-Sutcliffe criterion (Nash and Sutcliffe, 1970) is the most widely used criterion for pair wise comparison of modelled and observed data. It is defined as:

$$E = 1 - \left(\frac{\sum_{i=1}^{n}(O_i - S_i)^2}{\sum_{i=1}^{n}(O_i-\bar{O})^2} \right) \quad (4.8)$$

The E value is interpreted in the same manner as R^2 and a value close to one is always desired. A negative value of E however, would indicate that the simulation is worse than simply taking the mean of the observed measurements.

Legates and McCabe (as quoted by Krause *et al.*, 2005; Harmel and Smith, 2007) have found that E tends to be over sensitive to extreme values because of the squared value of the difference between observed and simulated values. Therefore, in cases of significant over or under predictions, the squared residual value is larger forcing E to be biased towards the lower range. For this reason, a modified version of E (E_j) was proposed by the same authors to counteract this problem. The squared residual component is now replaced with the absolute residual in E_j to the 1^{st} power. As a result, the oversensitivity due to flood peaks is reduced thus improving overall evaluation. E_j has been shown to produce lower values of efficiency than E which can either be interpreted as a worse simulation or room for more calibration. E_j is defined by Equation 4.9.

$$E_j = 1 - \left(\frac{\sum_{i=1}^{n} \left| O_i - S_i \right|^j}{\sum_{i=1}^{n} \left| O_i - \overline{O} \right|^j} \right) \qquad (4.9)$$

With $j \in N$

Looking at the contribution of over (under) prediction of higher and lower values, it can be agreed that higher values have a larger influence in terms of the difference of residuals. This is the case in either using the 1^{st} or 2^{nd} powers (j) as outlined in Equations 4.9 or 4.8 respectively.

The use of relative deviations are therefore proposed by Krause *et al.* (2005) to minimise the influence of absolute values of the residuals especially during high flows. Conversely, the contributions of the low flows are enhanced thus making the criterion ideal for measuring model efficiencies during low flows. This modification (E_{rel}) is given by Equation 4.10.

$$E_{rel} = 1 - \left(\frac{\sum_{i=1}^{n} \left(\frac{O_i - S_i}{O_i} \right)^2}{\sum_{i=1}^{n} \left(\frac{O_i - \bar{O}}{\bar{O}} \right)^2} \right) \quad (4.10)$$

In summary, the original version E is sensitive to the (over) under predictions warranting the result to be viewed with caution. To minimise this sensitivity, two modifications have been developed, each addressing a particular issue. The use of absolute values (E_j) is ideal for high flow predictions. When prediction of low flows is of more significance, use of the relative deviation (E_{rel}) is recommended.

4.5.1.4. Index of Agreement (*d*)

Legates and McCabe (as quoted by Krause *et al.*, 2005) states that Index of Agreement (Willmott, 1981) was developed to counteract the sensitivity of E and R^2 to differences in observed and simulated means and variances. It is also a widely used indicator of goodness-of-fit of hydrological models (Harmel and Smith, 2007) and is defined by Equation 4.11.

$$d = 1 - \left(\frac{\sum_{i=1}^{n} \left(O_i - S_i \right)^2}{\sum_{i=1}^{n} \left(\left| S_i - \bar{O} \right| + \left| O_i - \bar{O} \right| \right)^2} \right) \quad (4.11)$$

The range and interpretation of d is also the same as R^2. However, this indicator is also not spared from major disadvantages. Firstly, relatively high values of d (> 0.65) may be obtained for poor model fits and secondly, it is not sensitive to systematic model (over) under predictions.

For the aforementioned reasons, the two modifications earlier outlined for E have also been proposed for *d* by Krause *et al.* (2005) and serve the same purposes as E_j and E_{rel}. The Equations 4.12 and 4.13 define these modifications.

$$d_j = 1 - \left(\frac{\sum_{i=1}^{n} \left| O_i - S_i \right|^j}{\sum_{i=1}^{n} \left(\left| S_i - \bar{O} \right| + \left| O_i - \bar{O} \right| \right)^j} \right) \tag{4.12}$$

and

$$d_{Rel} = 1 - \left(\frac{\sum_{i=1}^{n} \left(\frac{O_i - S_i}{O_i} \right)^2}{\sum_{i=1}^{n} \left(\frac{\left| S_i - \bar{O} \right| + \left| O_i - \bar{O} \right|}{\bar{O}} \right)^2} \right) \tag{4.13}$$

4.5.2. The Calibration Approach

The WEAP model for the UVRB has been set up at the QC scale, which means there are a total of 91 catchments forming the hydrology module. WEAP does not have an inbuilt automatic calibration routine, therefore it has to be done manually by modifying the parameters and running the simulations until an optimum solution is arrived to. For that reason, calibration of each QC would consume a lot of time and resources. Therefore, the UVRB was sub divided according to the secondary catchment boundaries defined by DWA into three ‘zones’ for calibration. This results in each zone being a product of ‘lumping’ of a number of QC’s. During calibration, parameters were modified and applied to each ‘zone’ until an optimal solution was obtained. Figure 4.7 shows the three calibration zones for the UVRB.

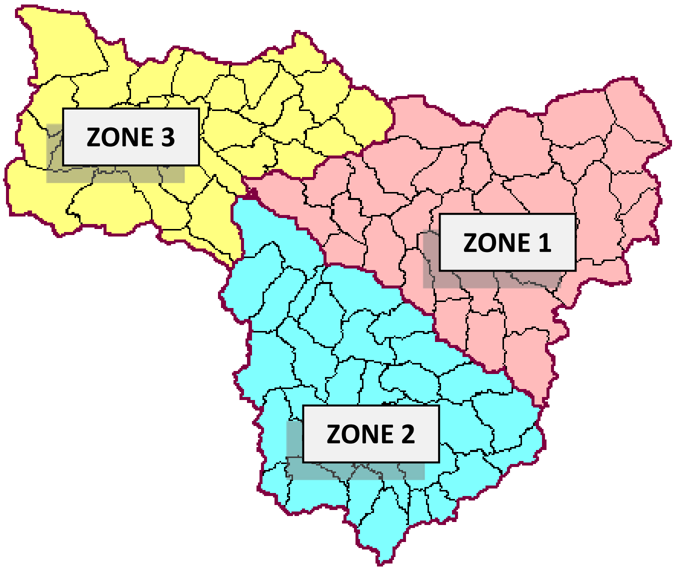


Figure 4.7: The Calibration Zones

Monthly time series of naturalised flow for each QC was available from the WR2005 Study. This data was used to assess the simulated flows. For each zone, the naturalised flows for all QC's were cumulated to obtain the flow at the outlet of the zone which was then compared with simulated flows at the same point. The reason behind using the naturalised flow data for calibration was the fact that the UVRB has been highly impacted by human influence. Therefore, if the observed flows were to be used, uncertainty as a result of the different unknowns due to the present situation in the catchment would have been introduced in the model setup. Using the naturalised flows ensures that the model parameters can be calibrated with fewer 'degrees of freedom' because of lesser uncertainty in the flows.

However, it should be borne in mind that the naturalised flows have been generated in another study using a different model (WR2005 Study using WRSM 2000 Model) and assumptions. Due to its widespread use in hydrological studies in South Africa, confidence in the data is high. Nonetheless, errors if any, in the generated flows will cross over into the model performance of this Study.

4.5.3. Parameter Estimation

Reference is made to Section 0 which gives an outline of all the parameters required to run a successful simulation. It can be seen that despite its conceptual simplicity, the model does require a relatively substantial number of parameters. The calibration task is further complicated because of lack of a parameter optimisation routine thus forcing the modeller to manually calibrate the model. This involves changing a parameter and running the simulation until an optimum performance is achieved.

For this Study, the number of parameters to be changed was kept to a minimum. As can be seen from the previous Section, most of the parameters have been derived based on credible sources. The finer spatial scale of the setup also provides relatively greater accuracy as compared to a coarser 'lumped' set up. Therefore, out of all the parameters, only four were 'unfixed' meaning changes were applied to them during calibration. The rest of the parameters were 'fixed'. Table 4.8 outlines the parameters and their status during calibration.

Table 4.8: Fixed and Unfixed Parameters Adopted for Calibration

Fixed	Unfixed
All Climate variables	Runoff Resistance Factor (RRF)
Land Use parameter	Preferred Flow Direction (PFD)
Root Zone Hydraulic Conductivity	Aquifer Hydraulic Conductivity
Root Zone Water Capacity	Crop coefficients (Kc)
Initial Z_1	
Groundwater Parameter	
Specific Yield	

It was assumed that the climate data are of good quality thus should not be modified. The fixed land use and groundwater parameters in Table 4.8 have been derived using credible data sources with a sound theoretical background and thus also assumed to be the best available data.

Modelled evaporation was compared to the mean annual evaporation (MAE) for the basin. Initial values of K_c resulted in gross underestimation of evaporation losses from the QCs. Therefore, it was decided to apply factors to the K(c) values beginning with 1.5 and using a step of 0.5. The modelled evaporation was checked for each QC, and K_c factor applied individually to achieve a close simulation of the MAE.

As for the unfixed parameters, the choice of RRF and PFD was dictated by the fact that they are empirically derived parameters. Therefore, modifying these parameters by application of adjustment factors would be acceptable as no other estimate can be inferred from available data. The aquifer hydraulic conductivity was set as unfixed so as to allow room for modelling of low flows.

The unfixed parameters were modified by application of stepwise adjustment factors. The assessment criteria outlined in Section 4.5.1 were used to gauge the performance of the model until an optimum solution was obtained. One parameter at a time was modified until the Efficiency Criteria could not be optimised any further.

4.6. Results and Discussion

4.6.1. Using Initial Derived Parameters

As a first step to obtaining insight to how the model performance would be, the initially derived parameters were used as is without any adjustment factors. The results are presented in Figure 4. a - d.

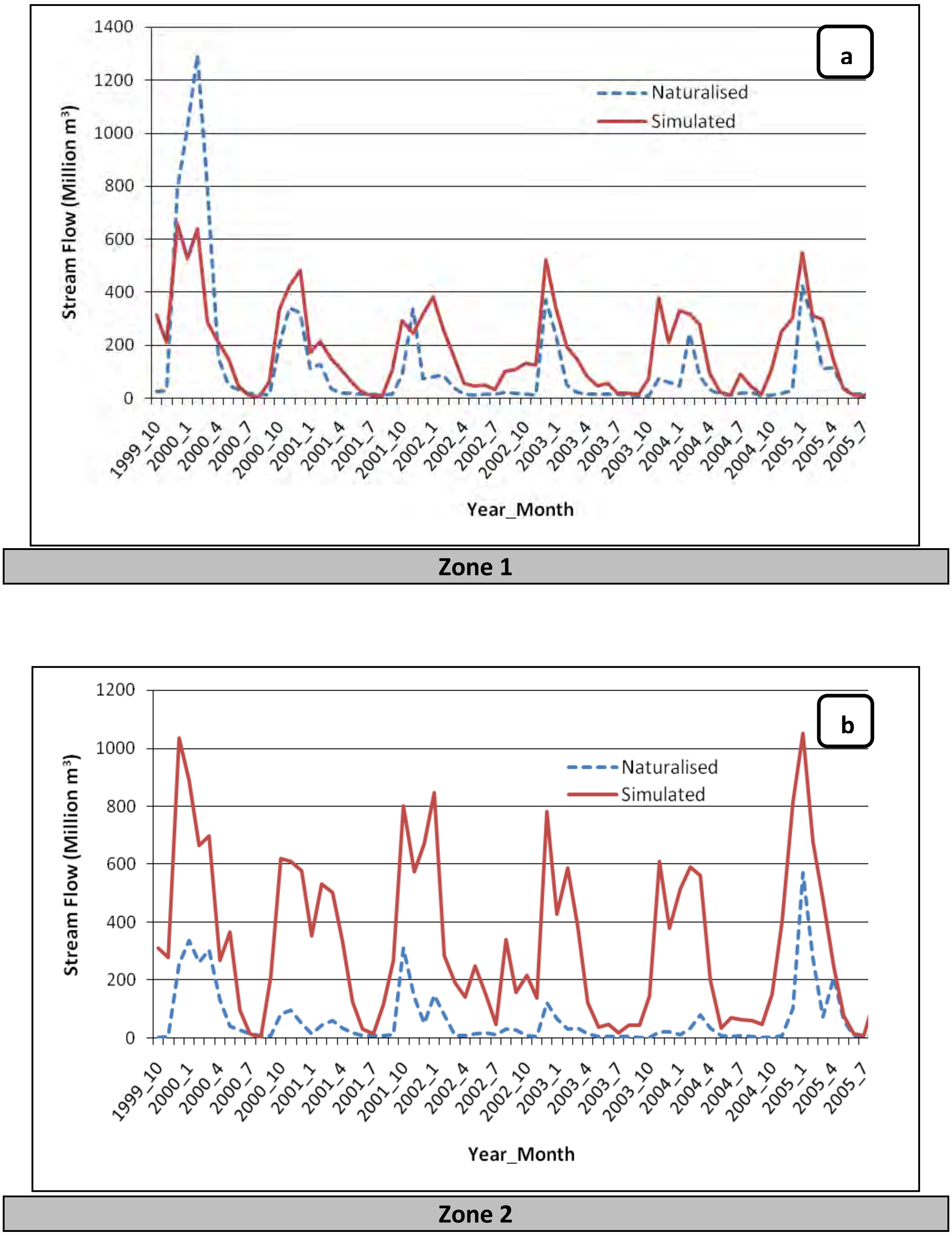
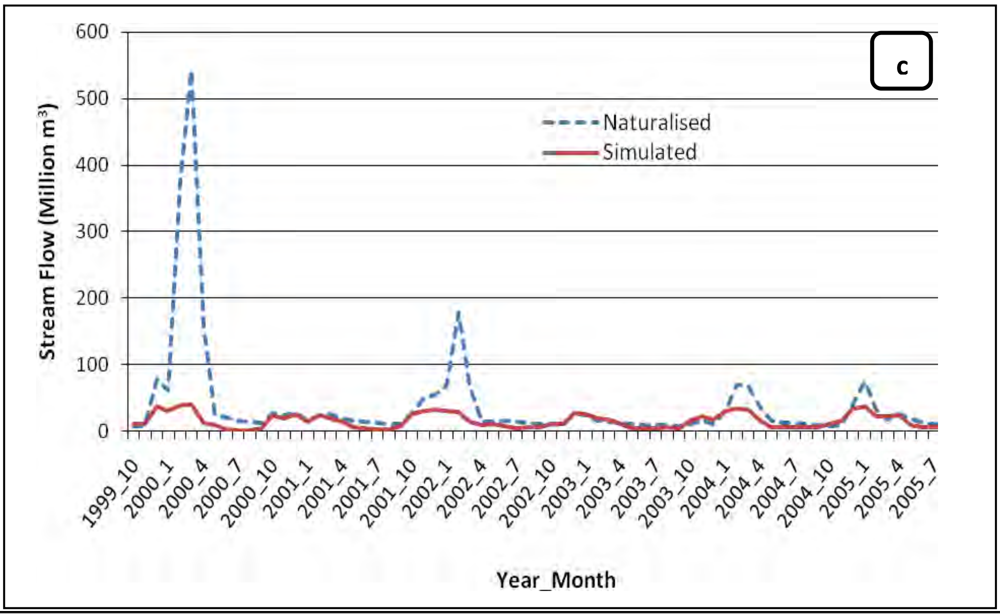
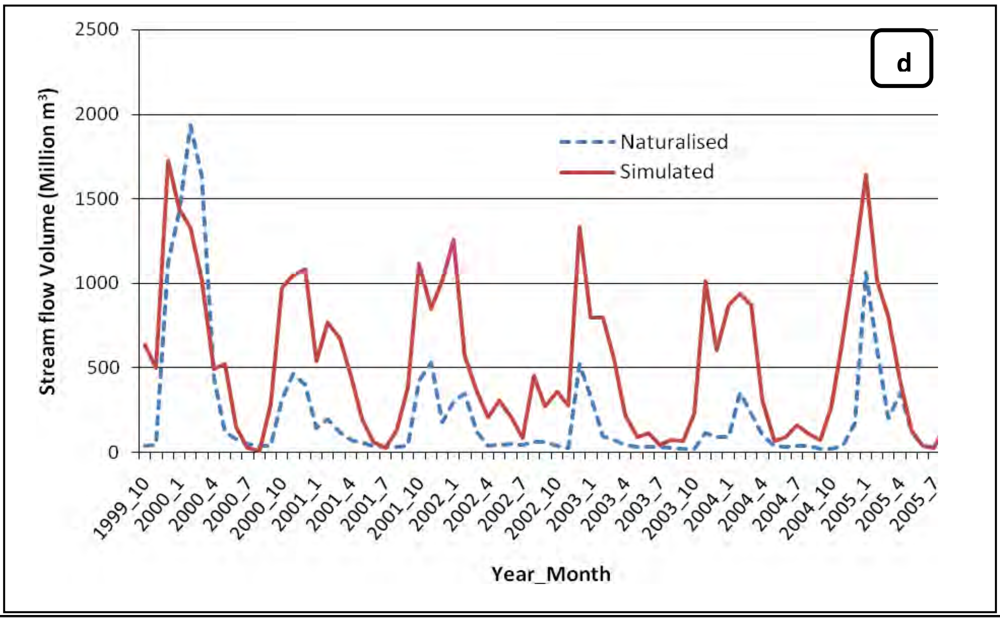


Figure 4.8: Simulation Results using Initial Parameters



Zone 3



Overall Basin

Figure 4.8: Simulation Results using Initial Parameters

From visual inspection, it is obvious that the model significantly overestimates the peak flows and low flows in Zone 1 and 2, but under predicts the peak flows while relatively capturing the low flows in Zone 3. Nonetheless, the system dynamics have been captured well as seen by the coincidental timing of the peaks and lows with the naturalised flows. The assessment criteria are not presented for the above results as they already do not satisfy the visual evaluation. Furthermore, there is still room for improvement as modification factors have not been applied yet.

4.6.2. Unfixed Parameter Estimation

The model systematically over predicted the high flow which means that the generated surface runoff and sub surface flow were in excess. Therefore, the runoff component required a reduction. However, upon inspection of the RRF values, it could be seen that most of them were near the value of 10 which is the upper limit of the range required in WEAP. This meant that the RRF could not be modified any further to reduce the runoff. It was concluded that the over prediction could only be attributed to the PFD for now. This conclusion was validated by the over prediction of flows during the dry months.

Therefore, the approach now focused on modification of PFD by applying a stepwise reduction of 0.1 to the initial assumed value of high and moderate interflow potential of the soil whilst maintaining the unmodified RRF. This resulted in the reduction of peak flows which was desired for Zones 1 and 2. The simulation however, now registered a gross under prediction for Zone 3. In addition, low flows were over predicted for all Zones which meant the sub surface contribution was higher than required. After numerous trials, it was determined that the high (moderate) interflow potential values of 0.1 (0.05) and 0.05 (0.025) for Zones 1 and 2 respectively gave optimum results for low flows (assessed using E_{Rel} and d_{Rel}). As for Zone 3, 25 out of the 27 QCs had soils with low potential. Upon inspection of the simulated flow time series, it was observed that the low flows were slightly under predicted. Therefore, the low interflow potential value of 0 was replaced with 0.01. A final value of 0.015 was determined to give best results.

All Zones now under predicted the peak flows, thus the next parameter to be modified was RRF. The same procedure outlined above was applied. However, in this case, a reduction factor was used which was multiplied with the initially derived RRF values. A stepwise reduction factor of 0.1 was adopted. The simulation significantly improved for all three Zones for the factor of 0.3. Thereafter, a step of 0.01 was applied. It was concluded that the optimum reduction factor for Zone 1 was 0.3, and Zone 2 and 3 was 0.28 respectively.

The aquifer hydraulic conductivity was then adjusted for all the zones by applying a factor of 1.5. It was observed that this factor resulted in poor efficiency criteria for all three Zones. Therefore, no modification was made to the initially derived values. Table 4.9 gives the final parameters and the respective optimised values and adjustment factors.

Table 4.9: Unfixed Parameters and Applied Adjustment Factors

Parameter	Value/ Adjustment Factor		
	Zone 1	Zone 2	Zone 3
Runoff Resistance Factor[a]	0.3	0.35	0.28
Preferred Flow Direction[b]	0,0.12	0, 0.05	0, 0.015
Aquifer Hydraulic Conductivity	None	None	None

[a] The figures represent the adjustment factor multiplied with initially derived RRF values

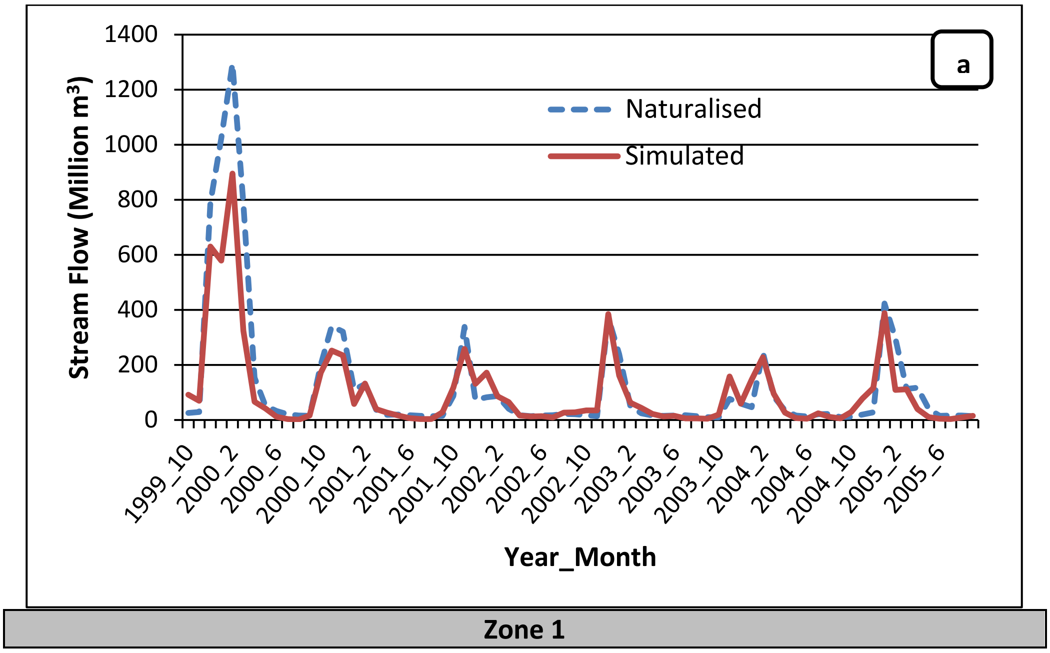
[b] The figures represent the final value used to signify low and high interflow potential.

4.6.3. Final Results of Calibration

The final results of the calibration process outlined in Section 4.6.2 are presented here.

4.6.3.1. Visual Evaluation and Descriptive Statistics for Stream Flow

Figure 4.9 shows the observed and simulated time series of stream flow for the calibration period. The peak flows are underestimated in most cases, especially the extreme occurrence in the first hydrological year HY1999. However, the moderately high and low flows in general have been predicted relatively well. Model evaluation statistics are presented in Table 4.10.



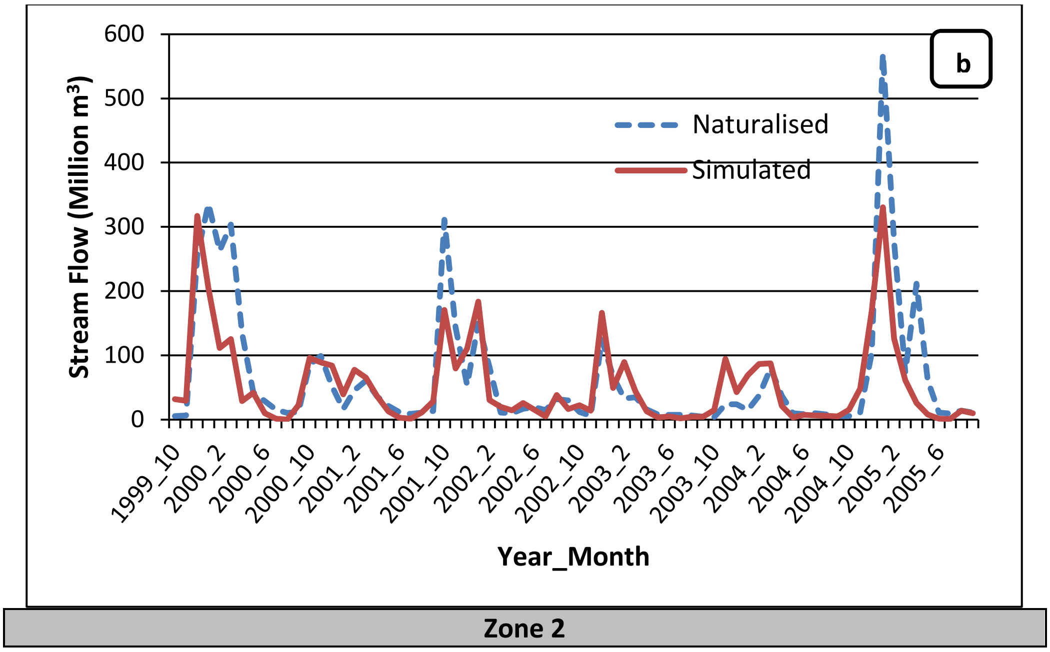
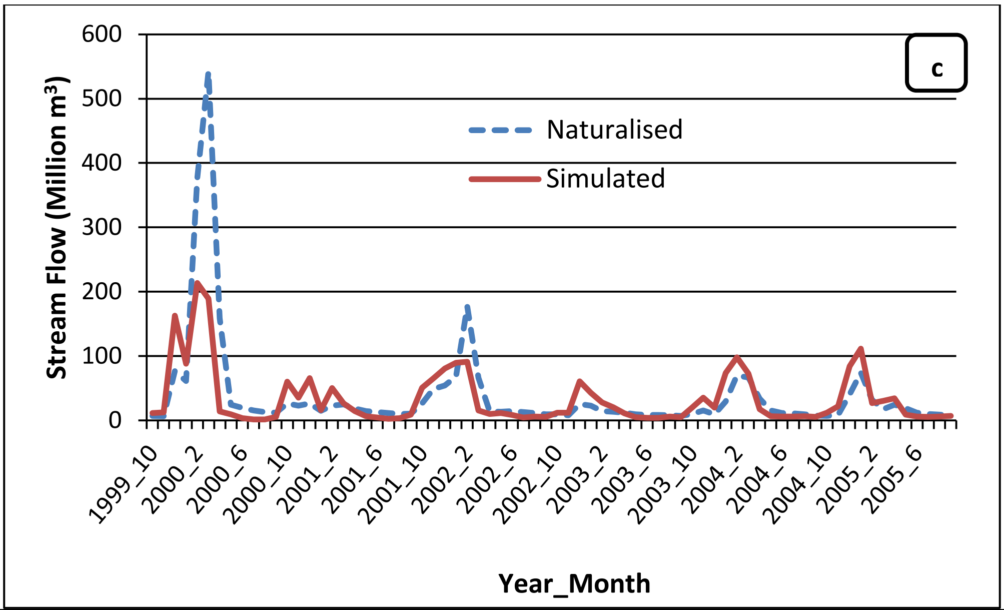
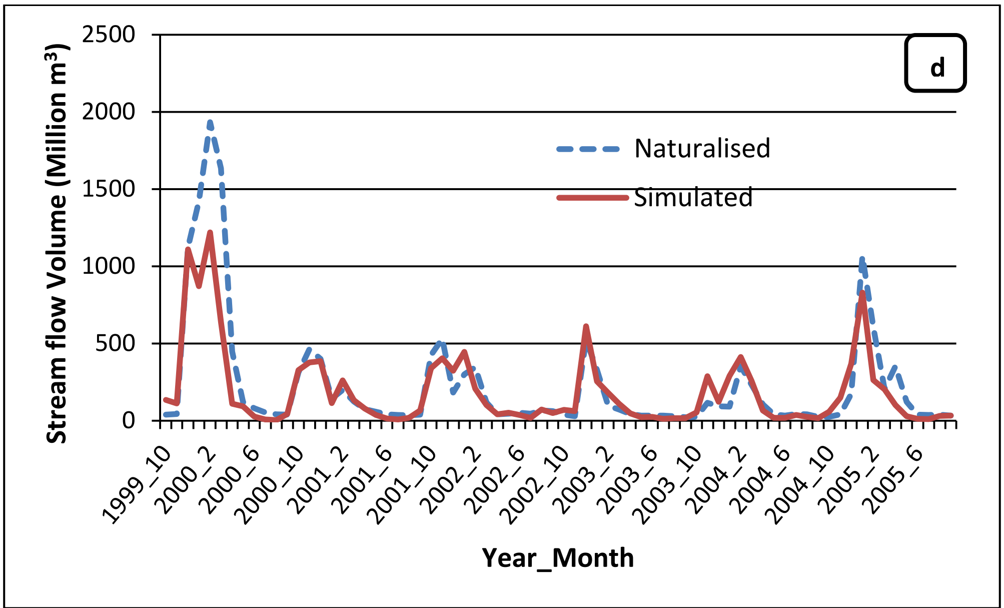


Figure 4.9: Simulation Results using Final Parameters



Zone 3



Overall Basin

Figure 4.9: Simulation Results using Final Parameters

Table 4.10: Model Statistics for the Simulation

Statistic	Zone 1		Zone 2		Zone 3		Overall Basin	
	O	S	O	S	O	S	O	S
Mean	122.68	98.72	65.42	53.71	38.25	33.21	226.35	185.64
SD	234.92	157.37	101.72	67.80	79.01	43.47	372.69	251.94
CV	1.91	1.60	1.55	1.26	2.06	1.31	1.64	1.36
Mean Annual Volume (Mm^3)	1472.15	1184.60	785.06	644.57	459.01	398.58	2716.23	2227.78

Where O = Naturalised, S = Simulated, SD = Standard Deviation and CV = Coefficient of Variation

The mean of the naturalised and simulated stream flow is within 20%, 18%, 13% and 18% of each other for Zone 1, 2, 3 and Overall Basin respectively. The simulated SD for Zone 1, 2 and Overall Basin is 33% lower than the naturalised flow, whereas 45% lower for Zone 3. This can be attributed to the high variability of both the naturalised and simulated stream flows. However, the values of CV for simulation are within 19% of the naturalised flows for all Zones except Zone 3 which is 36%. The large values of CV for naturalised flows also show the inherent high variability.

4.6.3.2. Efficiency Criteria for Stream Flow

The scatter plots of naturalised against simulated flows for all the Zones and Overall Basin is given in Figure 4.10. A linear regression line was fitted to the plots and the respective R^2 values calculated together with the slope and y-intercept.

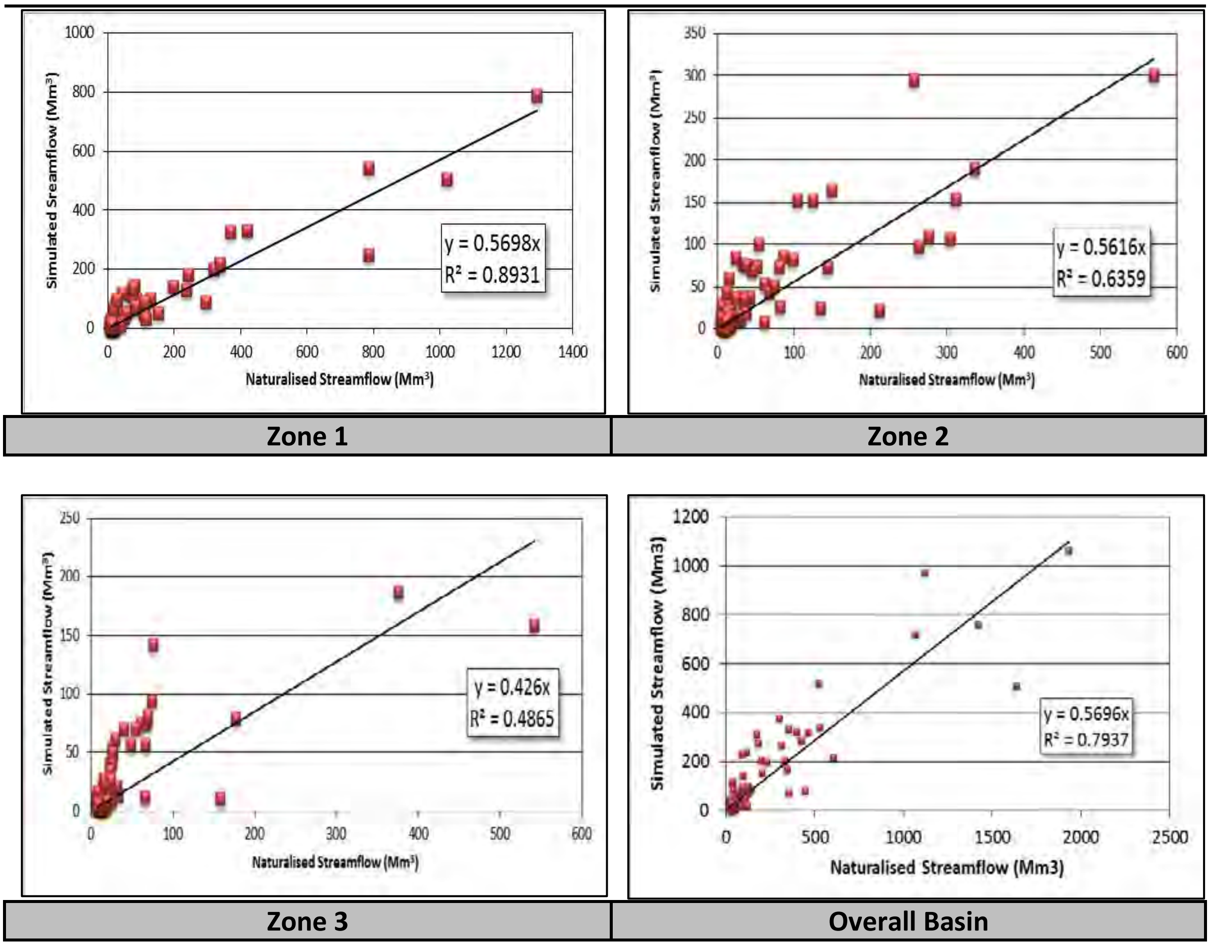


Figure 4.10: R^2 and Regression Coefficients for each Zone and Overall Basin

The results for the rest of the criteria are presented in Table 4.11. The highlighted rows in the table indicate the criteria weighted during calibration.

Table 4.11: Efficiency Criteria Results for Model Calibration

Assessment Criterion	Zone 1	Zone 2	Zone 3	Overall Basin
Root Mean Square Error RMSE	121.57	64.34	56.66	211.11
Mean Absolute Error MAE	54.88	33.93	21.41	97.87
Coefficient of Determination R^2	**0.8931**	**0.636**	**0.487**	**0.794**
• **Slope (m)**	0.569	0.562	0.426	0.570
Coefficient of Efficiency E	**0.728**	**0.593**	**0.479**	**0.674**
E_j (High Flow Prediction)	0.613	0.497	0.427	0.585
E_{Rel} (Low Flow Prediction)	**0.862**	**0.576**	**0.920**	**0.843**
Index of Agreement *d*	0.889	0.834	0.740	0.868
d_j (High Flow Prediction)	0.779	0.714	0.691	0.767
d_{Rel} (Low Flow Prediction)	**0.938**	**0.818**	**0.960**	**0.812**

In general, the model's performance in Zone 1 is the best of the other Zones. This can be seen from the high values of the assessment criteria (mostly > 0.8). Performance in Zone 2 and 3 is reasonable with criteria results ranging from 0.4 – 0.9. However, the performance of the model at the basin scale is good with most criteria ranging from 0.6 – 0.9. This means that the errors in the Zones are buffered at the larger scale.

The high flows are underestimated in most cases as shown in Figure 4.9. Nonetheless, Zone 1 performed well in capturing most of the high flow occurrences indicated by E_j and d_j of 0.613 and 0.779 respectively. However, the results were relatively low for the other Zones. This corresponds with weaker performance exhibited in the respective graphical time series plots. In overall, the basin model performed well as a whole in simulating the high flows with values of E_j and d_j equal to 0.585 and 0.767 respectively.

The focus of this Study is on assessment of future water availability in the basin. Therefore, the most important period in the hydrological year would be the dry months where demands could have a possibility of not being met. Therefore, the assessment of performance of the model is biased towards its confidence in low flow simulation. As outlined in Section 4.5.1, the modified versions of the E and *d* (E_{Rel} and d_{Rel}) which are beter suited for low flow prediction were more rigorously assessed relative to the others.

All Zones exhibited good performance under prediction of low flows as seen by the d_{Rel} (> 0.75). Under E_{Rel} however, Zones 1 and 3 performed well (> 0.8) but Zone 2 had a low performance (0.576). The reason for this result could not be established at the time. In general, the performance of the basin as a whole was good under low flows with E_{Rel} and d_{Rel} equal to 0.843 and 0.812.

To summarise the above, it can be said that the model shows good agreement between naturalised and simulated flows. This is backed by results from the rigorous statistical methods employed. Furthermore, the system dynamics have also been represented well as seen from the timing of the high peaks and low flows which mean the catchment processes are reproduced well by the model. An important goal is to capture the low flow dynamics as well for assessment of future water availability in the dry periods, which has been achieved for the UVRB.

4.6.3.3. Simulated Evaporation

The simulated evaporation was tweaked by application of multiplication factors to the K_c's for each QC. Despite applying factors ranging from 1.0 – 3.75 the simulation underestimated evaporation constantly, with an average underestimated MAE of 860mm. Nonetheless, the factors were not changed further because of time constraints as a result of running the simulation after every change in applied factors.

4.6.4. Sensitivity Analysis

A sensitivity analysis was carried out to determine how sensitive the model was towards a change in the unfixed input parameters. The best set of parameters derived during calibration was used as the base and a percentage change applied individually to the input parameters. The mean annual flow was used as a gauge for model behaviour to the change. The change in efficiency parameters for ±20% change in RRF is given in Table 4.12 and Table 4.13.

Table 4.12: Sensitivity Analysis of Model to Change in RRF

Assessment Criterion	Zone 1		Zone 2		Zone 3		Overall Basin	
	+20%	-20%	+20%	-20%	+20%	-20%	+20%	-20%
Root Mean Square Error RMSE	22%	-13%	17%	-8%	17%	3%	20%	-11%
Mean Absolute Error MAE	17%	-6%	9%	8%	0%	48%	15%	2%
Coefficient of Determination R^2	0%	-3%	2%	5%	-8%	-8%	0%	-3%
Coefficient of Efficiency E	-18%	-34%	-25%	-59%	-40%	-76%	-22%	-23%
E_j (High Flow Prediction)	-11%	3%	-9%	-8%	0%	-64%	-11%	-2%
E_{Rel} (Low Flow Prediction)	-4%	-31%	-24%	-85%	0%	-31%	-4%	-32%
Index of Agreement *d*	-10%	4%	-14%	5%	-26%	4%	-12%	5%
d_j (High Flow Prediction)	-7%	2%	-7%	-1%	-5%	-15%	-7%	1%
d_{Rel} (Low Flow Prediction)	-3%	-11%	-14%	-20%	-1%	-12%	11%	3%

Table 4.13: Sensitivity Analysis of Model to Change in PFD

Assessment Criterion	Zone 1		Zone 2		Zone 3		Overall Basin	
	+20%	-20%	+20%	-20%	+20%	-20%	+20%	-20%
Root Mean Square Error RMSE	0%	7%	-1%	9%	7%	8%	0%	7%
Mean Absolute Error MAE	1%	5%	5%	3%	21%	10%	3%	4%
Coefficient of Determination R^2	-3%	0%	3%	6%	-8%	-5%	-3%	1%
Coefficient of Efficiency E	-26%	-33%	-49%	-65%	-39%	-36%	-16%	-22%
E_j (High Flow Prediction)	-1%	-3%	-5%	-3%	-29%	-14%	-3%	-3%
E_{Rel} (Low Flow Prediction)	-21%	-6%	-94%	-7%	-12%	-5%	-23%	-5%
Index of Agreement *d*	0%	-3%	0%	-7%	-7%	-11%	0%	-4%
d_j (High Flow Prediction)	-1%	-2%	-19%	-3%	-11%	-7%	-1%	-2%
d_{Rel} (Low Flow Prediction)	-9%	-3%	-30%	-5%	-6%	-3%	4%	12%

The different Zones respond differently from the changes in RRF and PFD. R^0 does not vary significantly for the 2 parameters, with a range of 0-8% for ±20% change in RRF and PFD. However, for the other efficiency criteria, the model is significantly sensitive to change in the parameters. Therefore, it can be concluded that caution is required during calibration to achieve optimum results without compromising on the meaningful range of the parameters.

For this study, the calibrated values were adopted because of time constraints. It is advised however to carry out a more detailed analysis including all the parameters to determine the most sensitive ones and thereafter carry out the calibration.

4.6.5. The Concept of Model Validation

Model validation has been a topic of much controversy in the last decade since hydrological modelling came into the spotlight. Hassan (S.a) presents an interesting perspective on model validation collated from various literature, thus this Section draws largely from his work.

In the strictest definition, validation is defined as the demonstration of the accuracy of a model in representing the true system. However, this is simply not true because the physical system can never be defined completely. This leads to a misconception about the principle behind validation. In most studies, the conventional approach is to calibrate and then validate. A conclusion on the model performance is then weighted on the validation results, which if good, means that the model predicts the process well. However, this may not necessarily be the truth. This is reiterated by de Marsily, Combes and Goblet (1992) who state that comparison of a model output with new data does not mean the model is correct, but only increases its confidence.

Models are useful decision making tools only when they have passed a rigorous development, calibration and testing process (Hassan, S.a). Thus validation can be regarded as an additional filter for model performance assessment and also to instil further confidence in the calibration. In addition, validation is a long term iterative process aimed to build confidence in the model output. Thus it is not a onetime process which it has been misconstrued to be. As Hassan (S.a) further states, the validation process should “contain trigger mechanisms that will drive the model back to the characterisation-conceptualisation-calibration-prediction stage, but with a better understanding of the model”.

Therefore, a more holistic approach to model validation has been taken in this Study. Since the main objective of this Study is to model the present and future water availability of the UVRB, which would incorporate the present day and future water infrastructure and water demands, validation of the hydrologic module on its own would not serve as much purpose. Instead, it is proposed that the model will be validated after it has been set up to meet the aforementioned objective. Therefore, the overall model performance in simulating the present status of the UVRB will be assessed and regarded as its validation.

4.7. Conclusion

The WEAP hydrologic module was setup using parameters derived from credible sources of data and/ or application of justified assumptions. Calibration was carried out by adjusting 3 input parameters only. Different efficiency criteria were employed to assess the model performance. In general, the results show that the naturalised hydrology can be reproduced relatively well with minimal calibration (see Table 4.11.). It should be acknowledged however, that the peak flows are not well represented.

Overall, the following can be some of the reasons explaining the performance of the model assuming there are no errors in the naturalised flow data:

i) The ‘zoning’ of the UVRB for calibration. The re-zoning of the basin into different zones and not necessarily following the secondary catchments may result in a better model performance.

ii) The manual method of calibration is inconvenient and prone to judgement errors which may have resulted in inadequate calibration.

iii) The ‘fixing’ of all parameters except RRF and PFD may have limited the scope of calibration. It may be possible to improve the results if other input parameters were also adjusted.

CHAPTER FIVE

MODELLING THE PRESENT DAY HYDROLOGY

"Only within the moment of time represented by the present century has one species -- man -- acquired significant power to alter the nature of his world."

Rachel Carson

5.1. Introduction

This Chapter outlines the different input data required by the water allocation module in WEAP. The present day conditions have been superimposed on the naturalised hydrology set up in Chapter Four. The various existing water infrastructures and the current water abstractions in the UVRB have been set up. The results of the simulation are also presented.

5.2. Required Data

To successfully set up the water allocation module, information on the water infrastructure such as dams and inter basin transfers and the water demands are required. The detail to which the water demands are input depends on the modeller. A coarser approach of generalised demands (for example the total demand only) or a finer detail (such as the demands of different consumer categories) can be used.

The present day hydrology was simulated over the same period as the naturalised hydrology that is HY1999 to HY2004.

5.2.1. Land Use Changes

Land use change is described as the modification or changes, made by humans, to land cover from one type to another. In modelling the naturalised hydrology, a pristine state using the Acocks veld types was used for calibration of the model. The focus is now on the present state of the basin, and therefore the changes made to the pristine conditions need to be quantified. For this purpose, the CSIR land use dataset has been used to represent the present conditions of land use within the UVRB. This dataset covers the entire country and is the latest information on the land use available.

The two main parameters which change to accommodate the changes in land use are crop coefficients and runoff resistance factors.

5.2.1.1. Crop Coefficient (K_c)

Reference is made to Chapter 4 Section 4.4.2.2. in which the methodology for derivation of this parameter was outlined. The same methodology has been used in this Section, but with new crop coefficients to reflect the changed land uses. The crop coefficients have been extracted from Schulze (1995) for the land use categories which had corresponding K_c values. For those with no corresponding value, assumptions have been made. The different land uses and their equivalent categories are given in Table 5.1.

The main crop cultivated in the UVRB is maize and wheat (DWAF, 2004). However, the K_c values for maize were readily available and thus used to represent this category. However, the planting date of this crop has a phenological impact thus altering the monthly K_c sequence. Therefore, to accommodate the range of planting date options, the average was taken of the monthly K_c for all the planting date options.

For the case of (un)improved and degraded unimproved grasslands, the K_c values used for pristine conditions were reused. This is because this category does mean that humans have not largely impacted in the respective regions.

The forests in UVRB are mainly formed of Pine, Eucalyptus and Wattle (DWAF, 2002). The coefficients for Pine and Eucalyptus were readily available therefore an average of the two was taken to derive the monthly value. However, it should be noted that this land use category covers approximately 1.3% of UVRB thus not having a significant contribution to evapotranspiration losses.

Lastly, the mines and quarries and the different classes of urban infrastructure were lumped together and assigned the equivalent coefficient values for commercial infrastructure with 85 – 95% impervious surfaces. The coverage of Urban/ Built up land with grassland, bushland and woodland is 0.6% of the total basin area; therefore this assumption would not affect the results.

Table 5.1 gives the different land use categories from the CSIR dataset and their equivalent assumed from Schulze (1995).

Table 5.1: Land Use Categories and Equivalent in Schulze (1995)

Land Use Category	% Area of Basin	Equivalent category in Schulze (1995)
Cultivated: Temporary – commercial dryland	31.9	Maize (Dryland)
Cultivated: Temporary – commercial irrigated	0.8	Maize (Irrigated)
Cultivated: Temporary – semi commercial/ subsistence dryland	0.09	Maize (Dryland)
Degraded unimproved grassland	0.3	Same as Pristine
Forest and woodland	0.6	Alexandria Forests
Forest plantations	1.3	Eucalyptus/ Pine forest
Thicket and Bushland	3.3	Same as Pristine
Shrubland and fynbos	0.02	Negligible
Improved Grassland **Unimproved Grassland**	54.8	Same as pristine
Mines and Quarries **Urban / built-up land: commercial** **Urban / built-up land: industrial / transport** **Urban / built-up land: residential** **Urban / built-up land: residential (grassland)** **Urban / built-up land: residential (bushland)** **Urban / built-up land: residential (woodland)**	3.2	CBD/ Commercial 85 – 95% impervious

The multiplication factors applied in Chapter 4 Section 4.5.3 were maintained in this step.

5.2.1.2. Runoff Resistance Factor (RRF)

The same methodology outlined in Chapter 4 Section 4.4.2.3. has been used but with adjusted CN values to reflect the land use changes. In addition, the optimum adjustment factors determined during calibration are also kept constant. The CSIR dataset was superimposed on the soil map used earlier, both in GIS compatible format and the different land uses and corresponding soil hydrological groups for each QC was extracted.

Since exact CN's for the CSIR land use categories were not available, assumptions had to be made using the values given by Schulze, Schmidt and Smithers (1992). The land use categories and the corresponding CN values are given in Table 5.2.

Table 5.2: Various Land Use Categories and their Adopted Equivalent

Land Use Category	% Area of Basin	Equivalent category in Schulze, Schmidt & Smithers (1992)		
		AB	BC	C
Barren Rock Dongas and Sheet Erosion Scars	0.1	95	95	95
Cultivated: Temporary – commercial dryland	31.9	71	79	82
Cultivated: Temporary – commercial irrigated	0.8	41	57	65
Cultivated: Temporary – semi commercial/ subsistence dryland	0.09	77	85	88
Degraded unimproved grassland	0.3	74	83	86
Forest and woodland Forest plantations	0.6 1.3	47	64	69
Thicket and Bushland Shrubland and fynbos	3.3 0.02	49	68	73
Improved Grassland Unimproved Grassland	54.8	51	68	74
Mines and Quarries Urban / built-up land: commercial Urban / built-up land: industrial / transport Urban / built-up land: residential Urban / built-up land: residential (grassland) Urban / built-up land: residential (bushland) Urban / built-up land: residential (woodland)	3.2	78	86	88

The CN values for grassland, forests, thicket and bushland and cultivation given in Table 5.2 were adjusted for slope using the same factors used in pristine conditions given in Chapter 4 Table 4.4. Conversely, the values for the urban category were not adjusted considering that gradients are usually either eliminated or reduced during construction thus rendering the landscape gentler than would be found in pristine conditions.

5.2.2. Water Infrastructure

The main water infrastructures existing in the UVRB are storage dams and inter basin transfers (IBTs). The different parameters required to explicitly model these infrastructures are explained in detail in the following sections.

5.2.2.1. Dams

There are seven large dams which have been constructed in the UVRB used mainly for irrigation and water supply. The required data was obtained from the DWEA. The reservoirs are represented by nodes in WEAP and the different input parameters are entered for each node to model a particular reservoir. The following sub sections will each cover the particular input parameter for all the dams. Figure 5.1 shows the locations of the major dams in the UVRB.

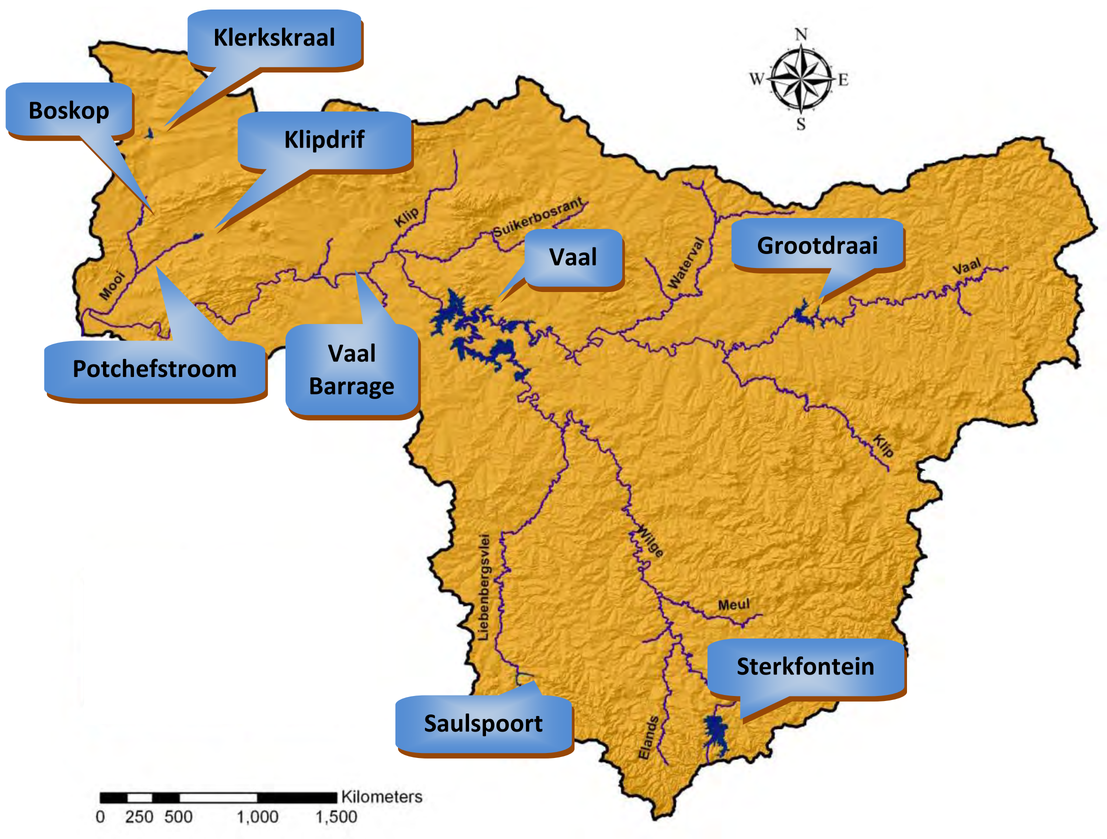


Figure 5.1: Location of the Major Dams in the UVRB

a) Storage Capacity and Initial Storage

The storage capacity represents the total capacity of the dam and the initial storage is the amount of water initially stored at the beginning of the first month of the simulation period (October 1999). The capacities of the dams were obtained from the Dams Database of South Africa available from DWEA. Dam balance data for each dam was obtained from DWEA's Hydrological Information Services (HIS) for the period of simulation. This data included *inter alia* a time series of storage volume, gross evaporation and precipitation. Table 5.3 shows the storage capacities and initial storage for the dams incorporated in this Study.

Table 5.3: Reservoir Storage Capacities and Initial Storages

Reservoir	Storage Capacity (Mm^3)	Initial Storage (Mm^3)
Grootdraai	382.5	281.60
Vaal	2609.80	2209.95
Vaal Barrage	55.4	46
Sterkfontein	2616	2313.37
Klerkskraal	8.25	7.98
Boskop	20.85	20.8
Klipdrift	13.58	10.8
Potchefstroom	2.03	2.03
Saulspoort	16.9	17.37

b) Volume Elevation Curves

The volume – elevation curves are used by the model to calculate the amount of evaporation from the dams. These curves were extracted from the area – capacity tables for each dam obtained from HIS. A 1 m elevation interval was adopted to accommodate the limited number of points which can be input in the model. The volume – elevation data is not available for the Vaal Barrage. Therefore, it was modelled as a box (straight line) using its gross storage capacity and height of dam.

c) Net Evaporation

The net evaporation is the difference between gross evaporation and precipitation on the dam water surface. A positive (negative) net evaporation represents a net loss from (gain to) the dam.

From the dam balance data mentioned earlier, the net evaporation could have been calculated for the simulation period because the gross evaporation and precipitation data are available. However, this would have limited the model’s evaporation calculation to the period of simulation only. For the case of future periods, the model would not have been able to calculate the net evaporation because gross evaporation values would not be available. Therefore, another approach which is dependent on a parameter which would be available for the future period was devised.

The spatial variation of mean annual evaporation (MAE) in South Africa was obtained in GIS format from the WR05 Study. In addition, the country is also categorised into evaporation zones under the previous WR90 Study (Midgley, Pitman, and Middleton, 1994). The latter was also available in GIS format. Therefore, the two datasets were superimposed together with the locations of the major dams to determine the range of MAE at the each dam location as well as the evaporation zone the dam falls in. Thereafter, the monthly variations of potential evaporation expressed as percentages of MAE and specific for an evaporation zone were extracted from the WR90 study. Table 5.4 gives the MAE and monthly variations expressed as percentages of MAE for each dam. The QC's in which the dams are located were used to supply the monthly precipitation value.

A simple formula was input in the model to automatically obtain the difference between the monthly potential evaporation and precipitation thus giving the monthly net evaporation. This approach is now solely dependent on precipitation values and will enable the calculation of net reservoir evaporation for future scenarios for which precipitation data will definitely be available. However, it is based on the assumption that the MAE and its monthly variations remain constant.

The above procedure was used to calculate initial values of net evaporation. As will be seen in Section 5.3.1.1, adjustment factors will be applied to get a good agreement between the observed and simulated net evaporation.

Table 5.4: MAE and its Monthly Variation (in %) for the Major Dams

		Dams				
		Grootdraai	**Vaal**	**Vaal Barrage**	**Sterkfontein, Saulspoort**	**Klerkskraal, Boskop, Klipdrift, Potchefstroom**
	Avg. MAE (mm)	**2100**	**2100**	**2400**	**1900**	**2400**
Monthly Variation expressed as percentage of MAE	Oct	10.35	10.9	10.97	10.85	11.11
	Nov	10.2	10.9	11.39	10.88	11.46
	Dec	11	11.7	12.37	11.71	11.87
	Jan	10.87	11.4	12.23	11.36	11.48
	Feb	9.38	9.37	9.86	9.37	8.98
	Mar	8.94	8.76	8.96	8.76	8.13
	Apr	6.88	6.62	6.55	6.62	6.33
	May	5.85	5.37	4.94	5.37	5.28
	Jun	4.82	4.36	3.78	4.36	4.17
	Jul	5.29	4.71	4.22	4.71	4.91
	Aug	7.26	6.83	6.12	6.83	6.97
	Sept	9.16	9.18	8.61	9.18	9.31

Data extracted from Midgley, Pitman and Middleton (1994) and the WR05 Study

d) Loss to Groundwater

This parameter represents the seepage losses from the reservoir. According to the dam balance data, there was no unaccounted for losses from the reservoirs. Therefore, this input parameter was ignored.

e) Reservoir Operation

The reservoir operation is simulated using four input parameters which are given in Figure 5.2 labelled 1 -4. User defined priorities are assigned for filling of the reservoirs. These range from 1 – 99, with the former and latter representing highest and lowest priority respectively. For this study, all reservoirs have been assigned the lowest priority (99). This means that the reservoirs will only fill after all demands have been met.

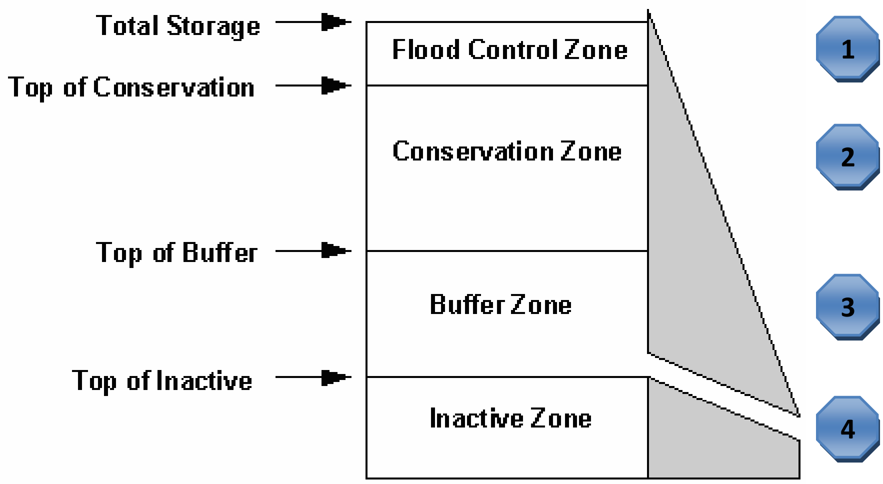


Figure 5.2: Reservoir Operation Zones (after SEI, 2007)

The conservation and buffer zones collectively form the active storage. WEAP will always ensure that the flood control zone is kept vacant; therefore the storage is capped at the top of conservation. The reservoir freely supplies demand whilst operating in the conservation zone. However, once the storage drops into the buffer zone, then releases are constrained according to a buffer coefficient to conserve the dwindling supplies. Water in the inactive pool is not available for allocation, but is susceptible to extreme evaporation conditions.

For the dams in question, reservoir operating rules could not be obtained. However, from an analysis of the time series of storage volume, the storage behaviour had a certain maximum over the 6 year period and which was consistently below the total storage capacity. Therefore this maximum was adopted as the top of conservation level. The other input parameters were assigned zero values to indicate no operating rules.

5.2.2.2. <u>Inter basin Transfers</u>

Inter basin transfers (IBTs) are volumes of water delivered from or to other basins. There are 4 main transfers from adjacent basins into UVRB and one transfer out. Figure 5.3 shows the various IBT sub systems and the locations of the dams which command them. Each IBT is discussed in detail in the following sub sections. Monthly time series of transfer volumes for the period of simulation was for all IBTs was obtained from DWEA.

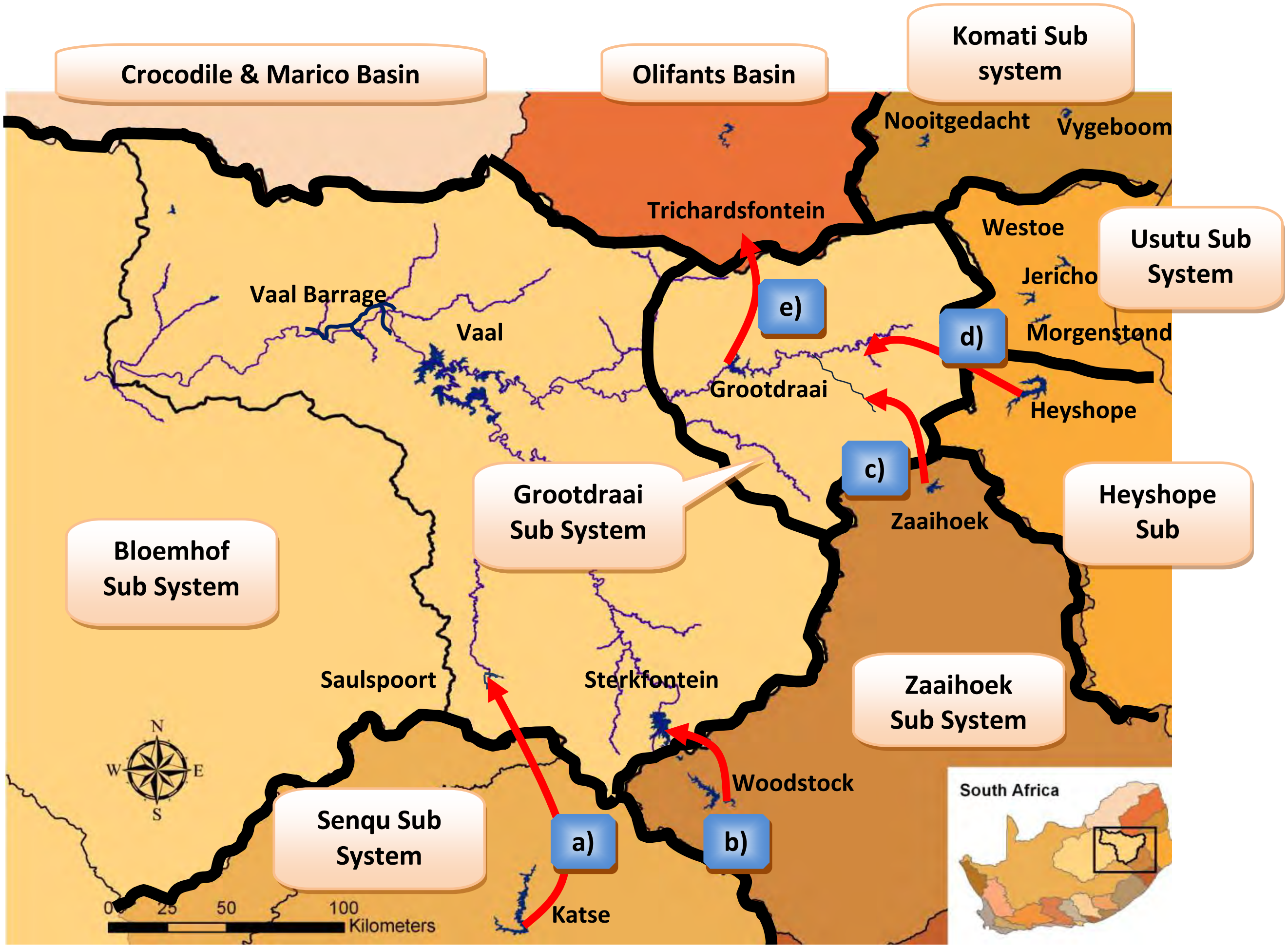


Figure 5.3: Inter Basin Transfer Sub Systems

a) Lesotho Highlands Water Project

This IBT originates from Lesotho and represents the water resource components of Phase 1A and 1B of the Lesotho Highlands Water Project (LHWP). This system consists of the Katse and Mohale dams and connecting transfer tunnels delivering water into Leibenbergslvei River, a tributary of Vaal River, via the Saulspoort Dam. The collective operation of this system is also referred to as the 'Senqu Sub System'. Monthly and annual volumes transferred are presented in Figure 5.4.

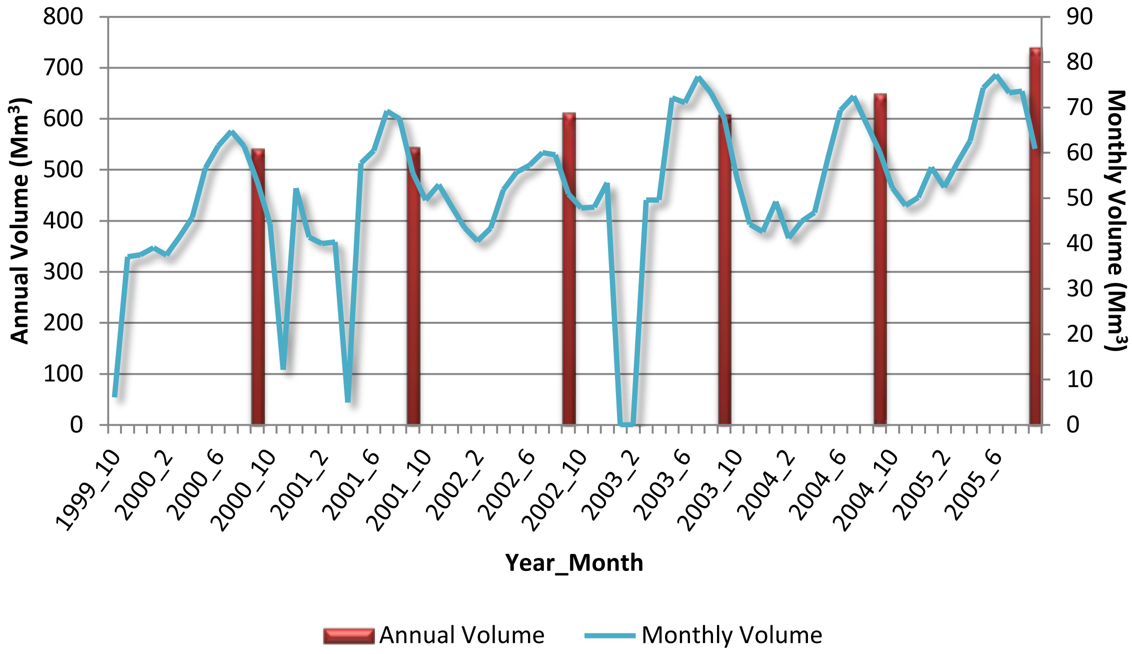


Figure 5.4: Annual & Monthly Volume of Water Transfer for the LHWP

There is a general upward trend in the transfer required in the UVRB from LHWP. This confers with the growing demands and decreased yield in the natural system.

b) Thukela – Vaal Transfer

The Thukela – Vaal Transfer Scheme transfers water from Woodstock Dam via Driel Barrage into Sterkfontein Dam. This IBT forms a major component of the 'Bloemhof Sub System', which is the collective operation of four large dams namely Bloemhof in the Middle Vaal WMA, Vaal and Sterkfontein Dams in UVRB and Woodstock Dam in Upper Thukela WMA. From records, this system has been operating mainly for generation of power, and has not been augmenting water supply to the UVRB during the period of simulation. Therefore, it has been excluded from the analyses.

c) Heyshope – Grootdraai Transfer

Heyshope dam, located on Assegaai River which is a tributary of Usutu River, supplies water to the 'Grootdraai Sub System' mainly for minor augmentation. The Grootdraai Sub System is formed by the Grootdraai Dam and mainly supplies the Industrial demands such as the Electricity Supply Commission (ESKOM) and South African Coal, Oil and Gas Corporation (SASOL).

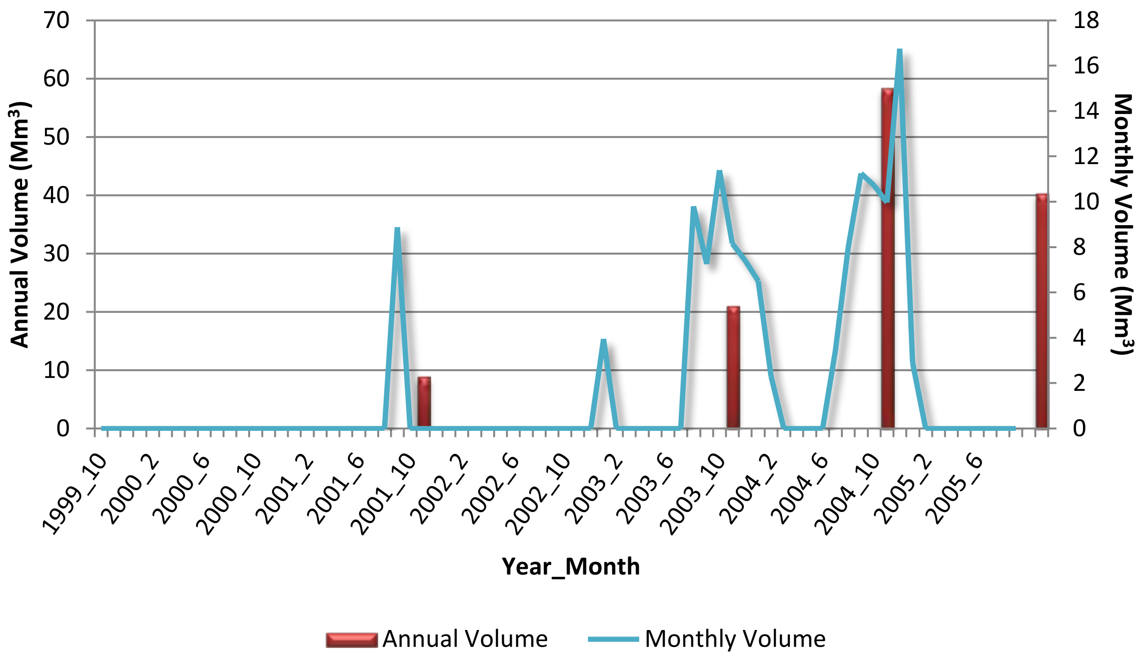


Figure 5.5: Annual & Monthly Volume of Water Transfer for Heyshope - Grootdraai System

d) Zaaihoek – Grootdraai Transfer

The Zaaihoek Dam is located on the Slang River which is a tributary of the Buffalo River in the Thukela Basin. The main purpose of this transfer is to meet the water requirements of Majuba Power Station. Support to the Grootdraai Dam is a secondary priority. Therefore, the transfers to Grootdraai Dam decrease over time to cater for the increasing water requirements of Majuba Power Station.

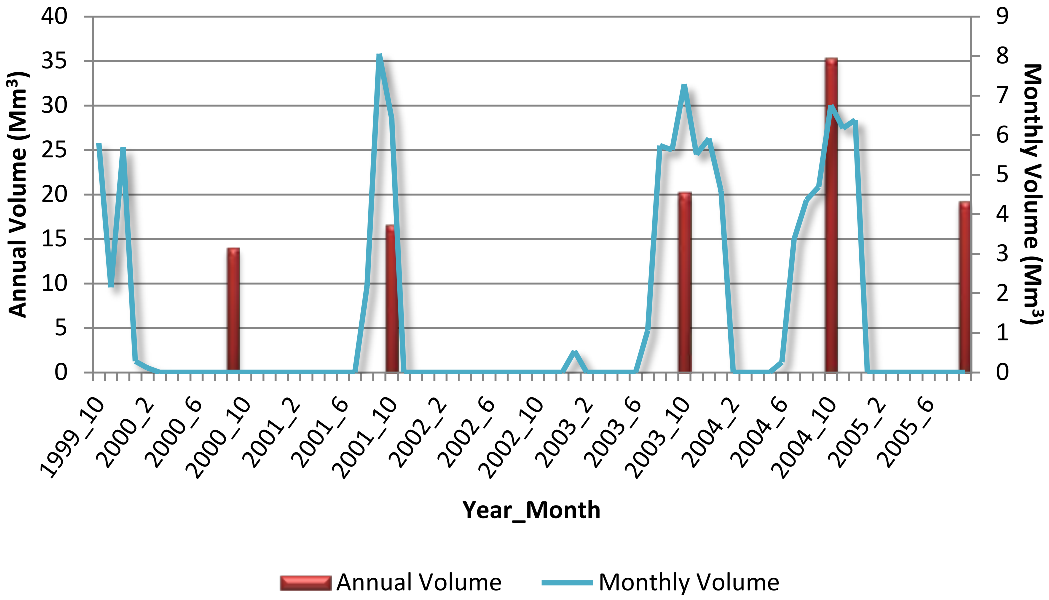


Figure 5.6: Annual & Monthly Volume of Water Transfer for Zaaihoek - Grootdraai System

e) Grootdraai – Vlakfontein Transfer

Water is transferred from Grootdraai Dam to Trichardsfontein Dam to partly supply the water requirements of SASOL. In addition, part of the water requirements for ESKOM's Kendal, Kriel, Matla and Duvha Power Stations is also met from this transfer.

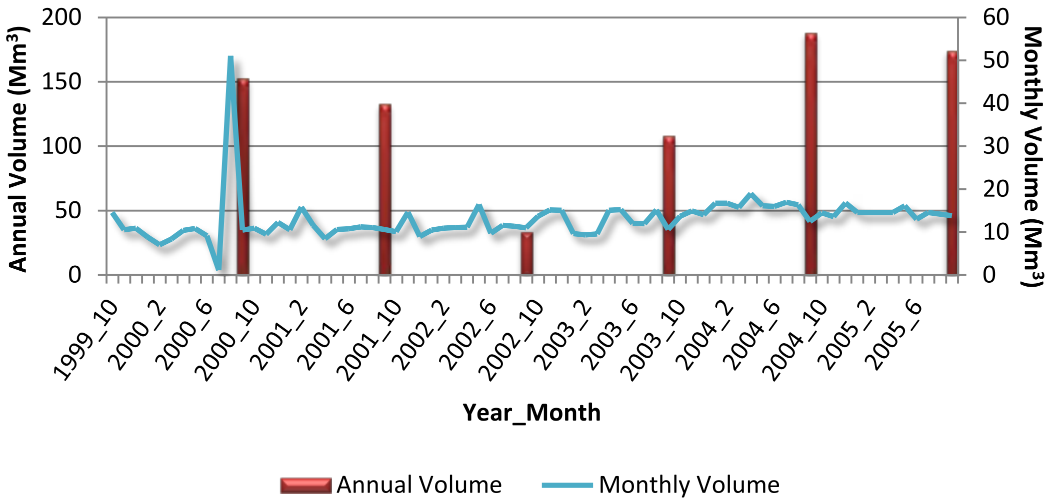


Figure 5.7: Annual & Monthly Volume of Water Transfer for Grootdraai - Vlakfontein System

5.2.2.3. Operation of the Integrated Vaal River System

The Integrated Vaal River System (IVRS) comprises of the aforementioned Lower Vaal, Bloemhof, Senqu, Heyshope, Zaaihoek, Grootdraai, Usutu, Komati, Witbank and Middelburg sub systems. These sub systems are located in the adjacent basins of the UVRB. The first two sub systems and the last four sub systems mentioned above have not been discussed. As a brief overview, the Lower Vaal sub system is dependent on Bloemhof for its water which in turn is supplied from the UVRB as compensation release. The Bloemhof sub system on the other hand comprises of the Bloemhof, Vaal and Sterkfontein Dams which are operated collectively. The driver of this system is the storage in Vaal Dam which if falls to the minimum operating level triggers release from Sterkfontein Dam. Another instance of release would be if Sterkfontein Dam is full and there is still water available in Woodstock Dam for transfer.

The Usutu, Komati, Witbank and Middelburg sub systems work collectively to transfer water to UVRB (Usutu and Komati) and from UVRB (Witbank and Middleburg) via the Zaaihoek and Heyshope and Grootdraai sub systems respectively. These sub systems are also collectively known as the 'Vaal River Eastern Sub-system' (VRES).

The modelling of all the sub systems was beyond the scope of this Study because it requires setting up of the hydrology of four different basins. Therefore, the inflow from each sub system into UVRB has been obtained and input into the model as monthly volumes, thus representing the collective functioning of the various sub systems.

5.2.3. Water Demand

The UVRB, together with the adjacent WMAs which form the IVRS, is responsible for providing water to the most populated and economically important regions in the country. These developments include numerous power stations, gold, coal and platinum mines, the petrochemical industry and most importantly agriculture. Bulk water supply in the Vaal River System (VRS) is mainly the responsibility of three water service providers. These are Rand Water which focuses on the UVRB and part of neighbouring Crocodile Basin, Sedibeng and Midvaal Water Companies which supply water to Middle and Lower Vaal. The service area of Rand Water is given in Figure 5.8. Water is mainly abstracted from the Vaal Dam and Vaal Barrage.

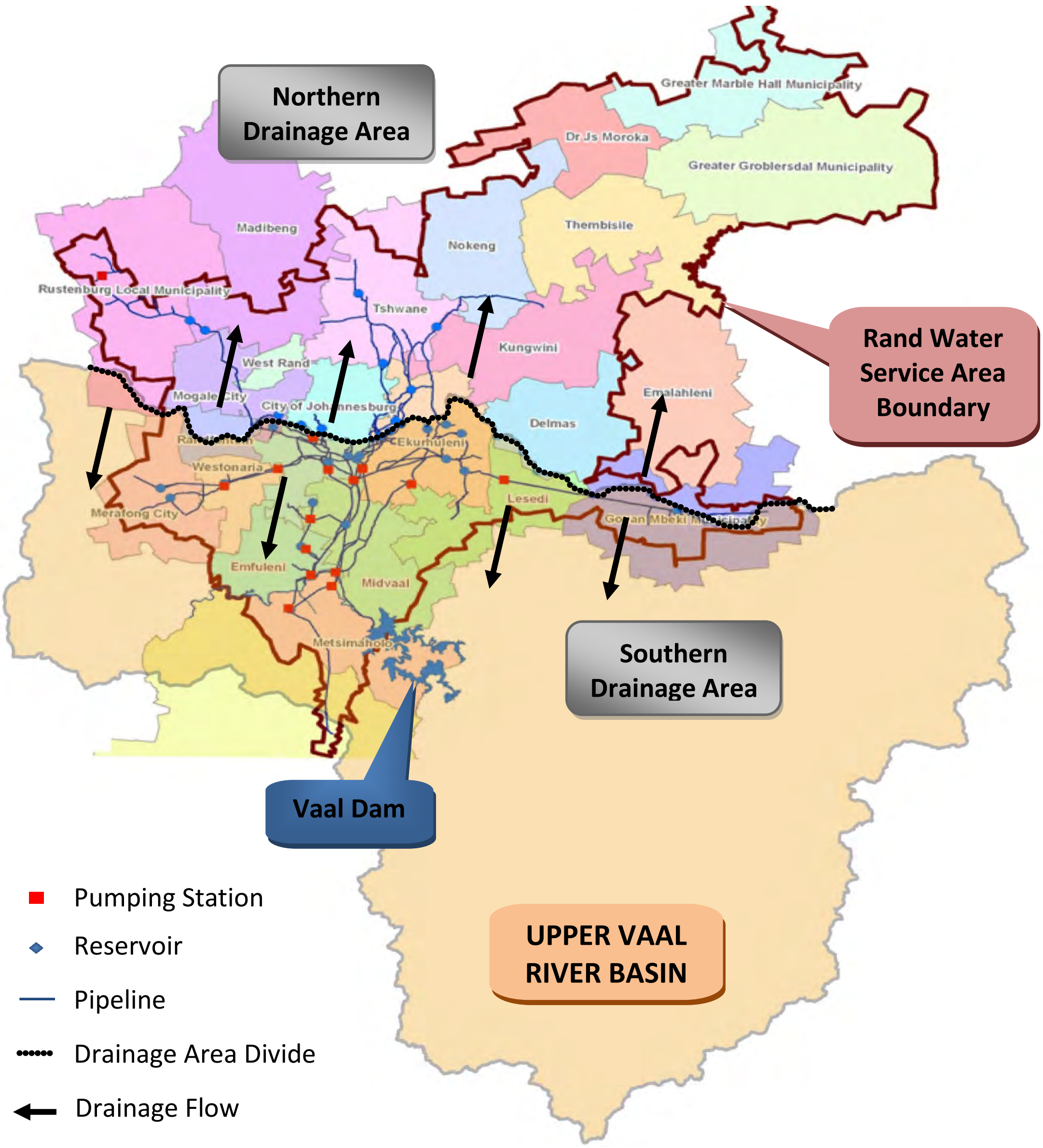


Figure 5.8: Service Area of Rand Water and its Drainage Divide

(The Rand Water Area map was downloaded from their website and geo-referenced with the UVRB Boundary)

In recognisance of its importance, the DWEA had commissioned an extensive update on the water demands in the entire Vaal River System (VRS) covering the urban, industrial and agricultural categories up to the year 2030. This update, completed in year 2006, is a suite of reports collectively called the "**Vaal River System: Large Bulk Water Supply Reconciliation Strategy**" and is the latest available information on water demands in the VRS. These reports will henceforth be referred to as the **Reconciliation Strategy**. The different aspects of water demand, re-use option, potential savings and groundwater assessment have been presented in individual reports given in Table 5.5.

Table 5.5: List of Reports in the Reconciliation Strategy

	Report Number	Title
1)	**P RSA C000/00/4405/01**	Urban Water Requirements and Return Flows
2)	**P RSA C000/00/4405/02**	Potential Savings Through WC/WDM In The Upper And Middle Vaal Water Management Areas
3)	**P RSA C000/00/4405/03**	Re-Use Options
4)	**P RSA C000/00/4405/04**	Irrigation Water Use And Return Flows
5)	**P RSA C000/00/4405/05***	Water Resource Analysis
6)	**P RSA C000/00/4405/06**	Dolomite Groundwater Assessment
7)	**P RSA C000/00/4405/07**	First Stage Reconciliation Strategy

* This Report was not available at the time of this Study

Therefore, this Study has adopted the findings from the Reconciliation Strategy and the results form the basis for water demand data applied in setting up the Water Allocation Module in WEAP.

The water consumers in the UVRB have been categorised into four main groups namely Urban, Industrial, Agricultural and Rural each of which is explained in further detail in the following sections.

5.2.3.1. Urban and Rural Demand

The urban water demand in the UVRB was collated from Reports 1 and 7 (Table 5.5) which document the extensive methodology used to calculate the present and future demands to the year 2030. As a first step, all the urban consumers in the Reconciliation Strategy have been divided into four groups. These are:

a) Large metros/ Municipalities supplied by Rand Water. These are Ekurhuleni, Johannesburg, Emfuleni, Randfontein, Tshwane, Mogale, Govan Mbeki and Rustenburg.
b) Other water users supplied by Rand Water which include smaller municipalities, individual users and mines
c) Water users supplied by Sedibeng Water or Midvaal Water Companies such as Matjhabeng Municipality. These users are located outside the UVRB hence not considered in this Study.
d) Smaller urban water users not covered in the above three groups

Secondly, since the major urbanised regions supplied from the VRS do not entirely drain in the Vaal Basin, the study area in the Reconciliation Strategy was split into two parts. The first one covers the areas draining into the Crocodile (West) River Catchment and is referred to as the northern DA. The second part covers the areas draining into the Vaal River System and referred to as the southern DA. The significance of this divide is that the return flows from the northern DA are discharged into the Crocodile River Catchment whilst those from the southern DA are discharged back into the VRS. Reference is made to Figure 5.8 for the description of the divide.

The foundation of the water demand calculation is the Sewage Drainage Area (SDA) serviced by a Sewage Treatment Works (STW). The study area was sub divided along the boundaries of the

SDAs. Population projections were input in the Urban Return Flow Model (URFM) for each SDA, together with the different housing categories to reflect the level of urbanisation and consequently the per capita demands. It was noted that the rural population was included represented by informal housing served by communal taps, Rural Development Houses (RDP)/ shanties with a water connection and dwellings with no piped water supply. In addition, water losses in the houses, the distribution system and STWs were also included. Return flow volumes were also accommodated based on percentages of the supplied water volumes.

Two main population base scenarios were derived namely the ‘National Water Resource Strategy’ (NWRS) and ‘August 2006’. Both scenarios are estimates of population carried out using the Census 2001, but the latter used a different approach thus having a slightly higher projection than the NWRS with a compounded growth factor of 1.66%. The NWRS and August 2006 scenarios are referred to as Scenario A and B respectively. For the other scenarios implementing WC/ WDM measures (Scenarios C, D and E), Scenario B was used as the base scenario**. Therefore, Scenario B has been adopted in this Study to represent the current and future status of water abstractions in the UVRB.** Another reason for this choice is that this scenario represents the worse-case scenario for the UVRB. For completeness, the different scenarios and their characteristics are outlined in Table 5.6.

All the aforementioned data was thereafter input in the URFM to derive five possible future water demands and return flow scenarios based on different source population data available and also on possible implementation of water conservation and water demand management (WC/WDM) strategies. This model was then calibrated for the year 2001 against population census data, supplied water volumes obtained from Rand Water and influent volumes (return flows) at the STWs.

Table 5.6: Different Population Growth Scenarios and WC/ WDM Implementation Measures

Scenario	Population Growth	WC/ WDM: Reduction in wastage in years from Implementation Date	WC/ WDM: Improved Delivery Efficiency in years from Implementation Date
A	National Water Resource Strategy	None	None
B*	August 2006	None	None
C	August 2006	5	10
D	August 2006	5	None
E	August 2006	10	None

*Scenario used in this Study

Figure 5.9 shows the water demands of the urban consumers supplied by Rand Water including the smaller municipalities and individual users for the present-day simulation period.

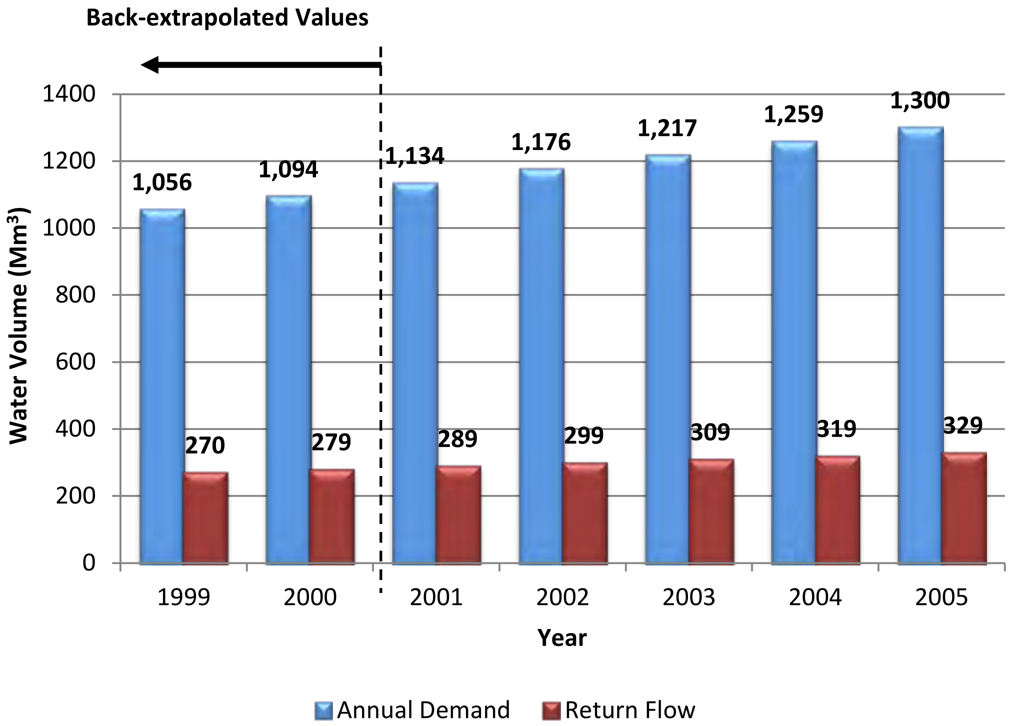


Figure 5.9: Urban Water Demand and Return Flows for Scenario B
(Extracted from DWAF (2007a))

For the regions which are not supplies by Rand Water, water demands were available separately under the ‘others users’ category. This included the smaller towns like Bethlehem, Deneysville, Frankfort, Harrismith, Memel and others. However, return flows were only available for some of the smaller towns for which demands had been calculated. Therefore, another data source called the Water Situation Assessment Model (WSAM) was used. The WSAM is a DSS database which has *inter alia* data on water demands and return flows but only for the year 1995 and is available from DWEA. Therefore, percentages of return flows for the towns for which no data was available in the Reconciliation Strategy were calculated based on the 1995 figures and applied as a constant for this Study.

Since the URFM was calibrated for the year 2001, and this Study begins in October 1999, back extrapolation was carried using demand growth rates for the period 2001-2005 to obtain the annual volume for year 1999 and 2000 (see Figure 5.9). In addition, annual water demand data is available in the Reconciliation Strategy, whereas monthly data is required for the WEAP model. To overcome this dilemma, the monthly variation in consumption was required to estimate monthly volumes from the annual figures. For this reason, readily available monthly bulk water supply volume records for a period of 6 years beginning January 2002 from Sedibeng Water Company (responsible for Middle Vaal) were thus used. It was assumed that the consumption patterns in the different service areas would not vary much from each. This bulk supply data were obtained having been grouped into Big Municipalities, Small Municipalities and Mines. Therefore, monthly variation factors were derived based on a 6-year average of the monthly bulk supply to big and small municipalities expressed as a percentage of the average total annual volume. In addition, the model is setup on the hydrological year. Therefore, the calculated monthly volumes were rearranged accordingly to obtain annual volumes beginning October 1999. Figure 5.10 shows the assumed monthly trend in consumption.

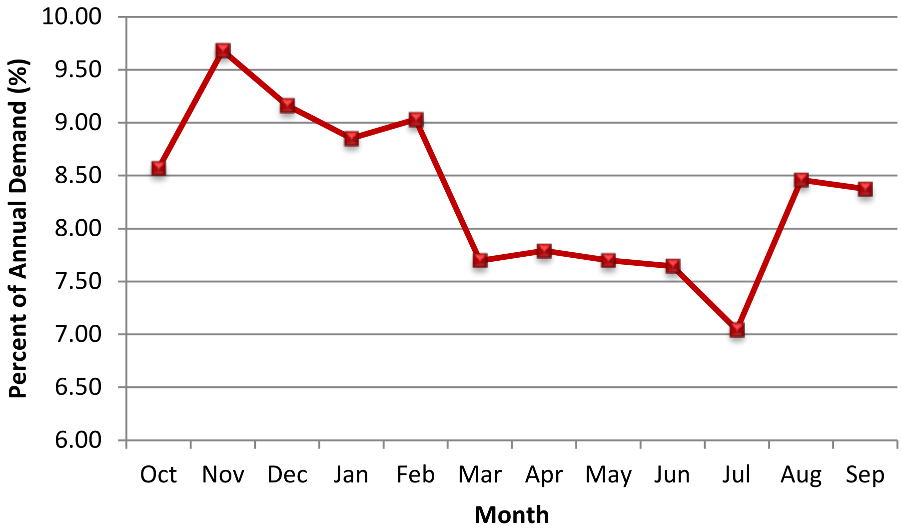


Figure 5.10: Monthly Variation (%) of Annual Urban Demand

The annual return flows for the southern DA were expressed as percentages of respective annual demands and it was observed that it ranged from 25.5% in year 2001 to 26.0% in year 2030. The intermediate annual return flow values were linearly (extra) interpolated and input in the model.

Reference is made to Report No 1 in Table 5.5 for an in depth explanation of the methodology used in the Reconciliation Strategy in developing the different demand scenarios.

5.2.3.2. <u>Industrial Demand</u>

There are three main industries which receive their water supply from the VRS namely ESKOM, SASOL and Mittal Steel. The present and projected water demands for these industries were obtained directly from them under the Reconciliation Strategy, based on their respective operations and management strategies.

Similar to the urban category, only annual volumes were available. Therefore, the same treatment outlined earlier for deriving monthly values was applied to the different consumer data in this category. In this case however, the average of monthly variation factors for Municipalities and Mines were used. These are given in Figure 5.11.

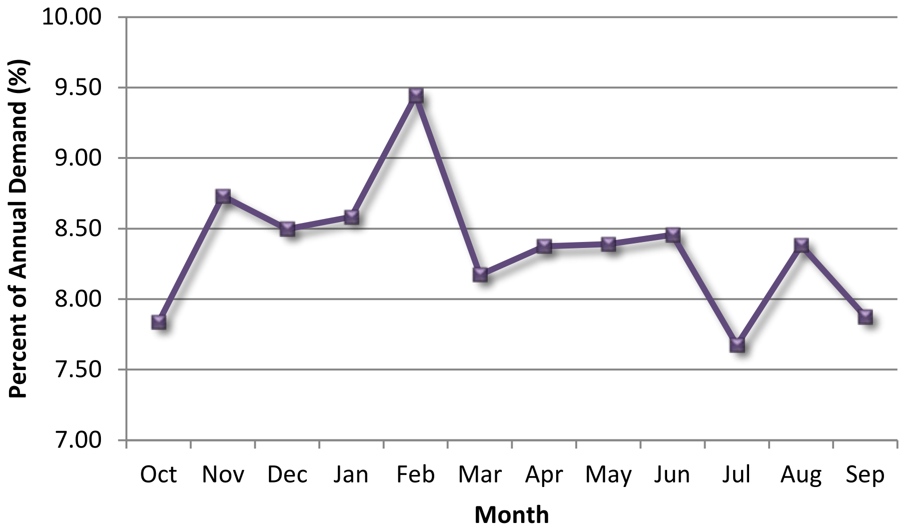


Figure 5.11: Monthly Variation (%) of Annual Industrial Demand

Water requirement volumes were available beginning year 2006 in the Reconciliation Strategy, therefore, the growth rates between years 2006 and 2010 for consumer category was used to linearly back extrapolate the intermediate years to the year 1999.

a) ESKOM

ESKOM currently has 12 coal fired electrical power stations which rely on the IVRS for their water supply. In addition, 3 more stations are planned to be commissioned in year 2010 onwards to meet the growing demands for energy, 2 of which will receive water from the Vaal Dam and the third from the VRES. Figure 5.12 shows the present water demands for individual and total annual demand for the power stations for the simulation period.

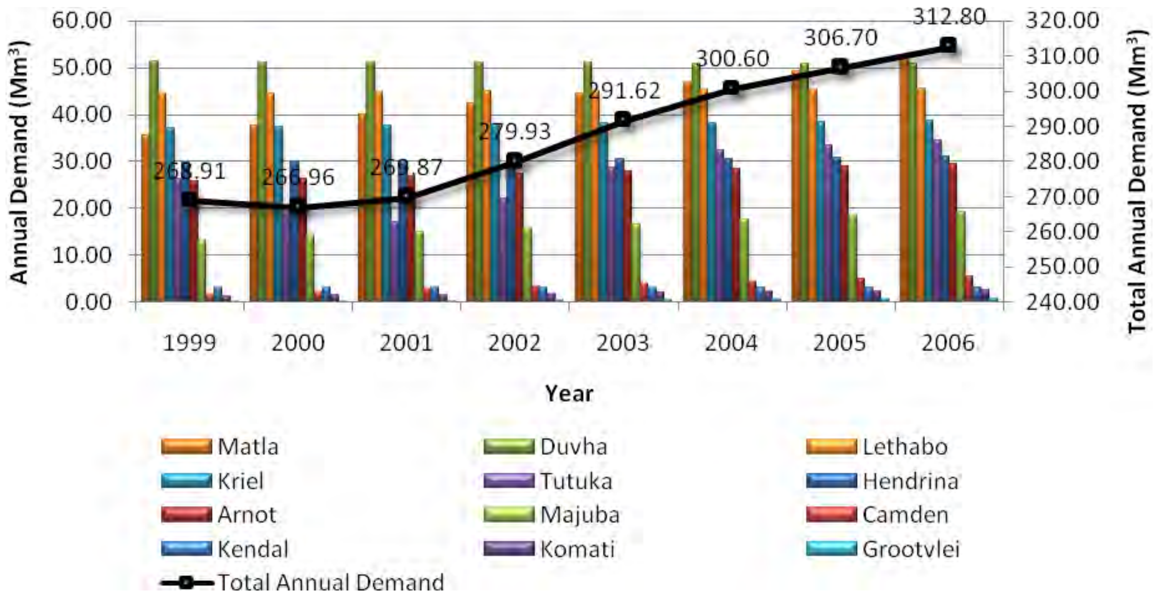


Figure 5.12: Annual Water Demand of Individual Power Stations and Total Annual Demand (Extracted from DWAF (2006))

However, not all the above stations directly receive their water from the UVRB. The only stations directly dependent on the UVRB are Tutuka, Grootvlei, Lethabo and two of the proposed new stations. As for Kriel, Matla, Kendal, Camden and one proposed station, they receive a major portion of their demand from the Usutu Sub-system, whereas Majuba is supplied from the Zaaihoek Sub-system. It should be noted that these stations also have a provision to be supplied from the UVRB via the Grootdraai Sub-system.

Therefore, in this study all of the aforementioned stations depending directly or indirectly on the UVRB have been included in the model. The water transfer from Grootdraai to Vlakfontein (see Section 5.2.2.2 e)) caters for augmenting water supply for the stations indirectly dependent on the UVRB.

b) SASOL

Two plants namely Secunda and Sasolburg Complexes are mainly served by the VRS via the Grootdraai and Vaal Dams respectively. The present water requirements are given in Figure 5.13.

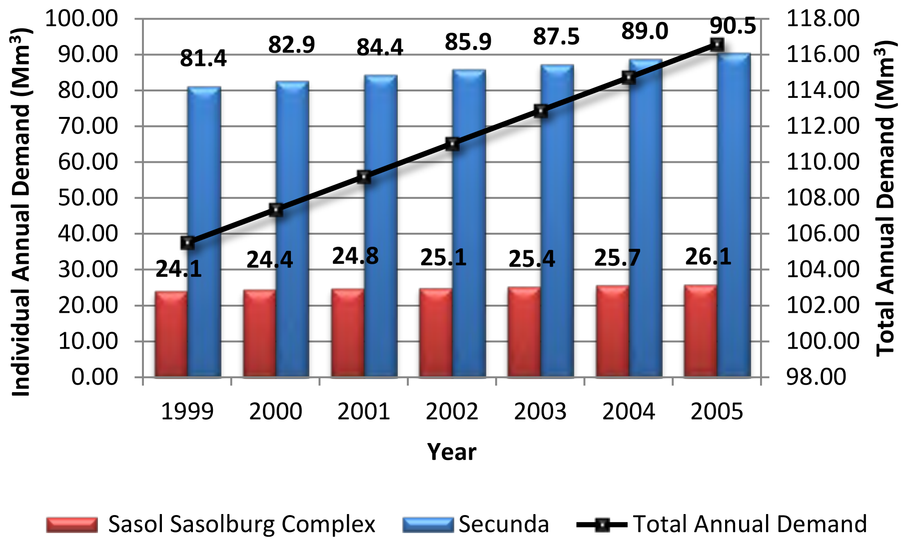


Figure 5.13: Annual Water Demands for SASOL
(Extracted from DWAF (2006))

Data on the transfer volumes from Grootdraai to Sasol Secunda complex was obtained from DWEA and compared with the demand volumes shown in Figure 5.13. It was observed that the transfer volumes were much higher. It was thus assumed that the transfer pipeline is also used for supply to en-route consumers. Considering that SASOL’s demand remains constant throughout the year because of its nature of production, the difference between the transfer volume and SASOL’s annual demand was calculated and expressed as a percentage of the transfer volume for each year. This value was then input in WEAP as an additional demand growing at the same rate as Rand Water’s supplied volume.

c) Mittal Steel

Mittal Steel receives its water from Vaal Dam and its projections are set to decrease from the current annual consumption of 17.4 million m^3 to 16.6 million m^3 in 2010 and remaining constant onwards till year 2030. Figure 5.14 gives the water requirements for this consumer.

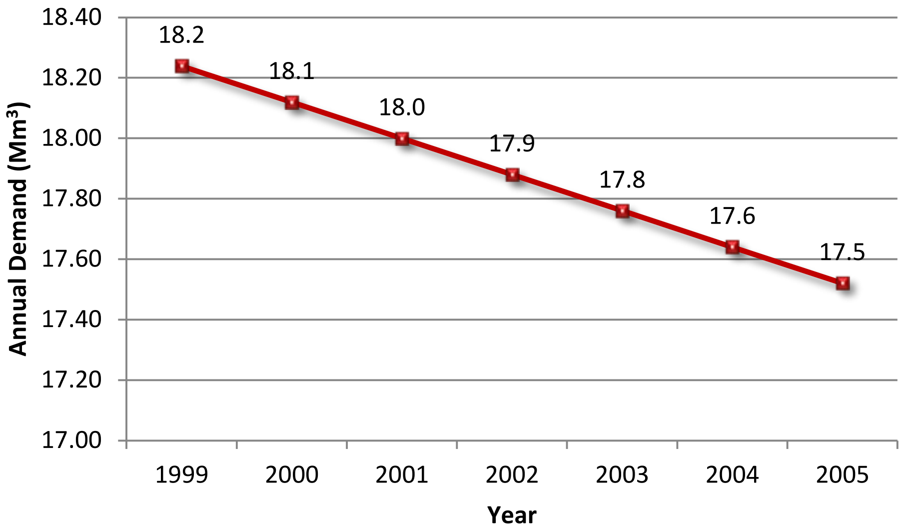


Figure 5.14: Present Water Requirements for Mittal Steel
(Extracted from DWAF (2006))

5.2.3.3. <u>Irrigational Demand</u>

According to DWAF (2006), irrigation water requirements constitute approximately 35% of the total water use in the VRS. The approach of calculating this sector's demand taken in the Reconciliation Strategy involved dividing the UVRB into two regions, one being upstream of the Vaal Dam and the other being downstream of the dam. In addition, the QC's in the respective 2 regions were clustered into a total of 13 sub catchments and irrigation demands computed for each. Figure 5.15 shows the 13 sub catchments used for computation of irrigational water demand.

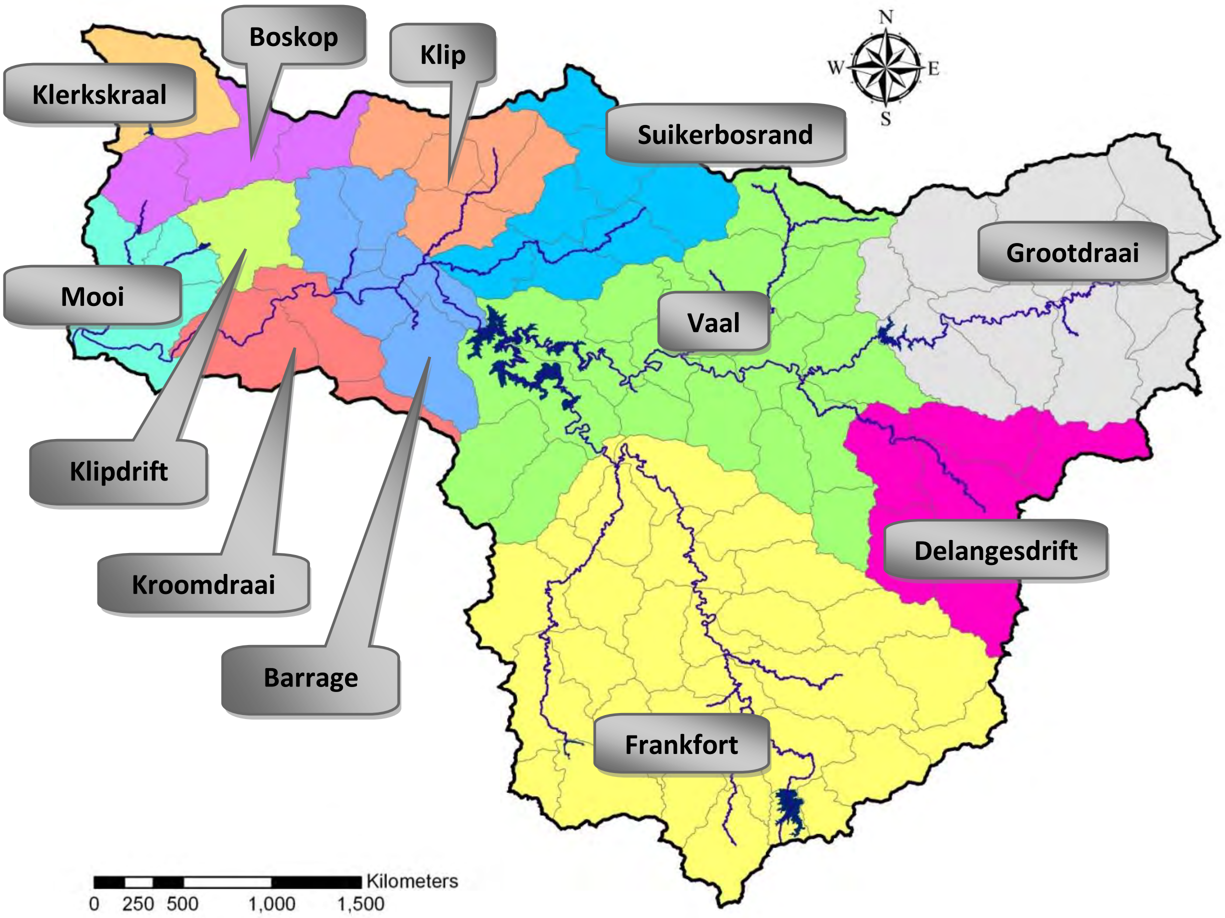


Figure 5.15: Sub-catchments defined for Computation of Irrigation Requirements

There has been a series of studies carried out for the determination of irrigational demand in the VRS. The earliest was in year 1999 called the Vaal River Analysis Update Study (VRSAU). This was followed by the Vaal River Irrigation Study carried out by Loxton Venn. Lastly, the Validation Study for the UVRB is currently ongoing and its preliminary results have also been included in the Reconciliation Strategy. Despite being under progress, a large part of the collected data had been processed thus given with confidence.

The results from the Validation Study have been adopted to represent the present conditions regarding irrigation water use in the UVRB. Annual water requirements have been given for the year 1998 and 2005 only. Therefore, linear interpolation was applied to determine the annual demands for intermediate years. The monthly variation of the annual demand was based on the monthly crop water requirements given in DWAF (2007b) for Mooi Irrigation Scheme which covers the Klerkskraal, Boskop and Mooi Sub-catchments (see Figure 5.15). The monthly crop requirement volumes were not used, but were expressed as a percentage of the annual volume. These percentages were then used as the monthly factors applied to the annual irrigation requirements.

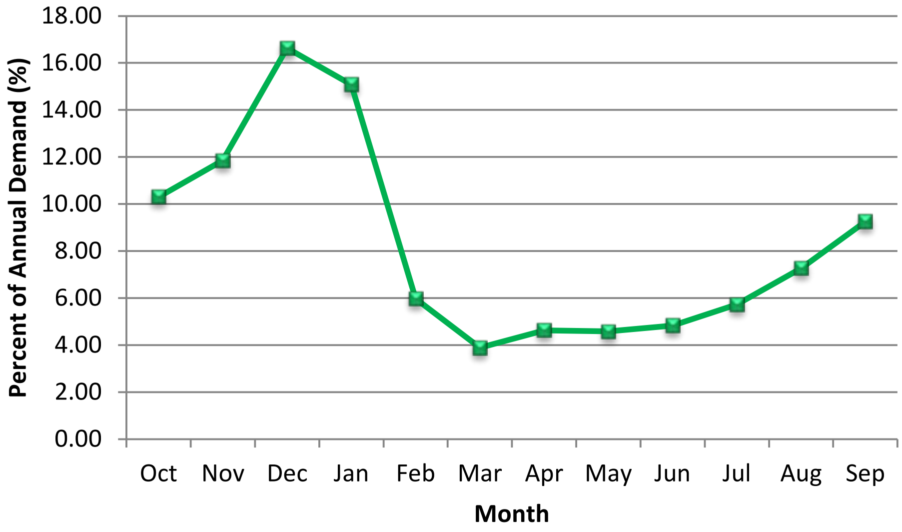


Figure 5.16: Monthly Variation (%) of Annual Irrigational Demand

The demand data extracted from DWAF (2006) are presented in Figure 5.17. Irrigation water use increased by more than 100% between the years 1998 and 2005 for the area upstream of Vaal Dam mainly in the Frankfort sub-catchment. The lawful estimate is therefore the abstraction volume of water which has been legally applied for. This estimate has been used as a basis for future scenarios and its use will be explained in Chapter 6.

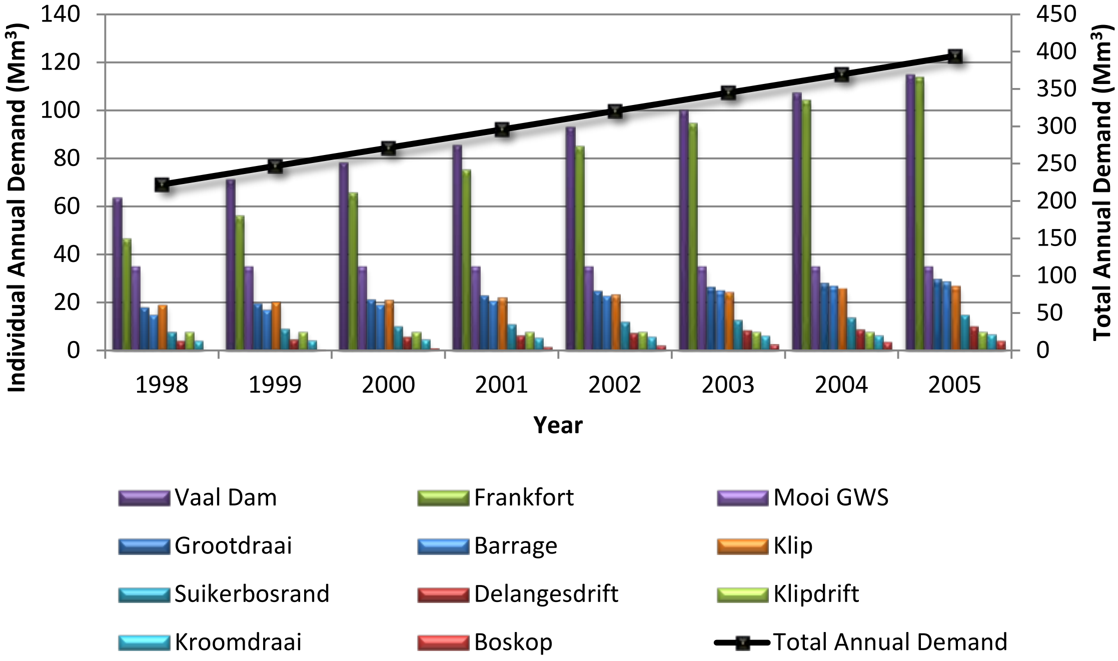


Figure 5.17: Sub-catchment and Total Annual Irrigation Water Requirements (Extracted from DWAF (2006))

5.3. Simulation Results

WEAP has the ability to model reservoir characteristics like storage and evaporation. Therefore, in addition to the stream flow simulation, results of evaporation and storage for the major dams as modelled by WEAP are also presented. Figure 5.18 gives the schematic of the WEAP setup for the present day simulation.

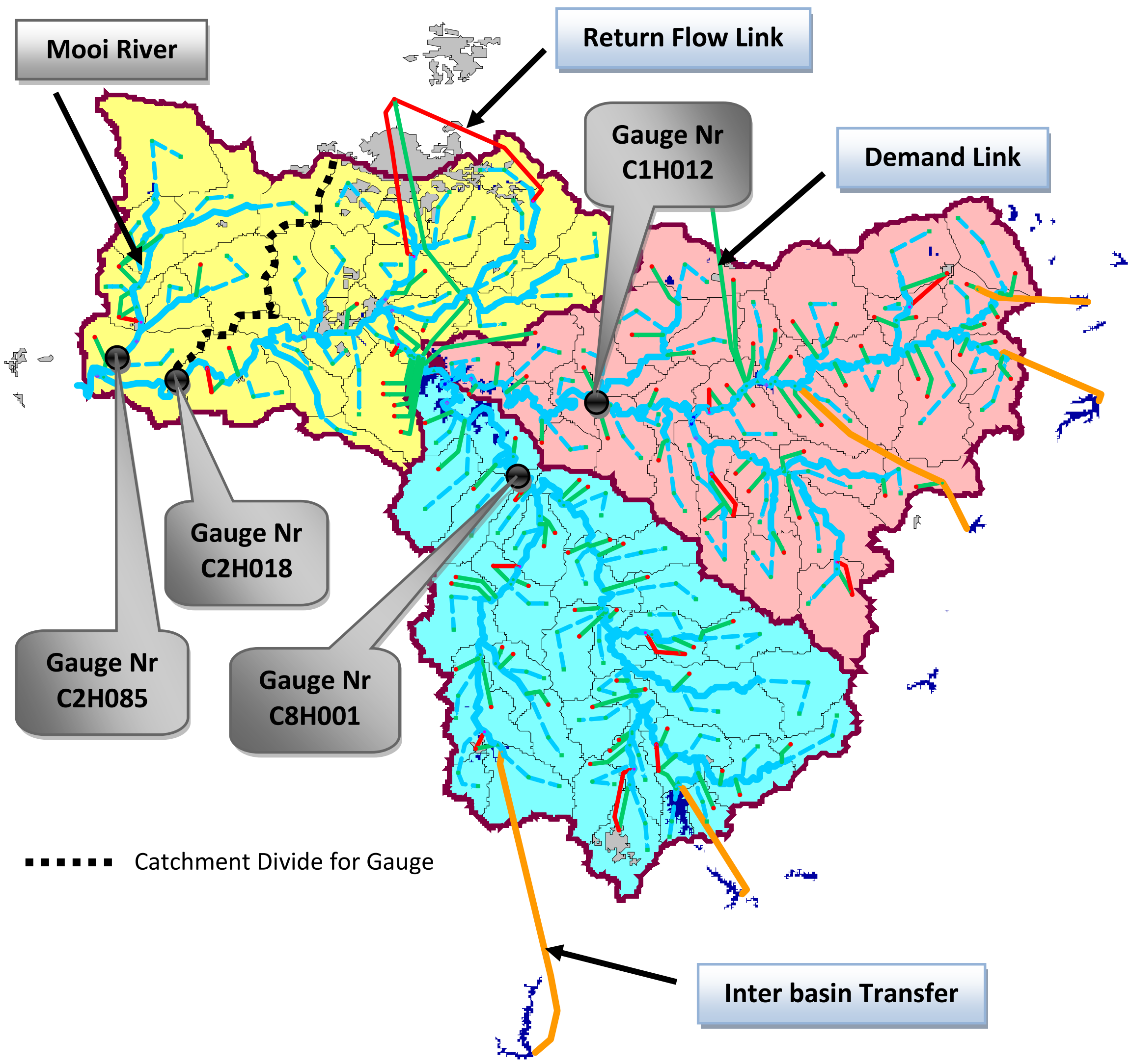


Figure 5.18: Schematic of Present Day Setup of the UVRB in WEAP

5.3.1. Reservoir Simulation

There are two main reservoir parameters which can be used to assess how the model simulates the reservoir operation namely reservoir storage volume and evaporation. These are discussed in the following sections.

5.3.1.1. Net Evaporation

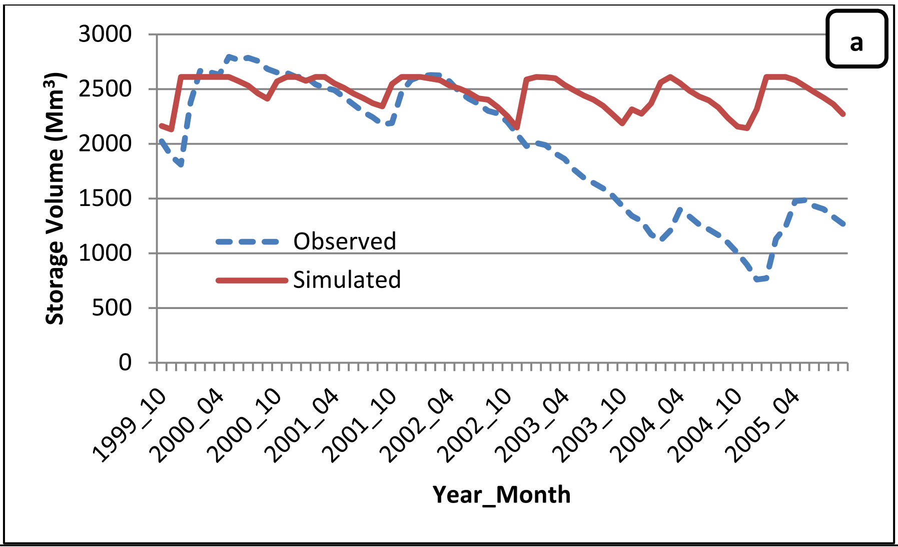
Simulation of reservoir evaporation was poor with the use of initially derived monthly evaporation values (see Section 5.2.2.1 c)). Therefore, an adjustment factor was applied to the monthly values and model simulation assessed using the total evaporation over the validation period, means, standard deviation and coefficient of determination. The optimum adjustment factors and the statistical parameters are given in Table 5.7.

Table 5.7: Adjustment Factor and Descriptive Statistics for Observed and Simulated Net Evaporation

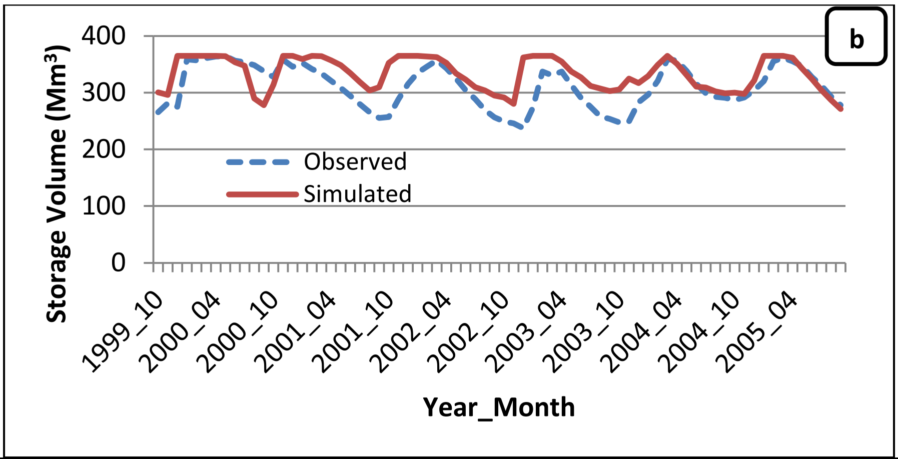
Dam	Evaporation Adj. Factor	Assessment Criterion						
		Total Evaporation (Mm^3)		Mean (Mm^3)		Standard Deviation		R^2
		Obs	Sim	Obs	Sim	Obs	Sim	
Vaal	0.7	1559.9	1595.67	17.79	22.16	12.44	10.37	0.400
Grootdraai	0.7	176.74	172.93	2.45	2.40	1.78	1.41	0.446
Saulspoort	0.75	17.05	17.04	0.24	0.24	0.21	0.15	0.617
Klerkskraal	0.7	20.69	21.47	0.29	0.30	0.18	0.13	0.273
Boskop	0.6	16.73	17.35	0.23	0.24	0.21	0.13	0.390
Potchefstroom	0.75	6.24	5.10	0.09	0.07	0.28	0.03	0.000
Klipdrift	0.65	22.29	22.14	0.31	0.30	0.24	0.17	0.654

5.3.1.2. Storage Volume

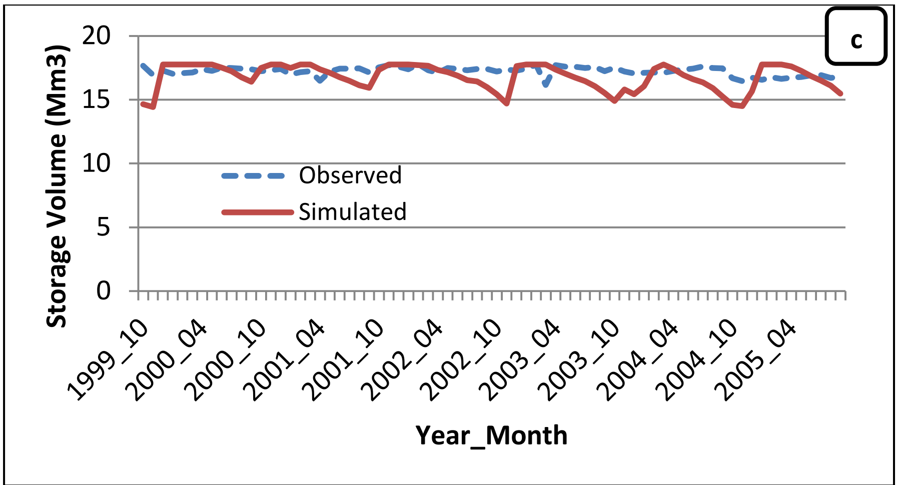
The simulation of dam storage is presented in Figure 5. a – g. From their visual evaluation, it can be seen that there is excess storage in the Vaal Dam from the year 2003 onwards. For this reason, its efficiency statistics reflect a poor agreement between observed and simulated storage. Grootdraai Dam storage has been simulated relatively well. As for the other dams, there are large reservoir draw-downs during the dry seasons.



Vaal Dam

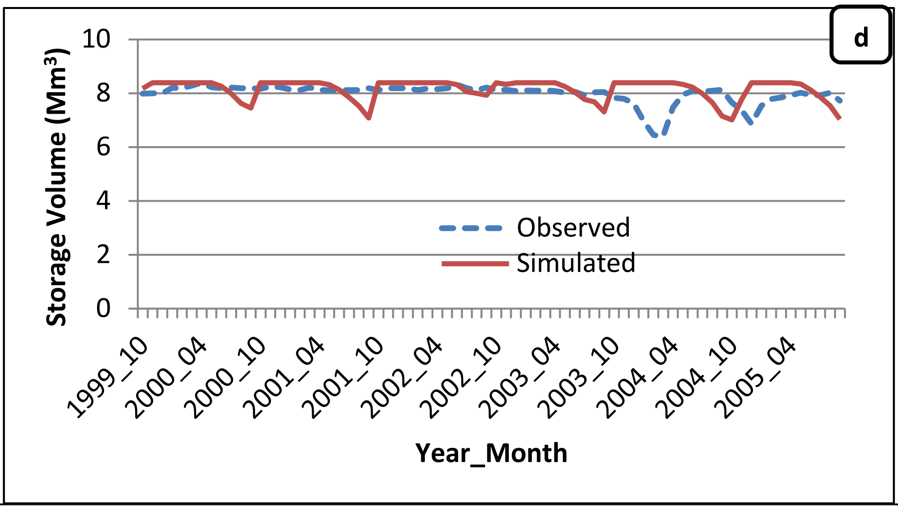


Grootdraai Dam

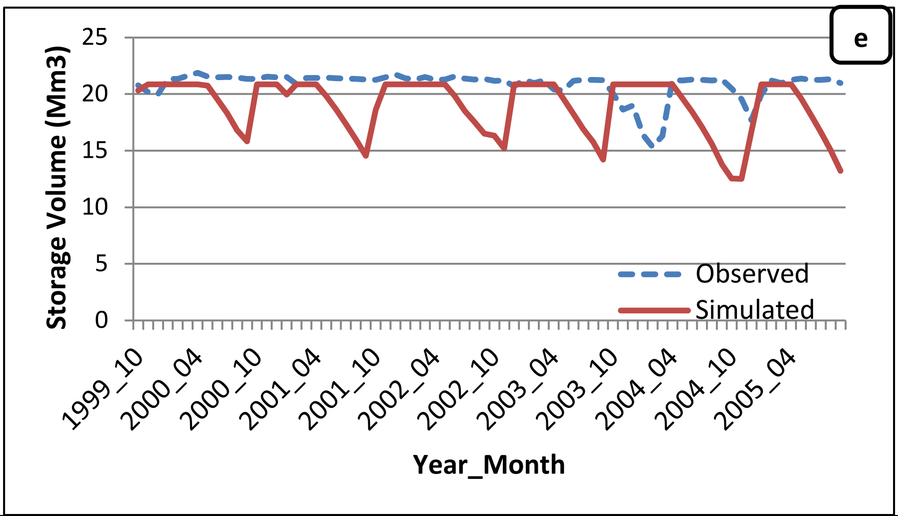


Saulspoort Dam

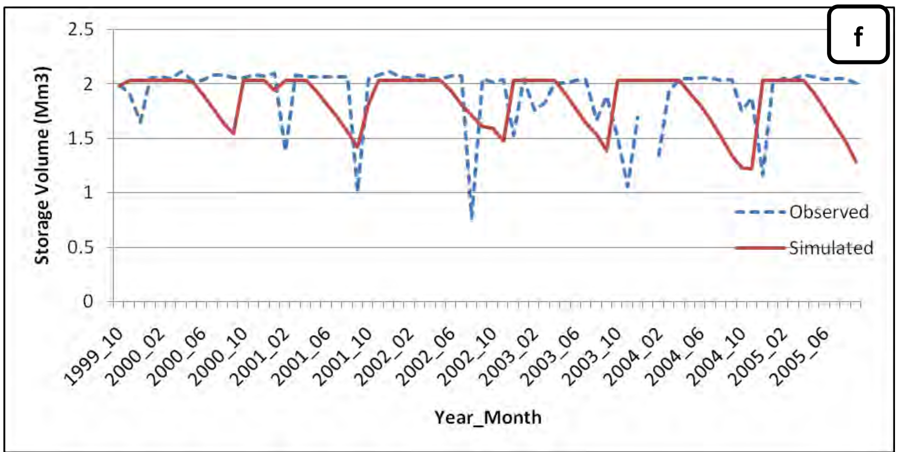
Figure 5.19: Simulation Results Dam Storage



Klerkskraal Dam

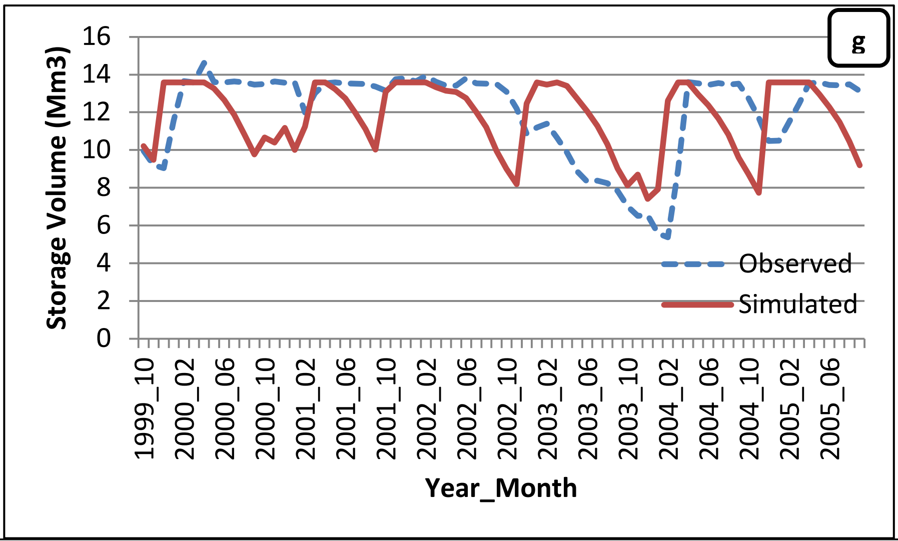


Boskop Dam



Potchefstroom Dam

Figure 5.19: Simulation Results Dam Storage



Klipdrift Dam

Figure 5.19: Simulation Results Dam Storage

Descriptive statistics to assess the simulation for each reservoir is given in Table 5.8.

Table 5.8: Efficiency Criteria Results for Dam Storage Simulation

Dam	RMSE (Mm^3)	MAE (Mm^3)	Coefficient of Determination		
			R^2	Slope (m)	y-intercept (b)
Vaal	759.72	561.41	0.183	0.103	2264
Grootdraai	38	28	0.362	0.467	188.2
Saulspoort	1.12	0.88	0	-	-
Klerkskraal	0.57	0.41	0	-	-
Boskop	3.42	2.51	0	-	-
Potchefstroom	0.44	0.3	0	-	-
Klipdrift	2.47	1.95	0.1	0.254	8.71

There is general lack of agreement between the observed and modelled storage for the reservoirs except for Grootdraai Dam. This is seen from the poor results of R^2. However, this result was expected because of the complexity of water resource operation in the VRS. As already mentioned, the UVRB does not operate independently of the adjacent basins. All the reservoirs operate as a 'super' system thus modelling each reservoir independently would not give the desired results.

5.3.2. Stream flow Simulation

Ideally, data from a stream gauge located at the outlet of a basin is used to compare the results of simulation with. However, this was not possible in this study because there were no gauges located exactly at the outlets of the Zones. For the case of Zone 1 and 2, the Vaal Dam is located at their outlets. As for Zone 3, there was one gauge positioned slightly downstream of the outlet but did not have data over the simulation period. Therefore, the nearest gauges located upstream of the outlets of Zones 1 and 2 were used (Gauges C1H012 and C8H001 respectively). Comparison for Zone 3 on its own was not possible; therefore it was partially assessed using the gauge on the Mooi River (Gauge Nr. C2H085). Gauge C2H018 was used to assess the cumulative performance of Zones 1 and 2 and part of Zone 3. It should be noted that all the gauges except C2H085 are located at the outlets of their respective QC's thus making its corresponding node in WEAP to be easily determined. C2H085 is located just before the confluence of Mooi and Vaal River which is near the QC outlet. Reference is made to Figure 5.18 for the locations of the gauges. The results of the stream flow simulation are presented in Figure 5. for each gauge.

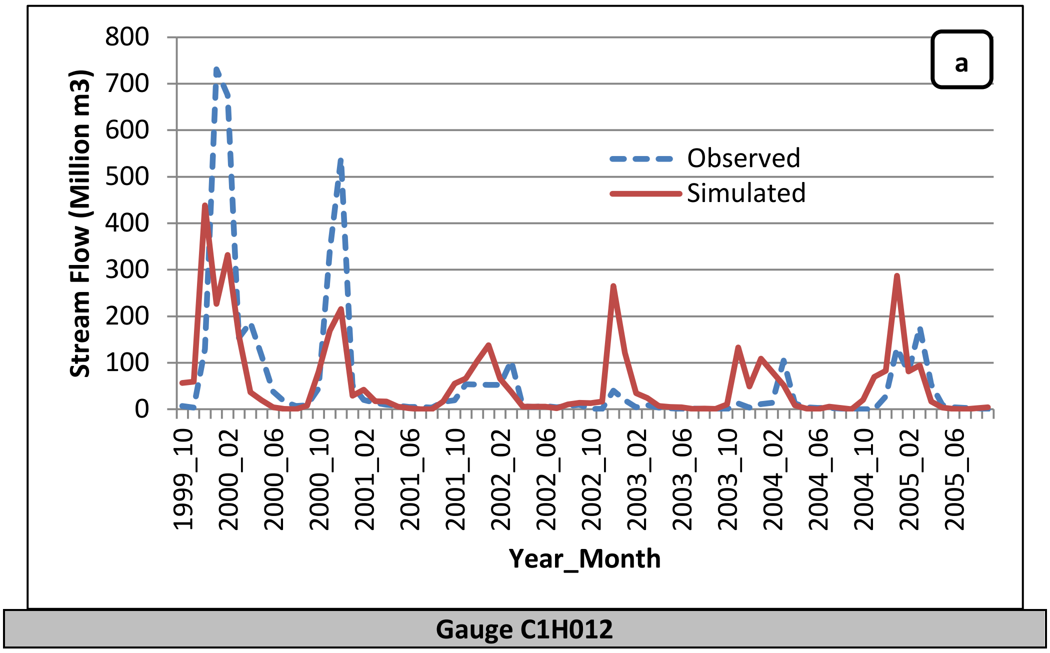
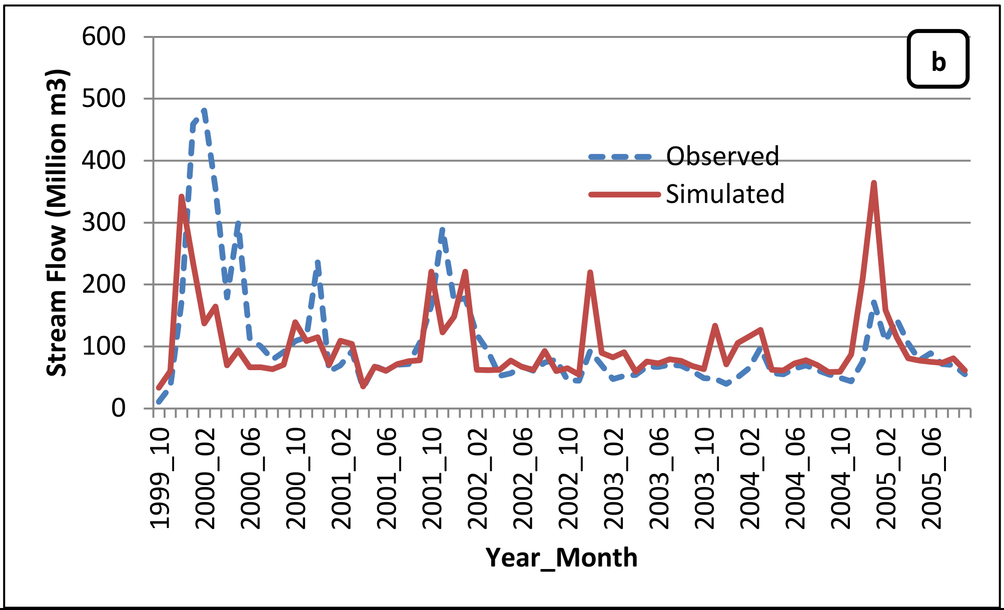
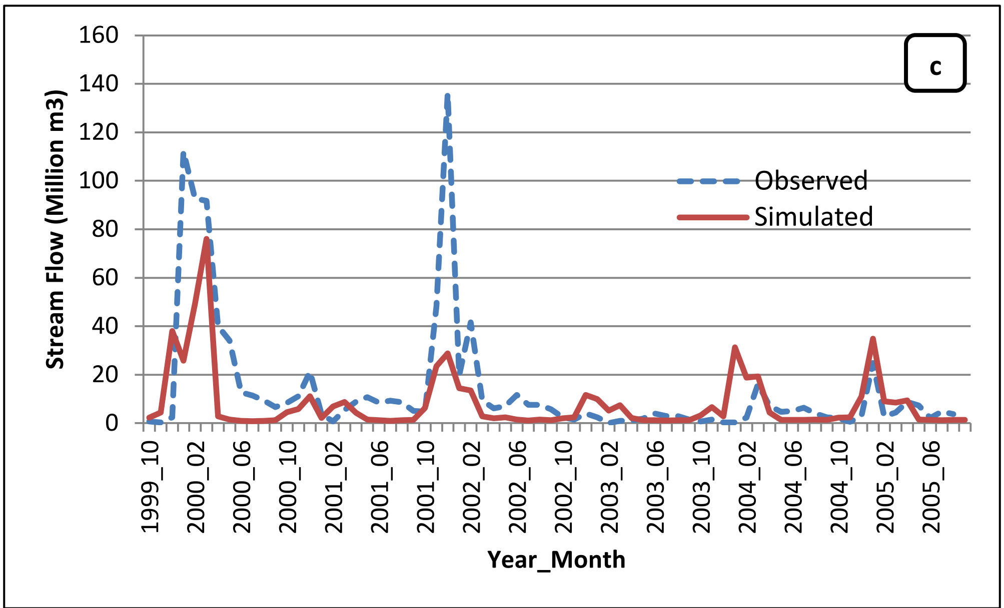


Figure 5.20: Simulation Results for Stream flow

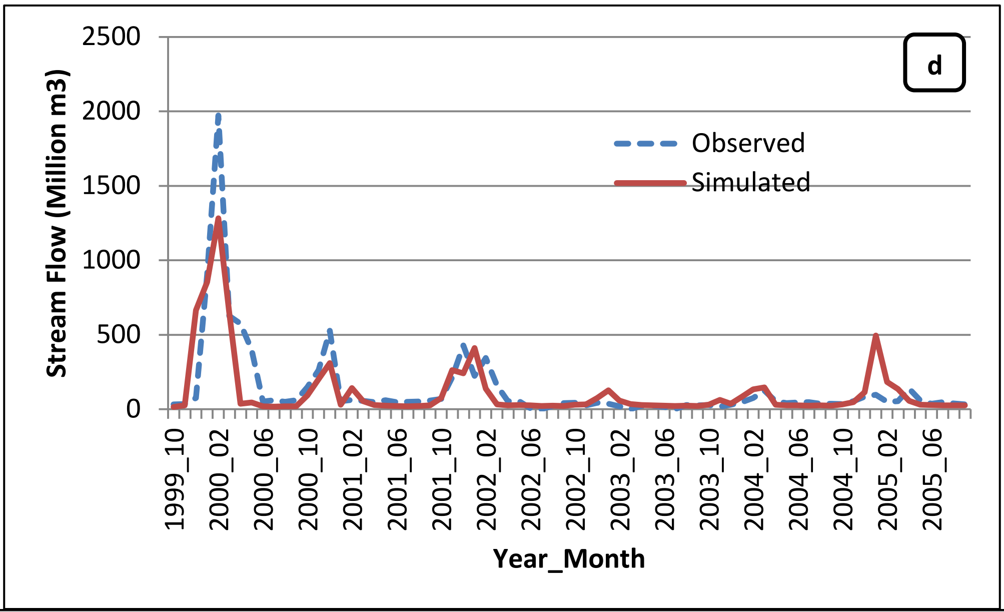


Gauge C8H001



Gauge C2H085

Figure 5.20: Simulation Results for Stream flow



Gauge C2H018

Figure 5.20: Simulation Results for Stream flow

In addition, efficiency criteria outlined and used in Chapter 4 have also been applied for evaluation of the stream flow simulation. A summary of the results is presented in Table 5.9.

Table 5.9: Efficiency Criteria Results for Model Validation

Assessment Criterion	C1H012	C8H001	C2H085	C2H018
Root Mean Square Error RMSE	105.11	78.81	20.13	151.82
Mean Absolute Error MAE	51.40	44.88	10.16	73.00
Coefficient of Determination R^2	**0.405**	**0.237**	**0.431**	**0.693**
• **Slope (m)**	0.399	0.342	0.331	0.646
• **y-intercept (b)**	32.87	64.77	3.59	30.28
Coefficient of Efficiency E	**0.405**	**0.200**	**0.363**	**0.686**
E_j (High Flow Prediction)	0.32	0.203	0.294	0.482
E_{Rel} (Low Flow Prediction)	-*	**0.510**	-	-
Index of Agreement *d*	0.730	0.629	0.675	0.892
d_j (High Flow Prediction)	0.980	0.973	0.791	0.939
d_{Rel} (Low Flow Prediction)	-	**0.784**	-	-

* - the (-) represents a negative value of E and *d*

The model performance is not as good as for the calibration period, with E values ranging from 0.2 to 0.4 for the Zonal performances. However, the basin performs well as a near whole with an E of 0.686. A similar result for R^2 was also obtained. In concurrence with the graphs, E_{Rel} and d_{Rel}

are poor with 3 gauges having negative values. This means that taking the mean of the flows would be a better estimate. Only data from Gauge C8H001 was well reproduced. The model overestimates most of the peaks except for the extremes.

In summary, the model performance is not very good at the zonal scale, but reasonable when considering a larger part of the basin. These results were expected because of the intrinsic uncertainties in modelling the present day situation. WEAP offers a simplified representation of the complex workings of basin hydrology and thus is much easier to model virgin conditions which are much simpler. As for the present day conditions, the system has many 'unknowns' and assumptions had to be made because determining them was beyond the scope of this Study. Some of the possible reasons to explain the performance are given as follows:

a) The derivation of RRF based on land use changes may have been overestimated thus having a larger instance of overestimation of flows.
b) The demand data used in this Study was taken as is under the assumption that it is accurate. This may be partially correct because it has its own set of assumptions and possible errors which may have translated into the results obtained in this Study. In addition, the back extrapolation of the demands may not be reflecting the true situation.
c) Some of the observed stream flow data obtained from DWEA have monthly values based on estimation which may give misleading results.
d) Reservoir operating rules could not be obtained in time, thus the reservoirs have been modelled without operating rules. This may have contributed to the poor results of most dams.
e) Upon closer inspection of Figure 5. c – g, a time lag can be seen between the observed and simulated draw downs. This may be attributed to the monthly consumption patterns assumed for the different consumers. In addition, the demands have been assigned to

surface water sources only. This area is a prime source of groundwater thus it is possible that part of the demand is met from groundwater sources.

5.3.3. Basin Evaporation

The same factors applied in Chapter 4 were maintained and the basin evaporation at the QC level was simulated. Figure 5.21 presents the modelled MAE for each QC.

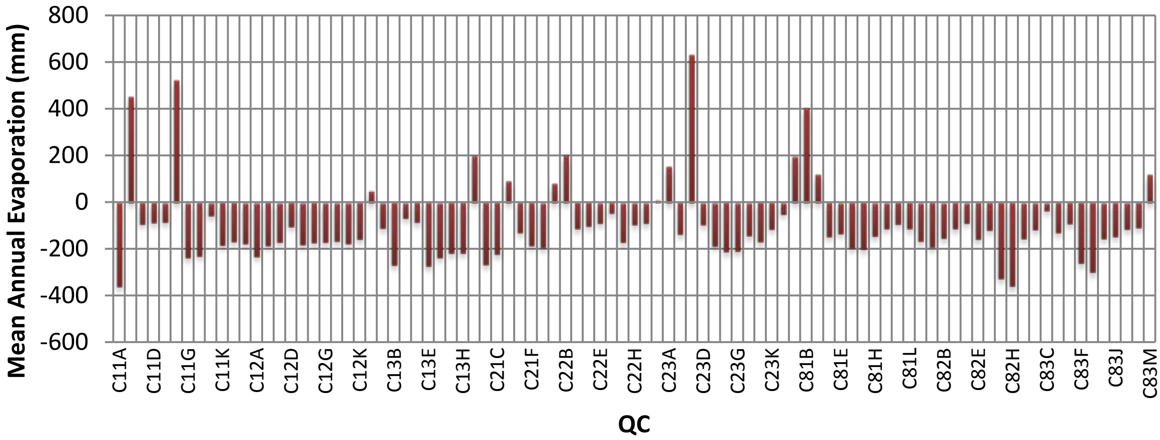


Figure 5.21: Modelled Mean Annual Evaporation for each QC

In general, the evaporation is underestimated by the model. The mean underestimation is 100mm.

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5.4. Conclusion

The water allocation module of WEAP was setup to reflect the present state of the UVRB in terms of its water infrastructure and water requirements using data from a variety of sources. The water demand data was obtained solely from the Reconciliation Strategy which is the latest available information for the region. The model performance was assessed by how well it reproduces the observed stream flows. The reservoir storage was also compared with observed data.

The model performance is reasonable in reproducing the stream flows, with a tendency of overestimation of most peaks except for the extremes which may also be due to measurement errors. The E and R^2 values range from 0.2 – 0.7. The system dynamics have been captured well shown by the corresponding timings of peaks and lows. On the other hand, the E_j and E_{Rel} values indicate relatively poor representation of low flows. However, the plots show 3 gauges except C2H085 with relatively well captured lows. In general, an acceptable performance of stream flows has been achieved for preliminary analysis.

The results for reservoir storage indicate a larger volume of water available in the system shown by the storage in Vaal Dam (see Figure 5. a). The reasons for this can be as follows:

a) The inflows to the dam have been overestimated by the model. This could be due to the RRF. Since WEAP only releases enough water to meet demands downstream, the excess water is stored.
b) The back-extrapolated demands are an underestimation.
c) There are additional demands in the basin which have not been accounted for.

In conclusion, the UVRB is a complex water resource system thus modelling such a system is a challenge. Since the UVRB operates as a system with the adjacent basins, the model can be expanded to include each of the adjacent basins and reservoirs so that the operating rules can be incorporated. This will possibly improve the model performance, as well as give a holistic picture of the resource system.

CHAPTER SIX

MODELLING THE FUTURE HYDROLOGY UNDER CLIMATE CHANGE

"If the wars of this century were fought over oil, the wars of the next century will be fought over water."

Ismail Serageldin

6.1. Introduction

This Chapter outlines the approach taken to simulate the impacts of climate change on the UVRB system. Justifications are given on why the particular climate change dataset and GCM models have been used, the steps taken in climate change data preparation and assumptions made in the process, quality checks on the climate data, projections of future water demand, the development of different scenarios for model runs and finally the results obtained from the simulation are presented.

6.2. Climate Models

General Circulation models have been developed which are used for modelling the earth's climate. These are complex mathematical formulations which attempt to describe how the climate works and how it would change if perturbations are introduced. However, due to the climate's inherent complexity, these models require extensive resources and computing power to run. Therefore, the spatial resolutions of these models are limited towards the coarser side. The IPCC Data Distribution Centre collates and distributes climate model data under different perturbation scenarios. The spatial resolution of these results is in the range of 2.8^{o} – 5.6^{o} by 73.2^{o} - 302.8^{o} grids. This resolution would translate to single grid areas larger than the whole UVRB.

Impact studies of climate change on hydrology at regional scales require grids at finer resolutions. A method to achieve this is downscaling of the GCM data (refer Chapter 2, Section 2.3.1.1) which was beyond the scope of this study, therefore another solution needed to be sought.

6.2.1. The TYN SC 2.03 Dataset

The TYN SC 2.03 data-set (Mitchell et al., 2004), developed by the Tyndall Centre for Climate Change Research at the University of East Anglia, comprises monthly grids of modelled climate, for the period 2001-2100, and covering the global land surface at 0.5 degree resolution. There are five climatic variables available: cloud cover, Diurnal Temperature Range (DTR), precipitation, temperature and vapour pressure. It comprises a total of 20 GCM runs, combining 4 possible future worlds of emission scenarios described by SRES (Arnell et al., 2004) with 5 state-of-the-art climate models. The emission scenarios were developed in the mid 1990s and are based on 4 different storylines (A1F1, B1, A2 and B2) to describe consistently the relationships between the forces driving emissions and their evolution and to add context for the scenario quantification. Each storyline represents different world futures (refer to Chapter Two Section 2.3.1.1). The five GCM models used are the

i) Hadley Centre Coupled Model Version 3 (HadCM3),
ii) National Center for Atmospheric Research (NCAR) Parallel Climate Model (PCM),
iii) Second Generation Coupled Global Climate Model (CGCM2),
iv) Common Wealth Scientific and Industrial Research Organization – Climate Model Version 2 (CSIRO2) and
v) European Centre Model Hamburg Version 4 (ECHam4).

Since the GCMs had a substantially coarser spatial resolution than 0.5 degree, Mitchell et al. (2004) interpolated the GCM-patterns to a higher resolution by applying a Delaunay triangulation and by relating them to the observed temperatures for the period 1961–1990.

The companion data-set CRU TS 2.0 may be used in conjunction with TYN SC 2.03 to provide complete time-series for the period 1901-2100. The control scenario for the 21st century may be duplicated into the 20th century, which provides a time-series for the period 1901-2100 without any long-term climate change.

The grids were designed for flexible application with a wide variety of impact models, such that:

i) Analysts may apply part or all of the scenario time series from 1901–2100 for any of the five climate variables included.
ii) By combining four emissions scenarios with five GCMs, the resulting 20 scenarios incorporate much of the uncertainty in future climate change.
iii) The grid-based design permits the data to be directly applied at grid-box resolution or as regional means. Finer resolution information may be derived by spatial or temporal re-sampling, statistical downscaling or weather generators.

The purpose of providing 20 different futures is to enable environmental modellers to represent the uncertainty in climate impacts arising from two distinct sources of uncertainty: uncertainty in the future emissions of greenhouse gases, and uncertainty in climate modelling. Each of the 20 permutations should be treated as equally likely. Between them, the 20 scenarios cover 93% of the possible range of future global warming estimated by the IPCC in their Third Assessment Report (2001). The control scenario may be useful for tuning models, and for establishing baselines.

It is better to use this data-set than to use direct GCM model outputs because:

i) There is complete consistency between the observed (20^{th}) and projected (21^{st}) centuries, which can only be obtained with direct model outputs by assuming that the modelled 20^{th} century matches the observed 20^{th} century.

ii) There is complete consistency between each of the emissions scenarios. In many cases, modelling centres have only performed and released simulations for one or two of the 'marker' SRES scenarios, but not for them all. This data-set provides the same information for each of the four 'marker' SRES scenarios.

iii) There is complete consistency between each of the climate models. The direct model outputs are generally available only on the native grids, which vary between models. Also, different models report different climatic variables. This data-set provides the same information for each of the five GCMs included.

The net effect of these advantages is that it becomes much easier to conduct systematic investigations into the future of the environmental system being modelled.

The scenarios present future climates in which the multi-decadal changes are taken from GCMs, but the baseline climate and inter-annual variability are taken from observations. The use of observed rather than modelled inter-annual variability has its disadvantages. However, using the observed variability avoids introducing differences (in homogeneities) between the representation of 20th and 21st century climate.

Reference is made to Mitchell *et al*. (2004) for further information regarding the science behind the development of the TYN SC 2.03 dataset.

6.2.2. Extraction of the Climate Data

The TYN SC 2.03 dataset represents climate data as grids covering a major part of the earth's surface. A single grid is 0.5^{o} x 0.5^{o} in size which is approximately 52km x 52km. All grids have been labelled numerically for easier identification of their location and coverage. Therefore, the first step was to identify the grids which cover the UVRB. A total of 36 grid boxes cover the UVRB and are shown in Figure 6.1.

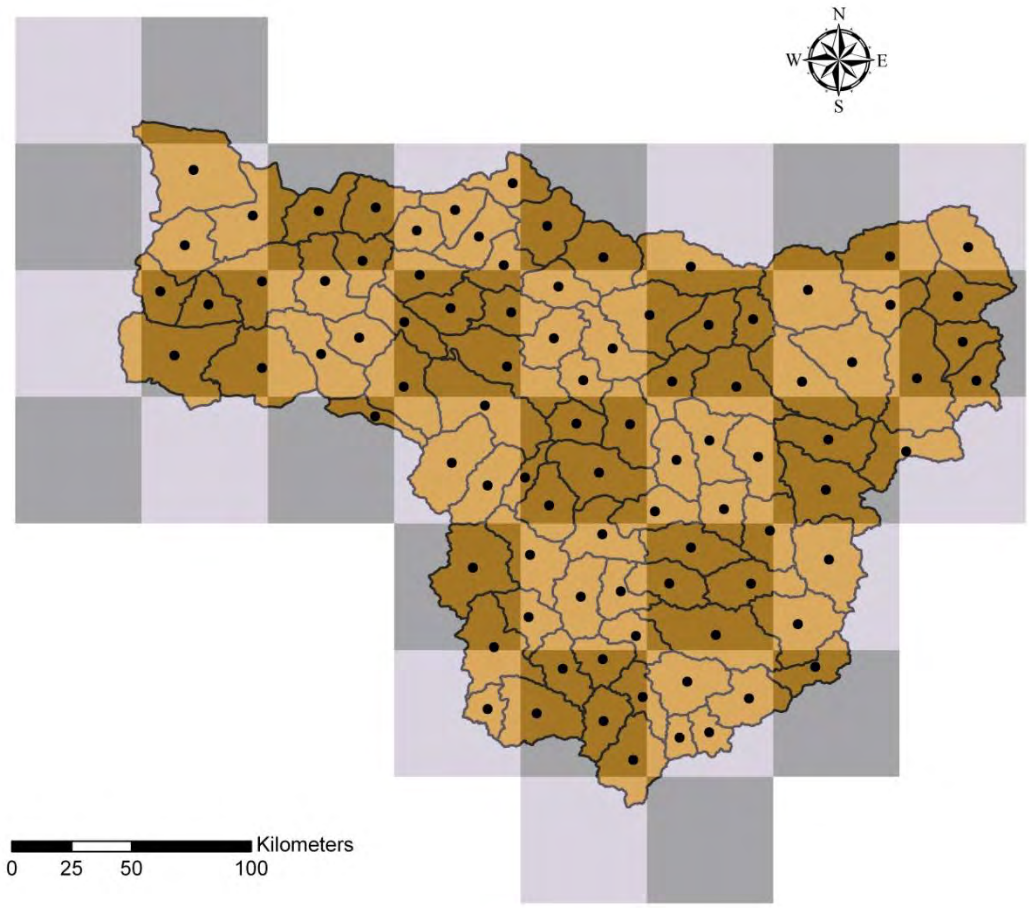

Figure 6.1: The TYN SC 2.03 0.5° x 0.5° Grid superimposed over the UVRB (the dots represent the QC Centroids)

The TYN SC 2.03 dataset is a package of different files containing the various parameters of GCM model results for different SRES scenarios and the climatic variables. Therefore, a formula is used to construct the future climate change scenarios given in Mitchell et al. (2004).

The climate change scenarios (x) have the same climatology (O) and variability (Ő) as in the control scenario and do not vary. The choice of scenario is determined by the choice of GCM (g) and SRES emissions (s), which in turn determine the pattern of change (p) and the global temperature anomalies (t') by which the pattern is scaled. Thus the climate change scenario is given by Equation 6.1.

$$x_{vgsiym} = O_{vim} + Ő_{viym} + (p_{vgsim} * t'_{gsy}) \quad (6.1)$$

Where:

Symbol	Variable
x	Scenario Datum
O	(observed) climatology
Ő	(observed) Residual
p	Response Pattern
t'	Global Warming

And where the subscripts are:

Symbol	Variable
v	Climate Variable
g	GCM Model
s	SRES Emission Scenario
i	Grid Box
y	Year
m	Month

The different parameters for the period between year 2000 and 2030 were manually extracted for each grid and constructed using Equation 6.1 in MS Excel for the 5 GCM models.

Reference is made to the Tyndall Centre for Climate Change Research website (http://www.cru.uea.ac.uk/~timm/grid/TYN_SC_2_0.html) which outlines the unpacking procedure using an example.

6.2.3. The Choice of SRES Scenarios

In this study, the commonly used climate change socio-economic and emission scenarios A2 and B2 were analyzed. The A2 scenario puts emphasis on self-reliance and preservation of local identities and economic development is primarily regionally oriented. The B2 scenario puts emphasis on local solutions to economic, social, and environmental sustainability (IPCC, 2001).

However, according to Bates et al (2008), best-estimate projections from models indicate that decadal average warming over each inhabited continent by 2030 is insensitive to the choice of SRES scenario used. Furthermore, emissions scenarios are driven by assumptions about population growth and associated changes in energy consumption. The UN 2000 medium projection leads to a global population of 9.3 billion by 2050. Therefore, the midrange population estimate can be considered to be B2, which estimates a world population of 10 billion by 2100 (van Lieshout *et al.*, 2004).

IPCC (2001) describes the B2 scenario as “a world in which the emphasis is on local solutions to economic, social, and environmental sustainability. It is a world with continuously increasing global population at a rate lower than A2, intermediate levels of economic development, and less rapid and more diverse technological change than in the B1 and A1 storylines. While the scenario is also oriented toward environmental protection and social equity, it focuses on local and regional levels”.

Therefore, the B2 scenario was adopted for assessment of the future conditions in the UVRB because it approximately represents the medium term global population projection and also the most likely future for Africa in terms of economic and technological advancement.

6.3. Climate Change and Upper Vaal River Basin

The climate change scenarios from the 5 GCM models are presented in this Section for 4 of the 5 required climatic variables in WEAP. Wind speed data is not available in the TYN SC 2.03 dataset.

All centroids falling within any particular grid were assigned that grid value (refer Figure 6.1). A second method would have been to assume the grid value to be at the grid centre, and then interpolate using spatial techniques to determine the values at each QC centroids. However, the former method was adopted because the GCM patterns have already been smoothened from the spatially coarser parent GCMs to 0.5^{o} resolution using the Delauney Triangulation method to avoid discontinuities between the grids (Mitchell *et al.*, 2004). Therefore further interpolation would result in additional errors.

6.3.1. Precipitation

The Mean Annual Precipitation (MAP) is shown in Figure 6.2 for period between Year 2000 and 2030. The average predicted precipitation of the 5 GCM models has a slight increasing trend over the 30 year period with 16 years experiencing higher than average annual rainfall.

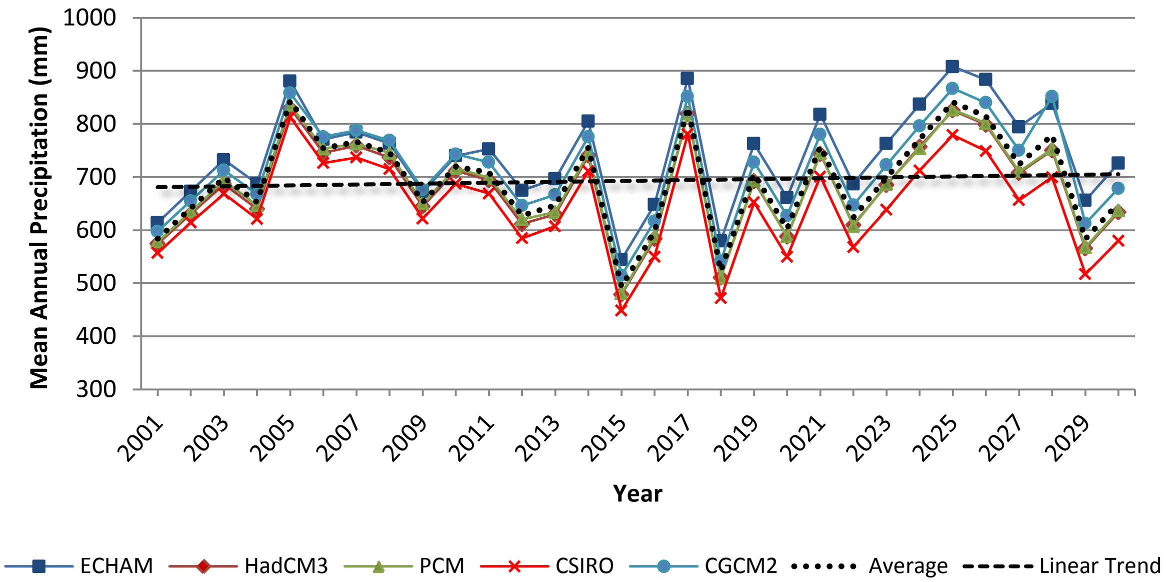

Figure 6.2: Mean Annual Precipitation for each GCM Model under SRES B2 Scenario

It can be seen from Figure 6.2 that the trend in rainfall decreases from year 2007 to year 2016 and then generally rises to the year 2026. However, there is large inter annual variability which is characteristic of South African rainfall. The period between year 2010 and 2022 has predominantly below average rainfall. This is indicative of a drier period.

Based on the projected MAP, it was decided to run the model using the wettest and driest GCM models which represent the best and worst cases respectively. Therefore, ECHAM4 (wet) and CSIRO (dry) were chosen for further analysis of impacts of climate change on the UVRB.

6.3.1.1. Correlation between Observed and TYN SC 2.03 Precipitation

The time series of observed and predicted precipitation was constructed from year 2001 to 2005 and is given in Figure 6.3. The peaks and lows and their timing has been captured relatively well. In addition, a correlation analysis was carried out between the observed and TYN SC 2.03 precipitation at the QC centroids. The R^2 values indicate a reasonably good correlation.

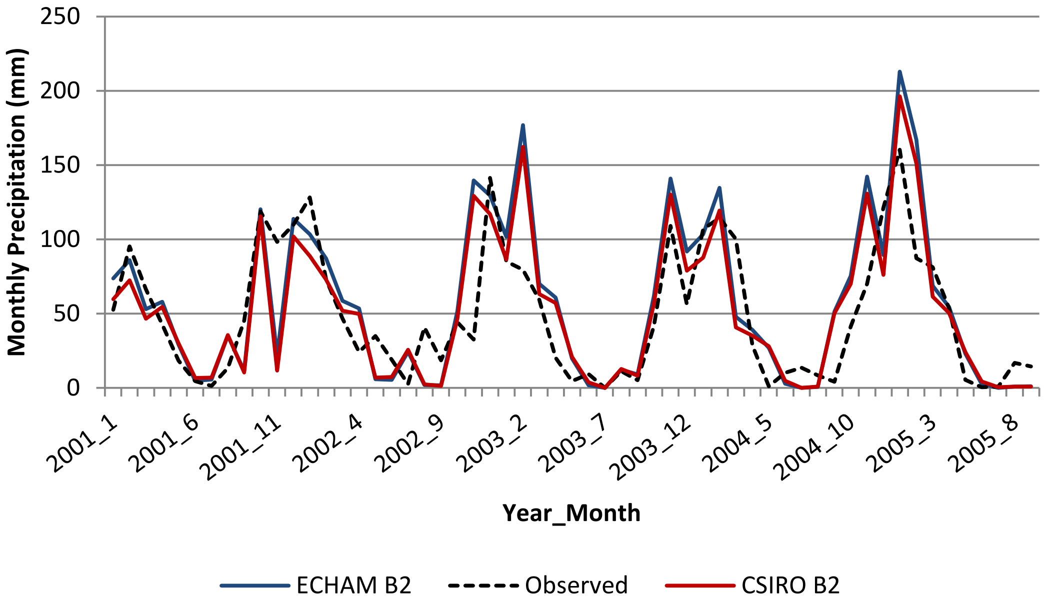

Figure 6.3: Time Series Plot of Observed against ECHAM4/ CSIRO B2 Precipitation

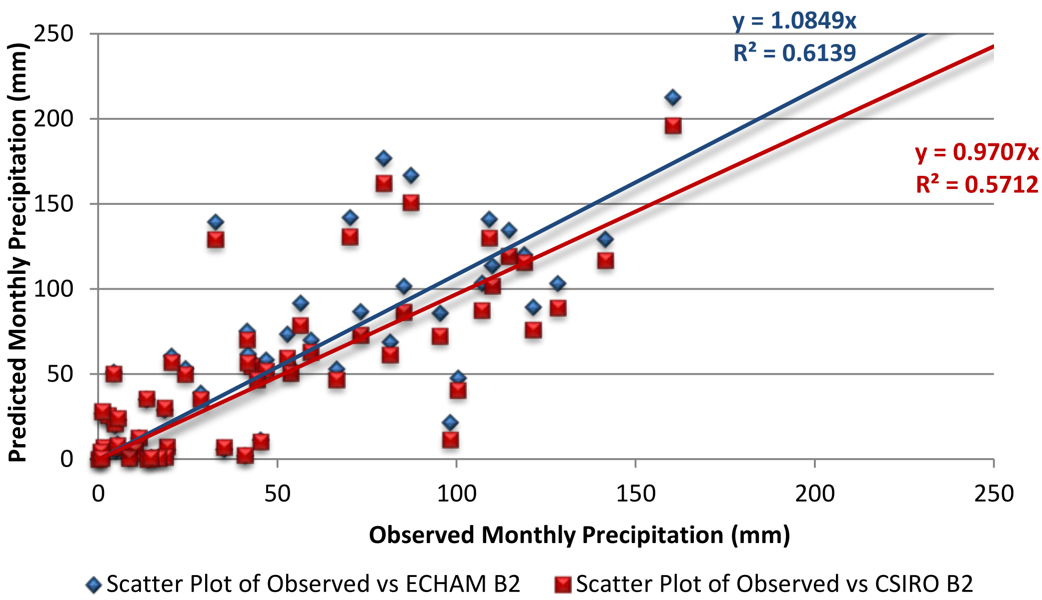

Figure 6.4: Scatter Plot of Observed vs ECHAM4/ CSIRO B2 Precipitation

The coefficients of variation (CV) were also calculated to determine the ability of TYN SC 2.03 dataset to capture the intra annual variation. These values are given in Table 6.1.

Table 6.1: CV comparison between Observed and TYN SC 2.03 Precipitation

Data	Coefficient of Variation (CV)
Observed	0.884
ECHAM4	0.932
CSIRO	0.924

The intra annual variation has been reproduced well by the TYN SC dataset indicated by Figure 6.3 and the CV values. Therefore, a relatively good correlation has been obtained between the two datasets which further instils confidence in the future projections of precipitation.

6.3.1.2. Analysis of Dry Season Precipitation

The months of June, July and August (JJA) represent the dry season in the UVRB. The predicted precipitation by the 2 GCM models was analysed for this season to determine the pattern in expected rainfall. The ECHAM rainfall pertaining to the monthly total of JJA precipitation for each year was extracted and plotted relative to CSIRO. Results show that despite ECHAM having a generally higher MAP than CSIRO, it has a lower precipitation relative to CSIRO in the dry season (JJA). Figure 6.5 shows the analysis of observed precipitation volume for the 2 GCM models over JJA period extracted from input data in WEAP. The relative precipitation also shows a rising trend over time, meaning that the difference between ECHAM and CSIRO dry season rainfall continues to increase.

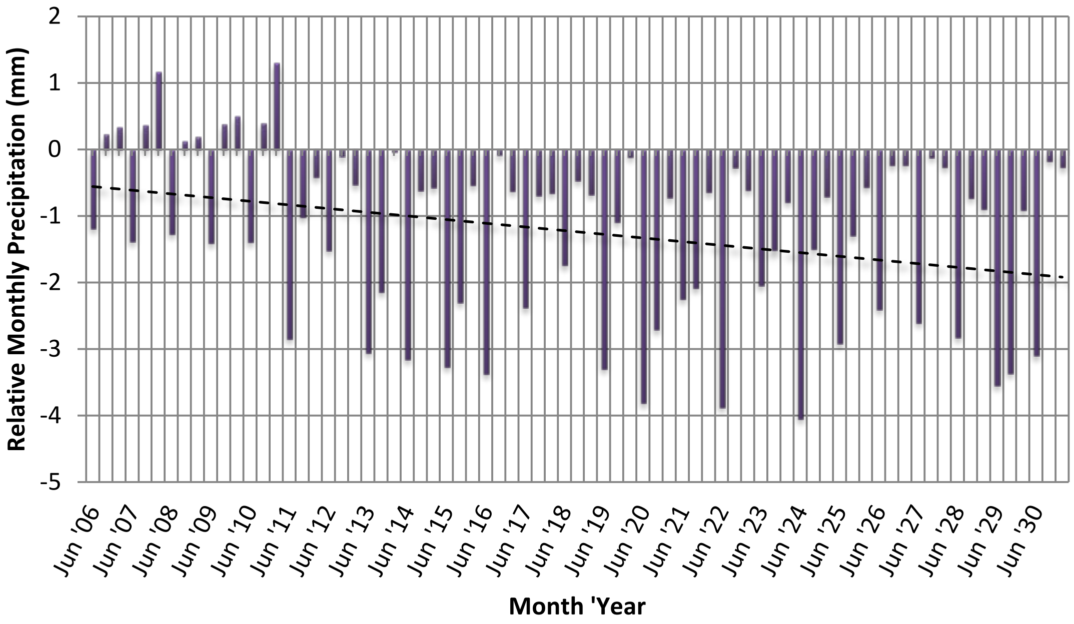

Figure 6.5: ECHAM Precipitation relative to CSIRO for JJA over the UVRB

6.3.2. Temperature

The analysis of predicted Mean Annual Temperature (MAT) shows a continuously rising trend up to the year 2021, after which there is a short decline to year 2026. It increases once again after that. This behaviour is illustrated in Figure 6.6.

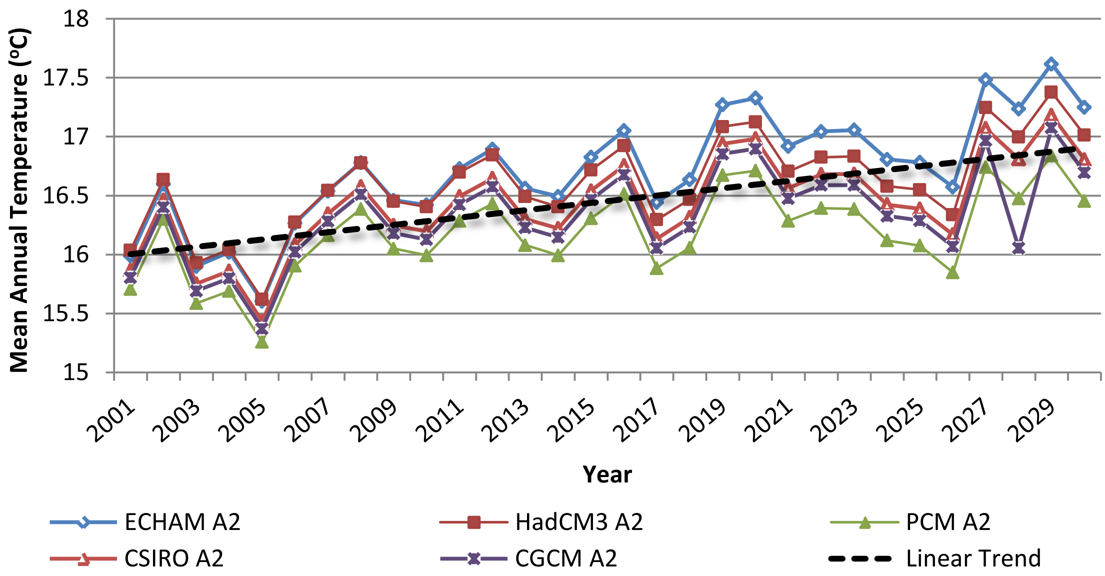

Figure 6.6: Mean Annual Temperature for each GCM Model under SRES B2 Scenario

6.3.2.1. Correlation between Observed and TYN SC 2.03 Temperature

A correlation analysis was carried out between observed and predicted monthly temperature for the period 2001 – 2005. The obtained R^2 values for correlation between observed and ECHAM4 and CSIRO are 0.914 and 0.913 respectively which suggest an excellent fit.

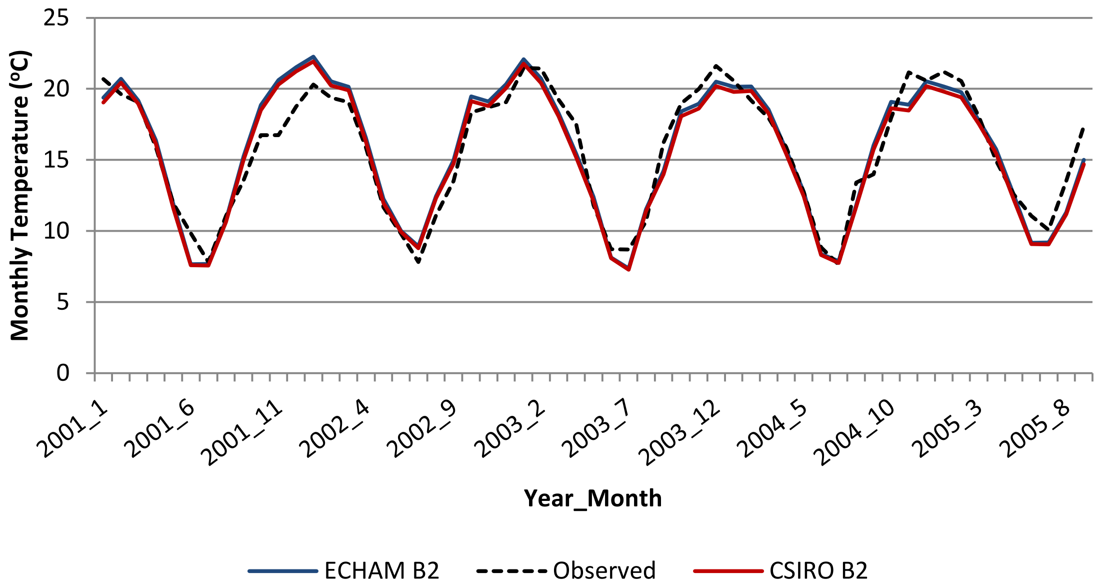

Figure 6.7: Time Series Plot of Observed against ECHAM4/ CSIRO B2 Temperature

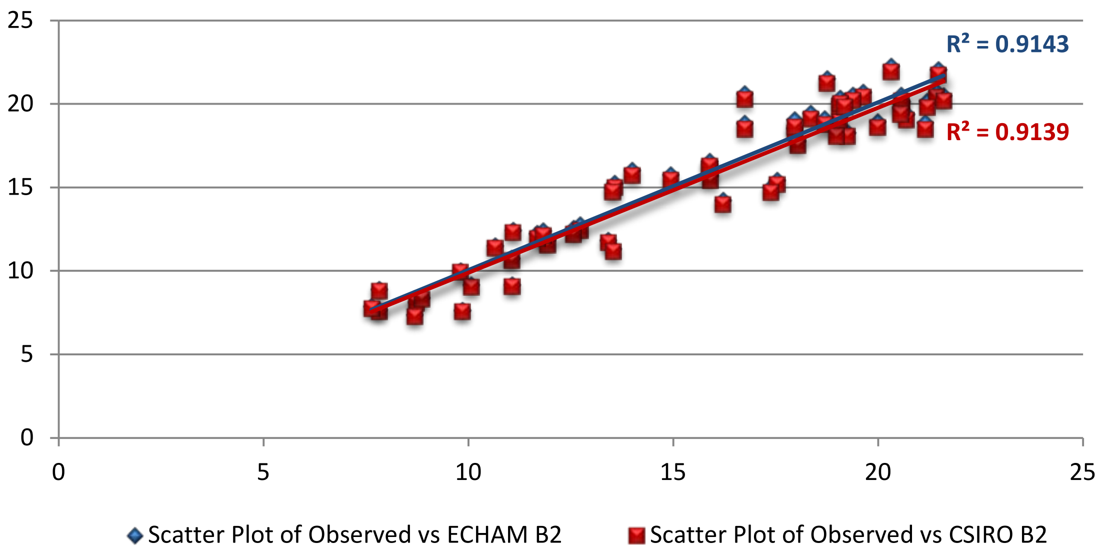

Figure 6.8: Scatter Plot of Observed vs ECHAM4/ CSIRO B2 Temperature

In addition, the coefficient of variation (CV) was also calculated to determine the ability of TYN SC 2.03 dataset to capture the intra annual variation and is given in Table 6.2.

Table 6.2: CV comparison between Observed and TYN SC 2.03 Temperature

Data	Coefficient of Variation (CV)
Observed	0.277
ECHAM4	0.292
CSIRO	0.291

The intra annual variation has been reproduced well by the TYN SC dataset indicated by Figure 6.6 and the CV values. Therefore, a relatively good correlation has once again been obtained between the two datasets which further instils confidence in the future projections of temperature.

6.3.3. Relative Humidity

The TYN SC dataset does not include the relative humidity (RH) variable, but has vapour pressure instead. In fact, available RH data from the GCMs were converted to vapour pressure. Therefore, the same equations used by Mitchell *et al.* (2004) for this conversion were applied to reconvert the vapour pressure to RH.

$$RH = \frac{100 * e}{e_s} \tag{6.1}$$

Where:

e = vapour pressure
e_s = Saturated vapour pressure

Mitchell *et al.* (2004) estimated the saturated vapour pressure from daily mean temperature using the Magnus equation given by Equation 6.2. However, since this study is on a monthly time scale, monthly values of vapour pressures and temperatures were used instead.

$$e_s = 6.107\exp\left(\frac{17.38T}{239+T}\right) \qquad \text{for } T_W > 0 \qquad (6.2)$$

$$e_s = 6.107\exp\left(\frac{22.44T}{272.4+T}\right) \qquad \text{for } T_w < 0 \qquad (6.3)$$

Where

T = the daily mean temperature

T_w = the wet-bulb temperature

The T_w is used to distinguish between frozen and liquid water and has an empirical relationship with dew point temperature given in Equation 6.4.

$$T_w = \frac{3T_d + 2T}{5} \qquad (6.4)$$

An assumption, based on New *et al* (as quoted in Mitchell *et al.*, 2004), that the minimum temperature can be used as a proxy for T_d was therefore applied. It was observed that T_w was always greater than 0 hence the use of Equation 6.2 to calculate e_s and thereafter using Equation 6.1 to determine the RH. The time series of Mean Annual Relative Humidity (MARH) is shown in Figure 6.9.

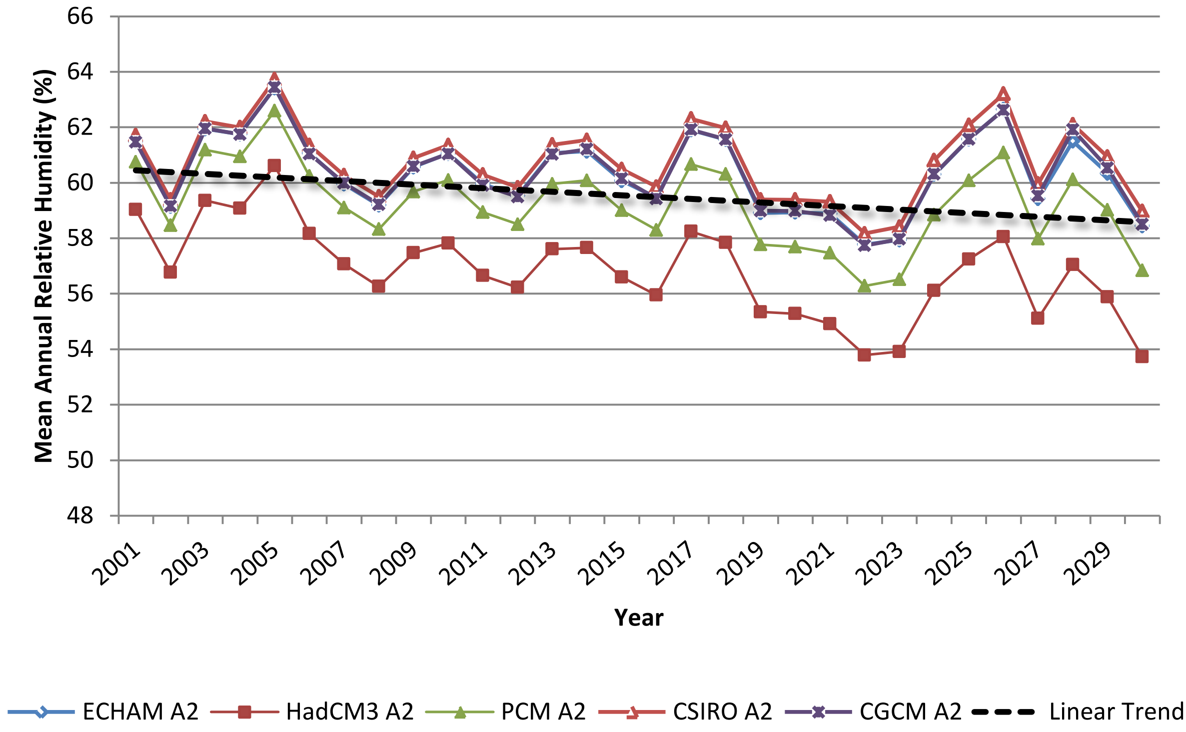

Figure 6.9: Mean Annual Relative Humidity for each GCM Model under SRES B2 Scenario

The MARH shows a decreasing trend over time. To explain this occurrence, the mechanism between humidity and temperature will be briefly outlined. The future climate has been shown to get warmer (see Figure 6.6). However, other characteristics of the regional temperature like dew point[1] may not change as much because the amount of moisture in the air may not increase or decrease. Therefore, an increase in temperature would lower the relative humidity of the region and vice versa.

6.3.3.1. Correlation between Observed and TYN SC 2.03 Relative Humidity

A time series and scatter plot of observed and predicted monthly RH was constructed and is given in Figure 6.10 and Figure 6.11.

[1] The dew point is the temperature to which a given parcel of air must be cooled, at constant barometric pressure, for water vapor to condense into water

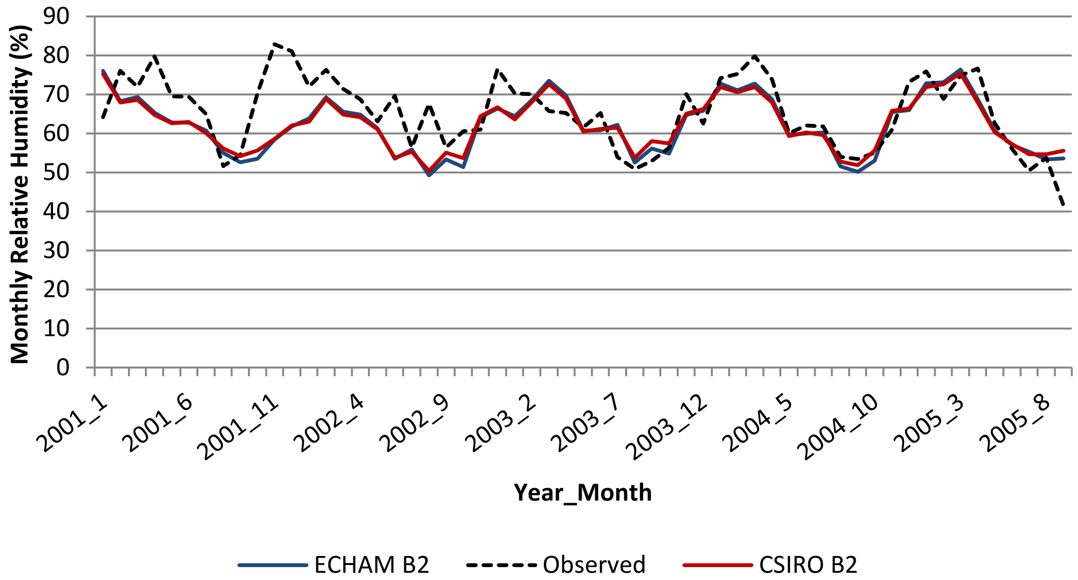

Figure 6.10: Time Series Plot of Observed against ECHAM4/ CSIRO B2 Relative Humidity

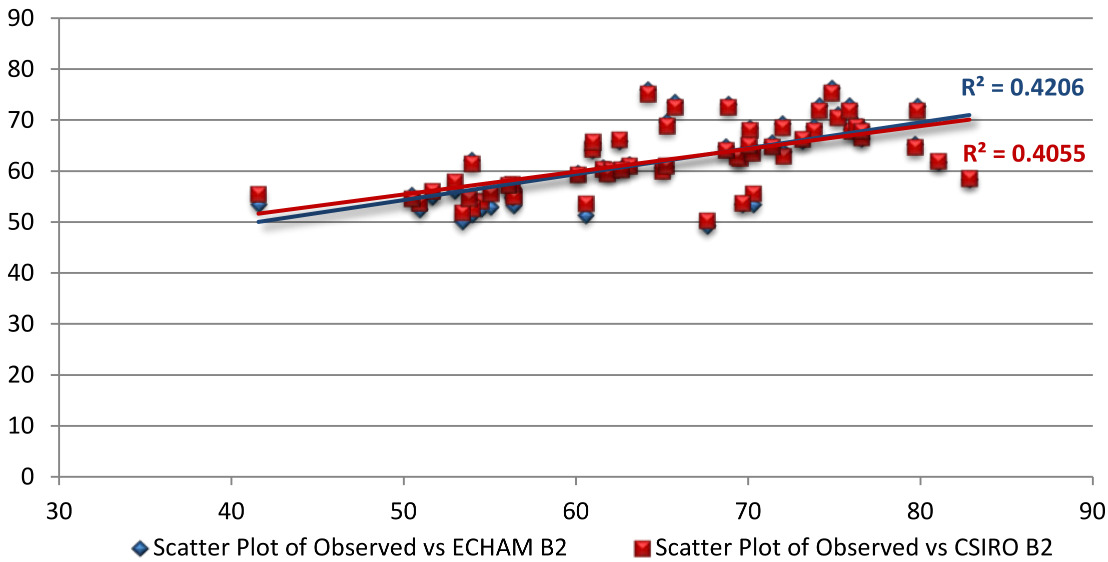

Figure 6.11: Scatter Plot of Observed vs ECHAM4/ CSIRO B2 Relative Humidity

The time series shows a fairly reasonable reproduction of the observed data in terms of the timing of the peaks and lows. However, the high values have been underestimated in most cases. The scatter plot concurrently shows a weak correlation. This is expected because of the assumptions and manipulations required to derive this climatic variable from vapour pressure. Nonetheless, this result is the best available under the circumstances and is thus adopted for the model.

6.3.4. Wind Speed

Wind speed is not available in the TYN SC 2.03 dataset. Therefore, as a first attempt, a correlation between observed wind speed and the other variables was looked into which yielded insignificant results. Thus wind speed did not share a correlation with any other climatic variables.

Thereafter, the observed wind speed data for stations around the UVRB with consistent records was analysed to see if there was a pattern or trend. The 5-year moving average of observed wind speed for these stations is given in Figure 6.12.

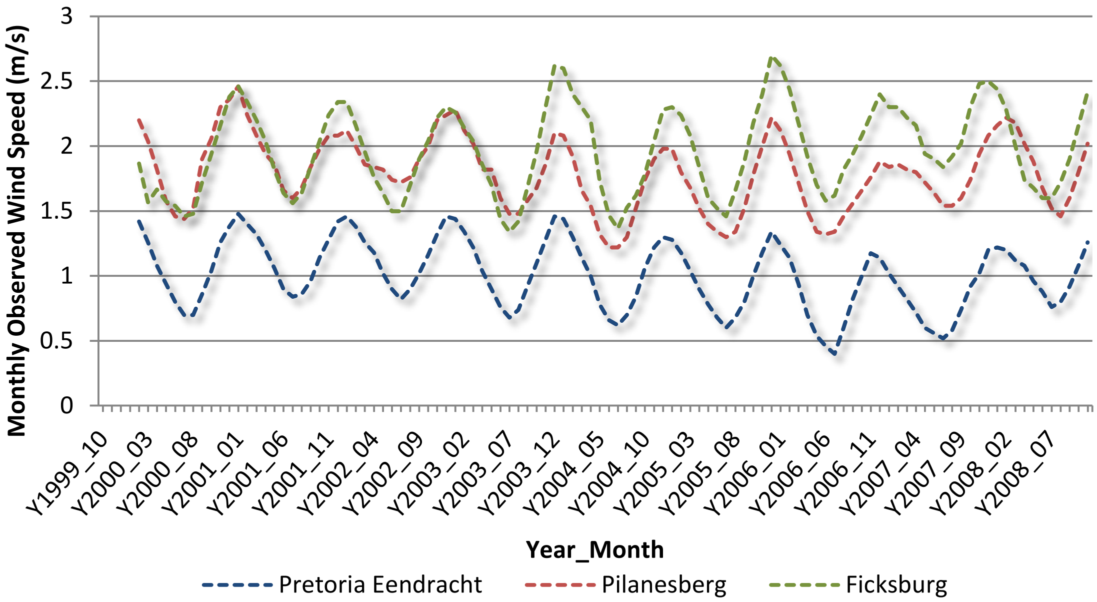

Figure 6.12: 5-Year Moving Averages for 3 Wind Recording Stations in the UVRB (Refer to Chapter 4 Figure 4.4 to see the location of these stations)

The monthly wind speed follows a periodic trend for all three stations over the 9 year period. Therefore, based on this result, it was decided to adopt the same trend and replicate the 6 year (original period of this Study) observed data (interpolated at each QC in Chapter 4 Section 4.4.1.4) for the remaining period 2006 to 2030.

6.4. Model Setup for the Future Scenarios

The model set up for simulation of the UVRB's future hydrology adds on to the previous setup for present hydrology, with modifications made to certain parameters. Therefore, the period of simulation is from October 1999 to September 2030, with the first 5 year period having the same data used in simulation of present day hydrology. The parameters which were modified have been outlined in the following sections.

6.4.1. Hydrology Module

6.4.1.1. Climate Variables

The monthly climate variables from ECHAM4 and CSIRO GCM models, derivation of which was outlined in Sections 6.2.2 and 6.3, were prepared for each QC for the simulation period. MS Excel files were prepared for the model to read the data from.

6.4.1.2. Land Use Parameters

Reference is made to Chapter 5 Section 5.2.1 which outlined the parameters that were modified for simulation of present day hydrology. For simulation of the future scenarios, the K_c and its multiplying factors remained constant under the assumption that the current state of land use will remain constant to the year 2030. As much as this assumption may not be valid, it provides the best case scenario for the simulation. In addition, land use patterns are highly dynamic, and although its spatio-temporal magnitude and direction can be quantified using other models like CLUE-S (www.cluemodel.nl), this component was beyond the scope of this Study.

Therefore, only the RRF was modified using the same methodology outlined in Chapter 5 Section 5.2.1.2 but using the predicted precipitation to generate new RRFs for each month and QC to the year 2030.

6.4.2. Water Allocation Module

As mentioned in Chapter 5 Section 5.2.3, the water demands for the different consumers in the UVRB have been projected to the year 2030 in a separate study. This data was adopted for this Study. The Scenario 'B' for projected water demands used in Chapter 5 was also used to simulate the future hydrology. The projections for different consumers are outlined hereafter. It should be noted that all consumers included in the model have been assigned an equal priority for water supply.

6.4.2.1. Urban Demand

The main urban demand is the water supply to Gauteng and adjacent environs by Rand Water Company. This demand is projected to grow from 1,291 Mm^3 in year 2005 to 1,765 Mm^3 in year 2030 indicating a 37% increase. Figure 6.13 shows the projected demand for Rand Water and associated return flows.

The monthly consumption pattern was assumed to remain the same (as shown in Chapter 5 Figure 5.10) to the end of the simulation period.

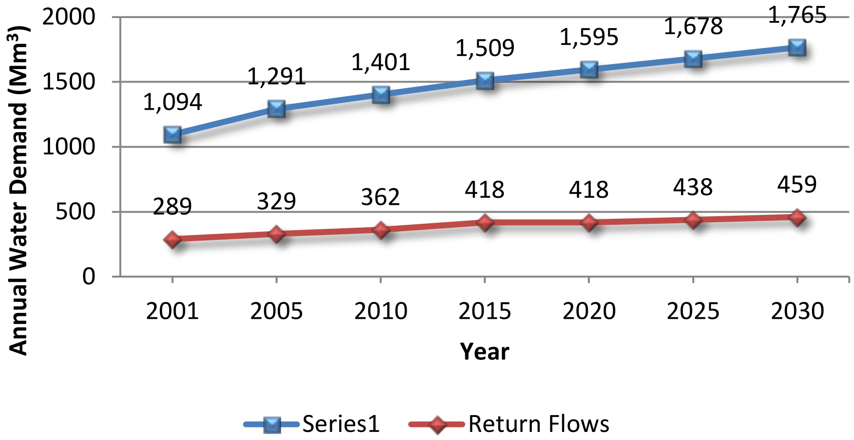

Figure 6.13: Projected Urban Water Demand and Return Flow (Extracted from DWAF (2006a))

6.4.2.2. Industrial Demand

As mentioned earlier, the three main industrial users of water are ESKOM, SASOL and Mittal Steel. Their projected requirements are given in Figure 6.14. Mittal Steel is working towards reducing its consumption and expects its demand to remain constant as from year 2010. As for ESKOM, its demand remains constant after year 2020.

The monthly consumption patterns for each of the three industries remain the same as initially formulated when simulating the present day hydrology.

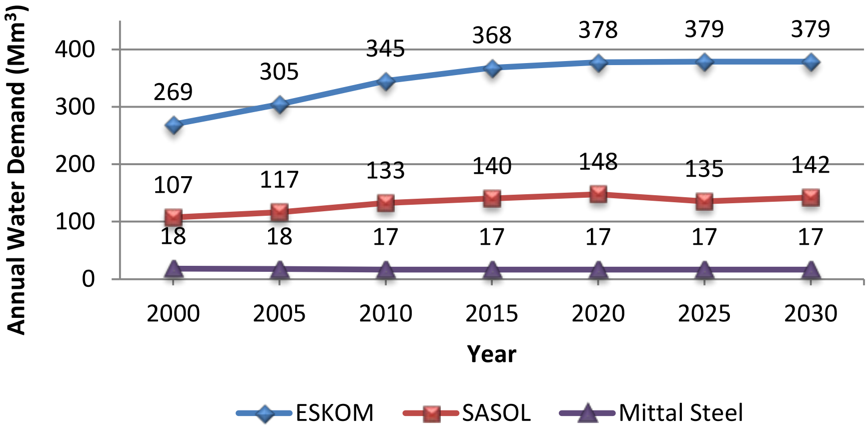

Figure 6.14: Projected Annual Industrial Water Demand (Extracted from DWAF (2006a))

6.4.2.3. The Vaal River Eastern Sub system Augmentation Project (VRESAP)

The VRESAP, also known as the Vaal River Pipeline Project, abstracts water from the Vaal Dam and has an ultimate capacity of 160 Mm^3 per annum (equivalent to 13.3 Mm^3 per month). This pipeline officially started transferring water in the year 2009. However, records obtained from DWA indicated a small volume already being pumped as from December 2008, with an average of approximately 5 Mm^3/ month up to May 2009. Therefore, it was assumed that this project will reach its full capacity by end of year 2010 following a stepped growth rate. The monthly projection of volume transferred by VRESAP is given in Figure 6.15.

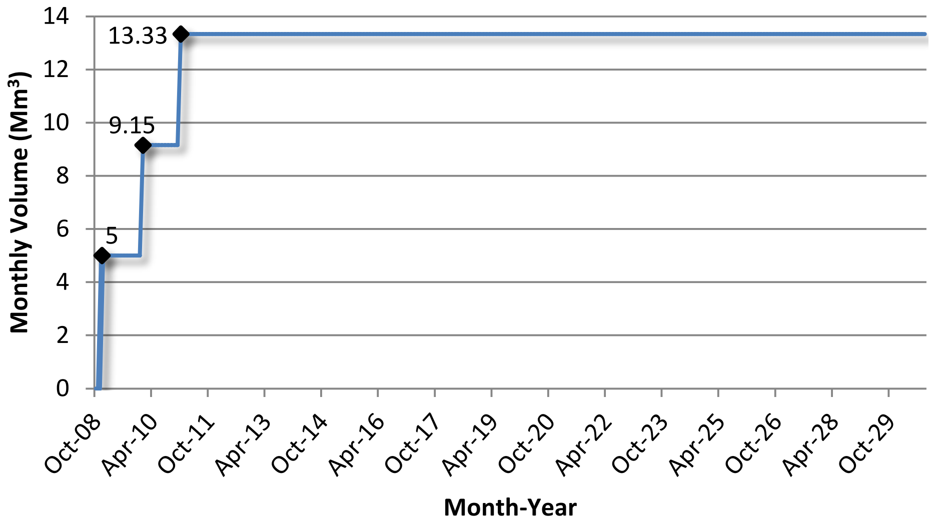

Figure 6.15: Projected Monthly VRESAP Demand

6.4.2.4. <u>Irrigation Demand</u>

Irrigation estimates determined for the year 2005 by the DWAF (2007) study indicated that the actual consumption was much higher than the lawful considered volume. The registered volumes in the Water Allocation Registration Management System (WARMS) database were used in the DWA study as an indication of the current state of consumption. As a result, the difference was assumed to be unlawful abstractions especially upstream of the Vaal Dam (Frankfort Sub Catchment: see Chapter 5 Figure 5.15). Therefore, 2 scenarios were developed to address the possibility of growth of the irrigation requirements to the year 2030. Table 6.3 shows the irrigation volume estimates for the UVRB.

Table 6.3: Indication of the Unlawful Irrigation Abstractions (Mm^3)

Sub Catchment	1998	2005	Lawful Estimate	WARMS
Grootdraai	18	30	12	46
Delangesdrift	4	10	3	11
Sterkfontein	0	0	0	0
Frankfort	47	114	45	192
Vaal Dam	64	115	25	200
Suikerbosrand	8	15	4	29
Klip	19	27	8	32
Barrage	15	29	10	28

Sub Catchment	1998	2005	Lawful Estimate	WARMS
Klerkskraal	0	0	0	0
Boskop	0	4	0	4
Klipdrift	8	8	8	8
Mooi GWS	35	35	35	24
Kroomdraai	4	7	3	20

(Extracted from DWAF (2006a))

The two scenarios proposed by DWAF (2007) potentially draws the future picture of irrigation water requirements in the UVRB and are labelled scenario 1 and 2. These are defined as follows:

a) Scenario I

It is accepted that the eradication of illegal irrigation use in the UVRB will be implemented. The assumptions of how it will be implemented are given below:

- Assume the growing trend, which was observed over the period 1998 to 2005, continuous for two years until 2008. This implies the interventions will take two years to become effective.
- Eradication of unlawful irrigation water use from 2008 onwards and assumes the water use will decrease over a period of 4 years.
- The assumption is made that the interventions will reduce the irrigation to the lawful volume plus 15% and that this will be achieved in the year 2011. The additional 15% above the estimates of the lawful water use is a conservative assumption providing for possible under estimations from the current data.

b) Scenario II

In the case of Scenario II it is assumed that no curtailment of illegal use will take place and that irrigation demand will continue to grow. This scenario is defined as follows:

- The irrigation water use will continue to increase at the trend observed between 1998 and 2005 until the registered volume in the WARMS database is reached.

However, DWAF (2007) concluded that Scenario II was not viable. Therefore, this Study considered Scenario I as the future trend the irrigation demands will follow. Figure 6.16 shows the pattern of irrigation requirement over the simulation period.

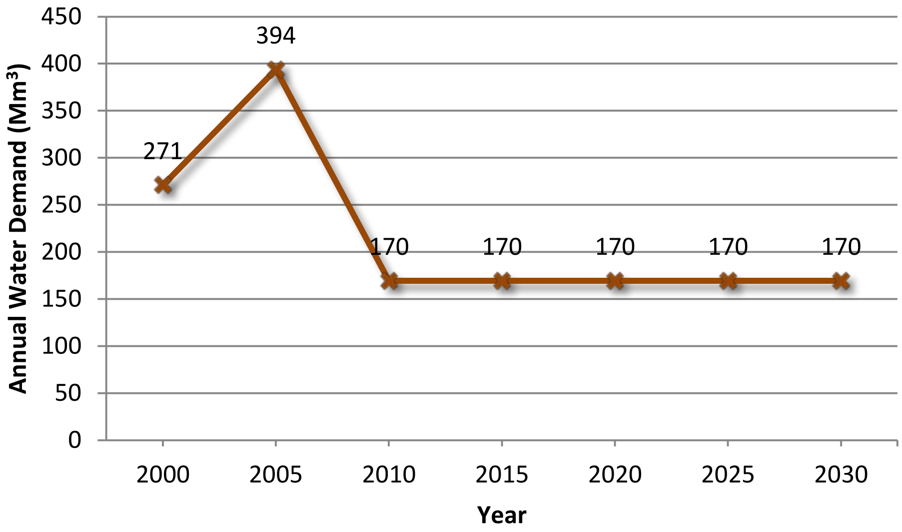

Figure 6.16: Projected Annual Irrigation Requirements (Extracted from DWAF (2006a))

6.4.3. Inter-Basin Transfers

The main inter basin transfer is the Lesotho Highlands Water Project (LHWP) which has delivered an annual volume of 543 Mm^3 in 1999 to 833 Mm^3 in 2007. The implementation of this project was in four phases, of which Phase I has been in operation since its commission in 1996. Construction of Phase II is currently on going and will augment the current supply by an additional 25.4m^3/s to a total transfer capacity of 55.4m^3/s. Phases III and IV are scheduled to be implemented by 2017 and 2020 respectively.

Therefore, taking into consideration the significance of LHWP and the large volume of water being transferred relative to the other inter-basin transfers, it was decided to simulate 2 future scenarios for the supply from the LHWP. These are Scenario A and B, and are explained in the following sections.

i) Scenario A

This scenario assumes that the volume of water transferred by the LHWP remains constant at the rate for the year 2008. The idea behind this scenario is to have the worst case scenario for the future considering climatic and/ or other changes in the source basin which may constrain the current and proposed transfer of water. Figure 6.17 shows the current transfer volume (blue) and projected volumes (red) under scenario A.

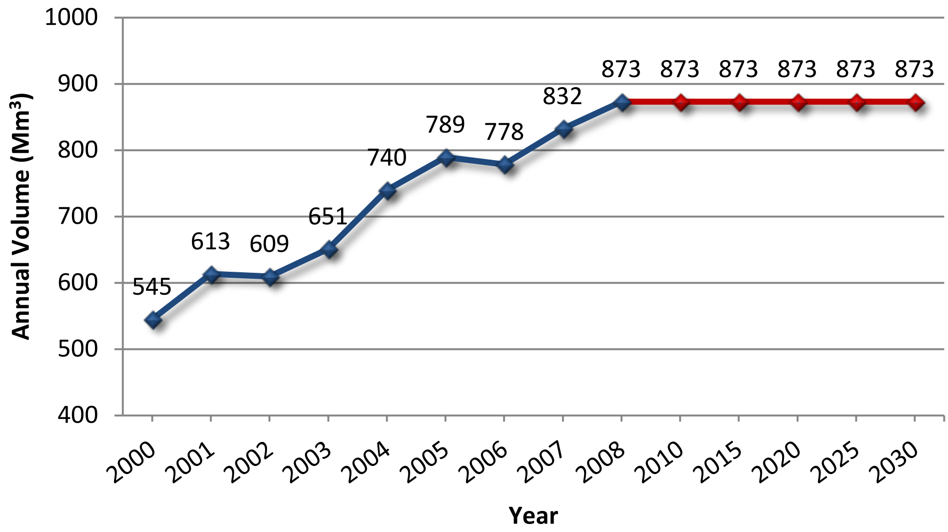

Figure 6.17: Projected Annual LHWP Transfer (Scenario A)

ii) Scenario B

An analysis of volumes transferred from the year 1999 to 2008 was carried out and the trend determined using simple regression analysis. The results indicate that the annual transfer volume has been increasing following a linear trend, with an R^2 of 0.954. Therefore, the regression equation was used to extrapolate annual transfers for the years 2009 to 2030. This is elaborated in Figure 6.18. It should be noted that the maximum capacity of the LHWP after all phases are implemented will be approximately 72m^3/s by the year 2020. The projected transfer volume in the year 2030 in this case is still within this capacity.

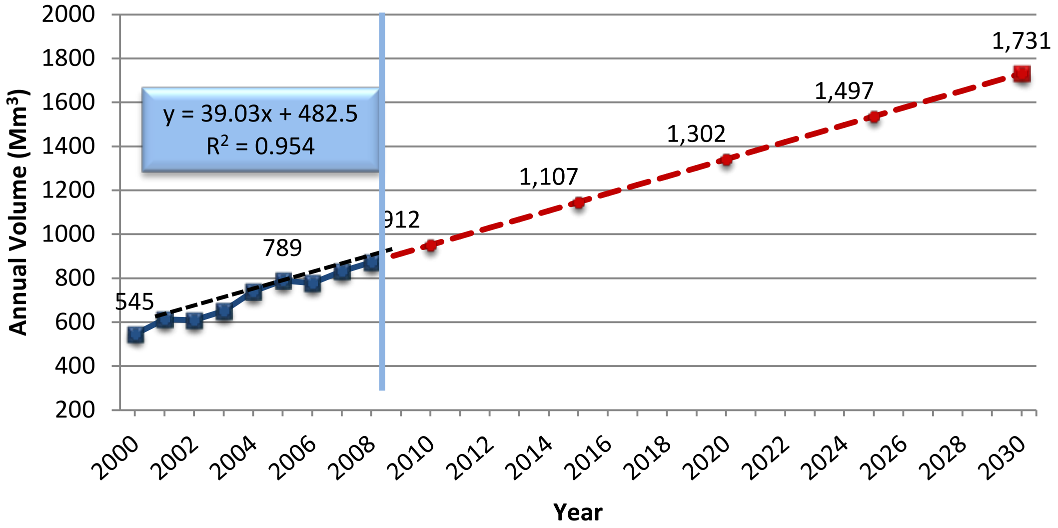

Figure 6.18: Projected Annual LHWP Transfer (Scenario B)

The other annual inter basin transfer volumes have been assumed to remain constant at the year 2007 annual volume for both scenarios A and B up to the year 2030. This is because of their relatively small volumes, a decision based on recorded data obtained from DWA.

6.4.4. Water Conservation & Water Demand Management Measures

A comprehensive study was commissioned by DWA (DWAF, 2006b) on the potential savings which can be made if Water Conservation/ Water Demand Management measures (WC/ WDM) were to be implemented. Three possible scenarios of management measures were developed which are outlined as follows:

i) Scenario C: 5 Years water loss programme and efficiency

- Water losses can be controlled within the next 5 years (2005 to 2010) and maintained afterwards.
- Water use efficiency is implemented by targeting the billed consumption. It was assumed that a 1% per annum efficiency could be gained from year 2015 increasing to 30% in the year 2025.

ii) Scenario D: Reduction in wastage over 5 years

- Water losses can be controlled within the next 5 years (2005 to 2010) and maintained afterwards.
- No water use efficiency is introduced.

Scenario D is basically the same as Scenario C with the exception that it only addresses the reduction in wastage and does not include any saving from more efficient water practices. This scenario assumes that certain actions can be implemented over a period of 5 years after which the

capital costs will decrease and only maintenance costs will remain.

iii) Scenario E: Reduction in wastage over 10 years

- Water losses can be controlled within the next 10 years (2005 to 2010) and maintained afterwards.
- No water use efficiency is introduced.

Scenario E is basically the same as Scenario D and only addresses the reduction in wastage. This scenario, however, assumes that certain actions can only be implemented over a period of 10 years which is considered to be more realistic than Scenario D. **Therefore, this is a more favourable and realistic scenario than either of the two previous scenarios**.

Table 6.4 gives the proposed reductions in wastage over time as per Scenario E.

Table 6.4: Reduction in Loss from WC/ WDM Measures

Year	% Reduction in Loss
2004 – 2005	2
2009 – 2010	9
2014 – 2015	15
2019 – 2020	15
2024 – 2025	14

However, the Report was completed in year 2007; therefore it was assumed that the proposed reductions before this year were not implemented. Therefore, the breakdown given in Table 6.4 was applied as from year 2009 to the year 2030 instead. In addition, since Rand Water represents the main urban consumers dependent on the UVRB, the WC/ WDM measures would initially be implemented in this supply region. Therefore, **the reduction was only applied to Rand Water's demand**. Figure 6.19 shows the Rand Water abstractions with and without the conservation measures.

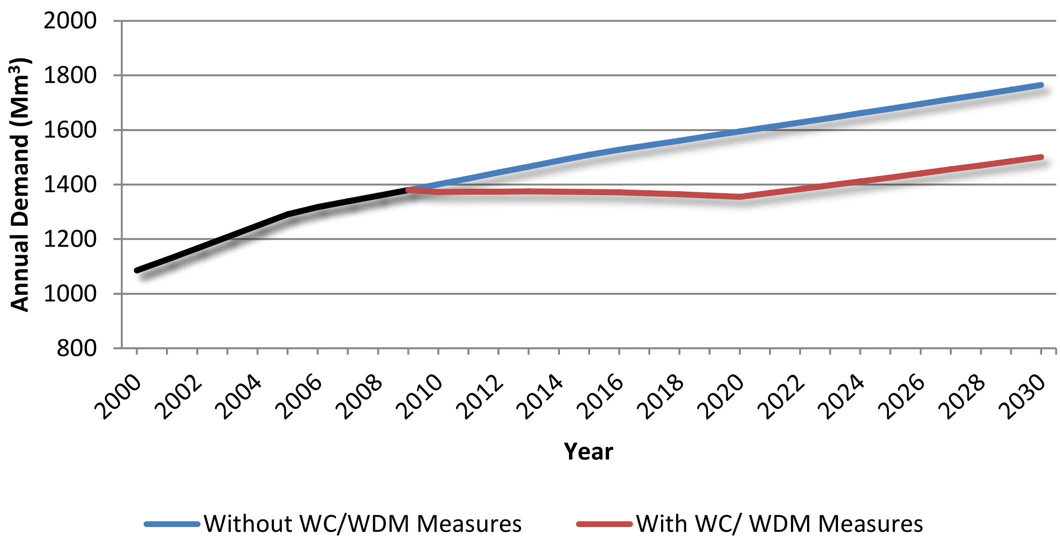

Figure 6.19: Rand Water Demand with and without WC/ WDM Measures

6.4.5. Ecological Reserve

According to DWAF (2003), “the ecological component of the Reserve refers to that portion of stream flow which needs to remain in the rivers to ensure the sustainable healthy functioning of aquatic ecosystems, while only part of the remainder can practically and economically be harnessed as usable yield”.

Current provisional assessments indicate that, as a national average, about 20% of the total river flow is required as Ecological Reserve which needs to remain in the rivers to maintain a healthy biophysical environment (DWAF, 2002).

The monthly time series of water requirements for the ecological component of the Reserve have been determined at the outlet of each QC by the DWA. These time series have been analysed for various lengths of the critical drought to establish the system yield required for the ecological component of the Reserve (DWAF, 2002). However, a comprehensive Ecological Reserve has not been determined for the UVRB and the whole Vaal Basin for that matter (DWAF, 2002).

Table 6.5 shows the proportion of MAR required as the ecological reserve determined at key points. These points coincide at the catchment outlets.

Table 6.5: Ecological Reserve as a Portion of MAR

Key Point	Riverine Ecological Requirement
	% Virgin MAR
Wilge (C83M)	13.4
Klip River (C13H)	13.4
Grootdraai (C11L)	8.9
Suikerbosrand (C21G)	9.4
Klipspruit (C22E)	9.7
Mooi (C23K)	22.6
Barrage to Mooi (C23L)	9.7

Extracted from DWAF (2002)

Therefore, this Study has assumed the aforementioned percentages for monthly simulated stream flow instead of MAR so as to have an indication of whether this requirement will be met in the future. The objective here is not to have a conclusive result on whether this requirement will be met because studies on required reserve volumes have not yet been carried out. The aforementioned assumption only goes to give a 'what if' analysis on the ER if the percentages given in Table 6.5 were to be adopted. It should be noted that these percentages lie within the national average of 20%, thus the assumption that the individual requirements determined even after a comprehensive study will be close to the above figures would be valid.

The key points have been approximately placed on the schematic of the UVRB in WEAP as shown in Figure 6.20.

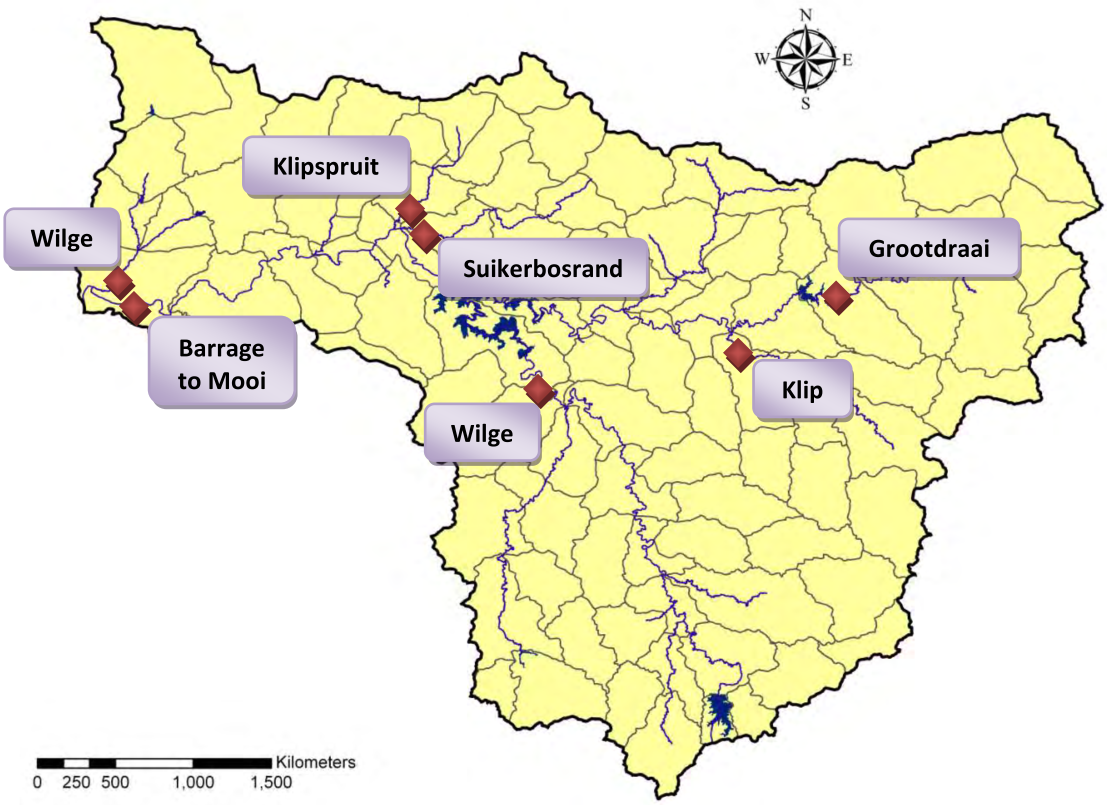

Figure 6.20: Location of IFR Key Points in WEAP

6.5. Scenario Results

The model was set up under a combination of 2 climate change, 2 inter basin transfer from LHWP and 1 water demand and conservation (WC/WDM) scenarios. These scenarios are outlined in Table 6.6.

In addition, the simulation results are for the basic condition that all consumers have an equal right to water. Therefore any form of consumer priority in supply has not been considered.

Table 6.6: Summary of Developed Scenarios for the UVRB Model

Scenario	Climate Model	LHWP Transfer	WC/WDM	Case
1	ECHAM4	Scenario A	None	Worst
	CSIRO			
2	ECHAM4	Scenario A	Scenario E	Medium
	CSIRO			
3	ECHAM4	Scenario B	None	Best
	CSIRO			

6.5.1. Scenario 1: LHWP Scenario 'A'/ No Implementation of WC/WDM

This scenario adopts a situation whereby the inter basin transfer from the LHWP will remain capped at the year 2008 volume. Since LHWP is the largest water transfer into the UVRB, this scenario was developed solely to demonstrate the situation which would arise if this source was constrained in the future.

6.5.1.1. Streamflow

Simulated stream flows under scenario 1 are presented for the UVRB Zones 1, 2, 3 and Overall Basin respectively.

i) Zone 1

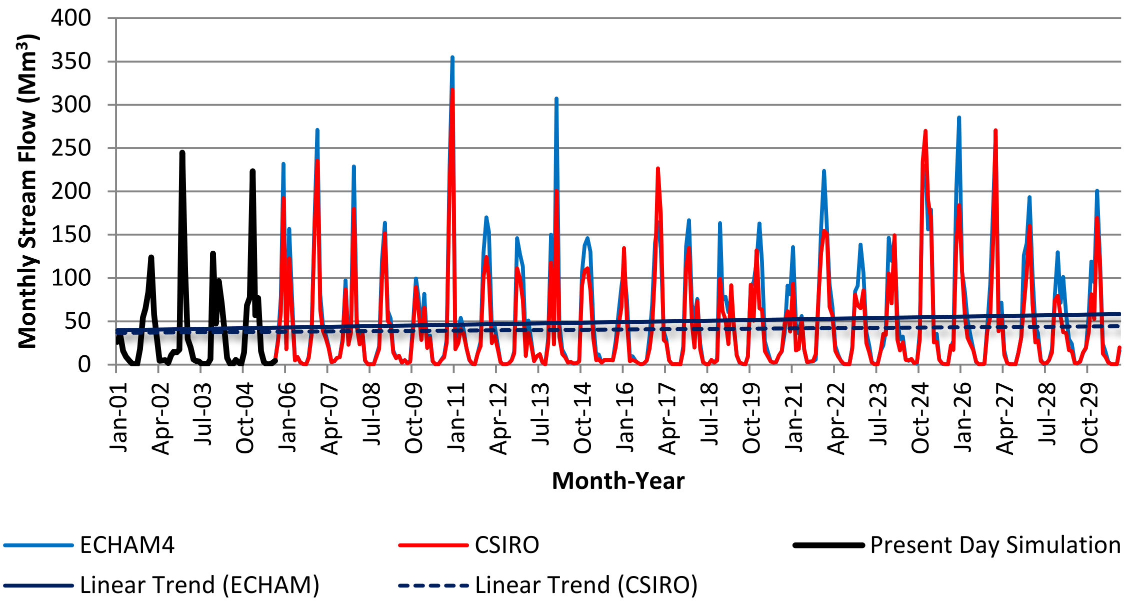

Figure 6.21: Simulated Monthly Stream Flows for Zone 1 under Scenario 1

ii) Zone 2

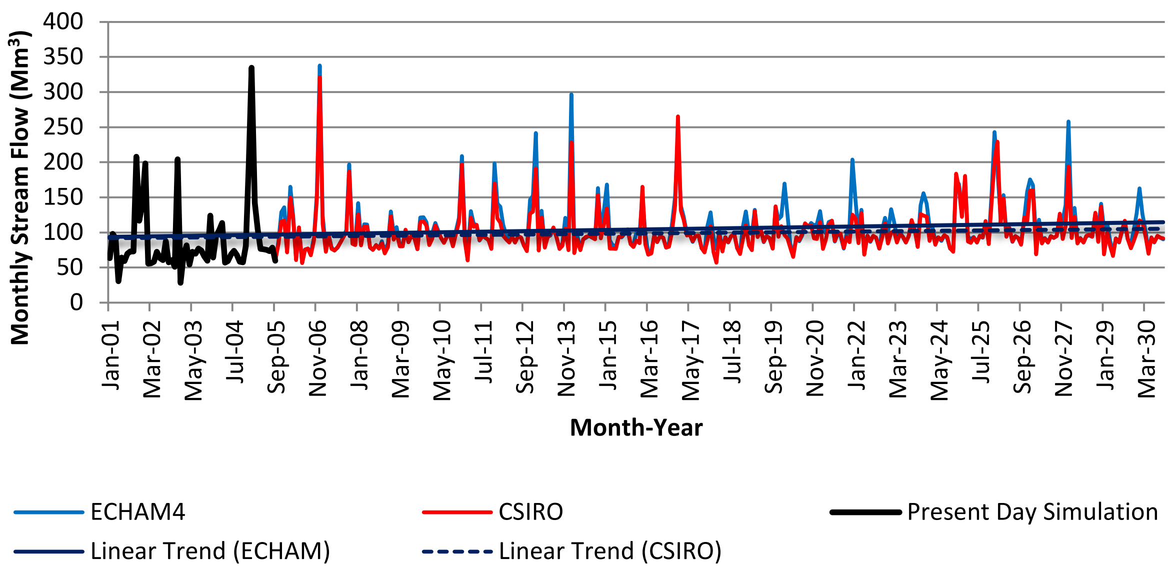

Figure 6.22: Simulated Monthly Stream Flows for Zone 2 under Scenario 1

iii) Zone 3

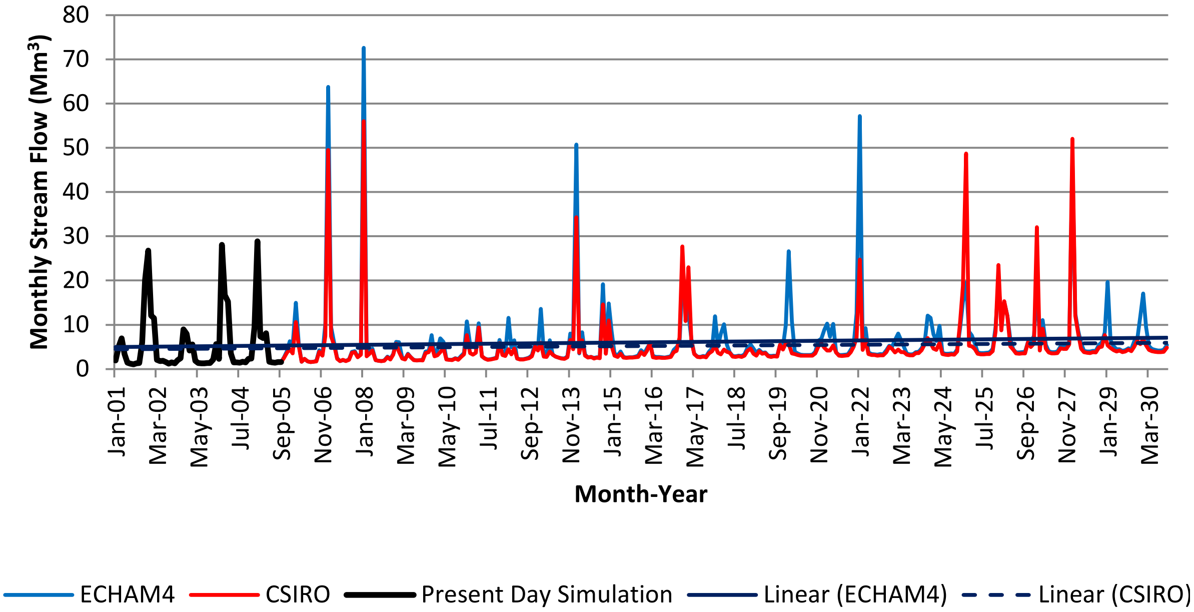

Figure 6.23: Simulated Monthly Stream Flows for Zone 3 under Scenario 1

iv) Overall Basin

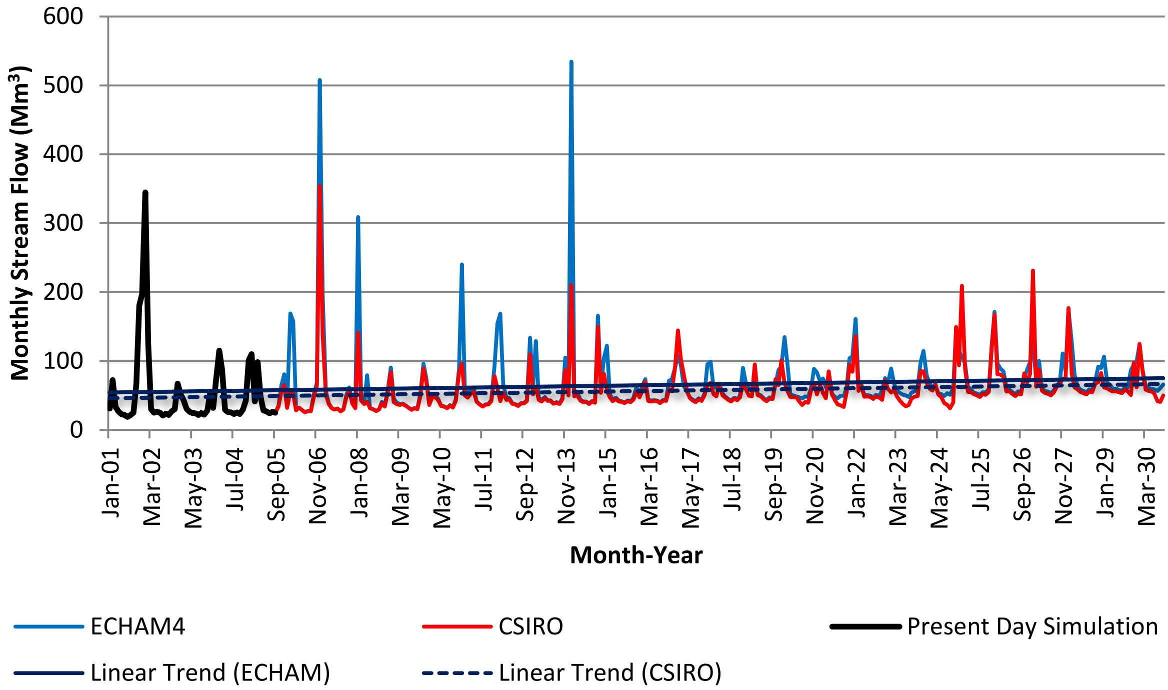

Figure 6.24: Simulated Monthly Stream Flows for Overall Basin under Scenario 1

Stream flows for all zones, especially Zone 3, show a rising trend with ECHAM producing larger peaks compared to CSIRO. The general and seasonal Mann Kendall test was carried out on the simulated stream flow which confirmed the presence of an increasing trend shown in Figure 6.21 to Figure 6.24. At a 5% significance level (α), the null hypothesis stating there is no trend in the simulated stream flow was rejected for all scenarios. Furthermore, a trend was also detected in the time series when seasonality was considered. Table 6.7 outlines the results of the trend analysis.

Table 6.7: Results from the Mann Kendall Trend Analysis for Scenario 1

Trend Test	Climate Model	Scenario 1	
		P-Value	Kendall's Tau
General Mann Kendall	ECHAM	< 0.001	0.369
Seasonal Mann Kendall		< 0.001	0.560
General Mann Kendall	CSIRO	< 0.001	0.346
Seasonal Mann Kendall		< 0.001	0.504

The period between years 2017 to 2024 has smaller peaks which show that this possibly signifies a relatively dry period.

A mean monthly stream flow analysis was carried out on the 40 year historical stream flow recorded at the gauge used to measure overall basin performance in comparison with the simulated stream flow statistics that is the mean, minimum, maximum, mean plus one standard deviation and mean minus one standard deviation. The latter two statistics shows the stream flows occurring at least 68% of the time. The graphical plots of the above mentioned statistics for Scenario 1 are given in Figure 6.25 and Figure 6.26 for each of the GCM model.

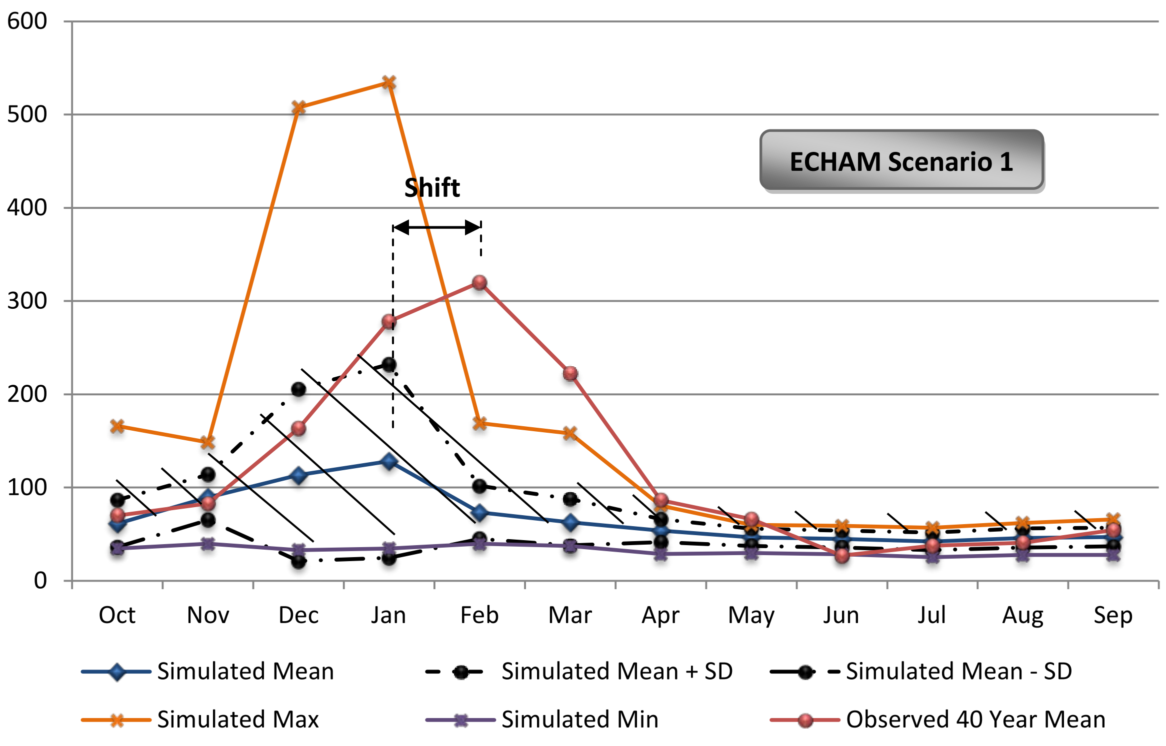

Figure 6.25: Simulated Mean, Maximum, Minimum, One Standard Deviation & Historical Mean Monthly Stream Flows (ECHAM)

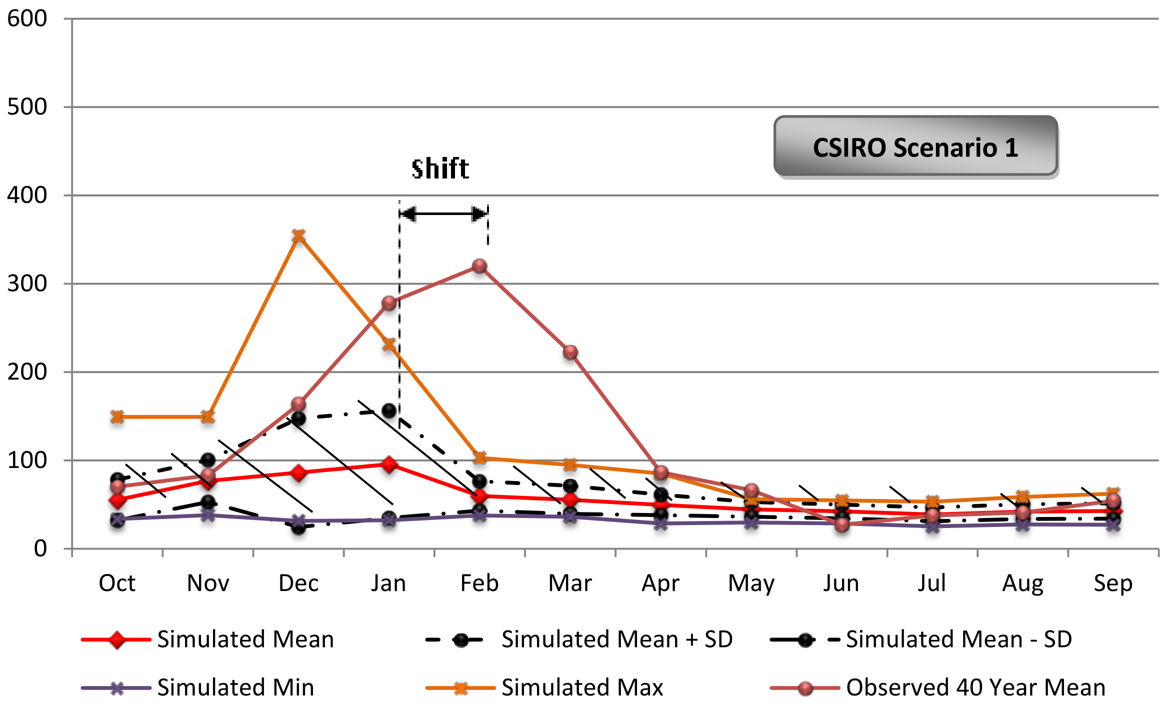

Figure 6.26: Simulated Mean, Maximum, Minimum, One Standard Deviation & Historical Mean Monthly Stream Flows (CSIRO)

It can be observed that historical mean monthly stream flows are higher than the simulated values despite rainfall predicted to be more in the future. This can be attributed to the fact that water demands are much higher in the present compared to the past 40 years and will continue to rise in the future thus having a negative impact on the stream flows. In addition, the month having the peak stream flow has shifted by one month to January.

6.5.1.2. Reservoir Storage

The reservoirs have been modelled with the lowest priority in WEAP. This means that preference is given to meeting water demands over reservoir filling. Storage results for the two main reservoirs in the UVRB are presented hereafter.

i) Vaal Dam

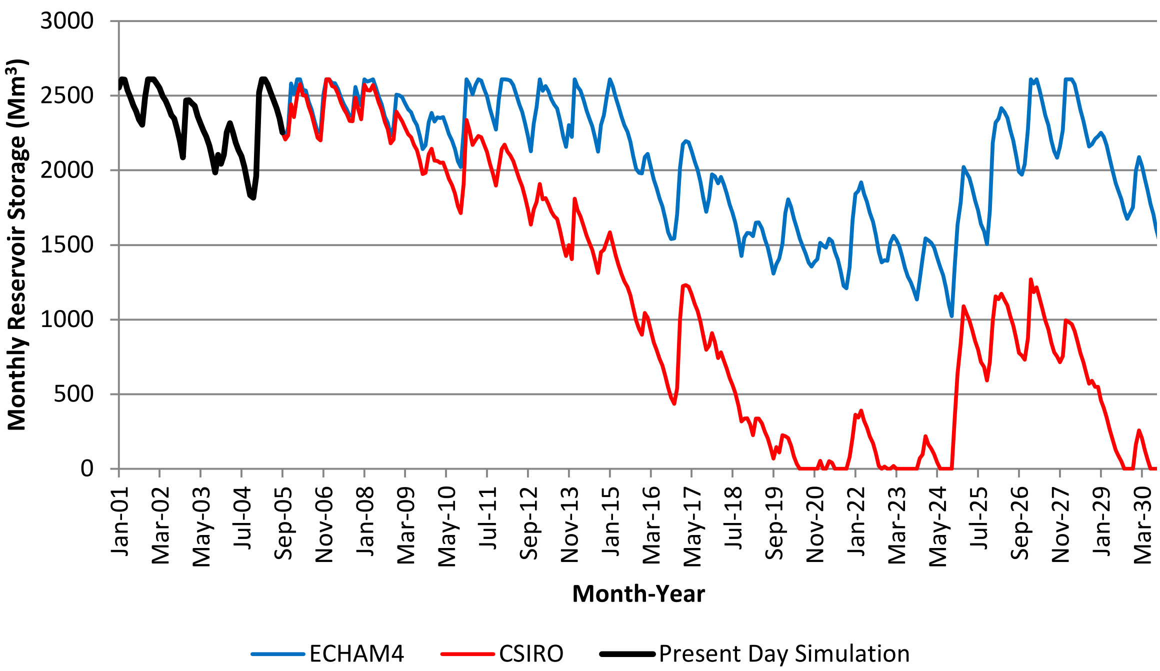

Figure 6.27: Vaal Dam Simulated Monthly Reservoir Storage under Scenario 1

ii) Grootdraai Dam

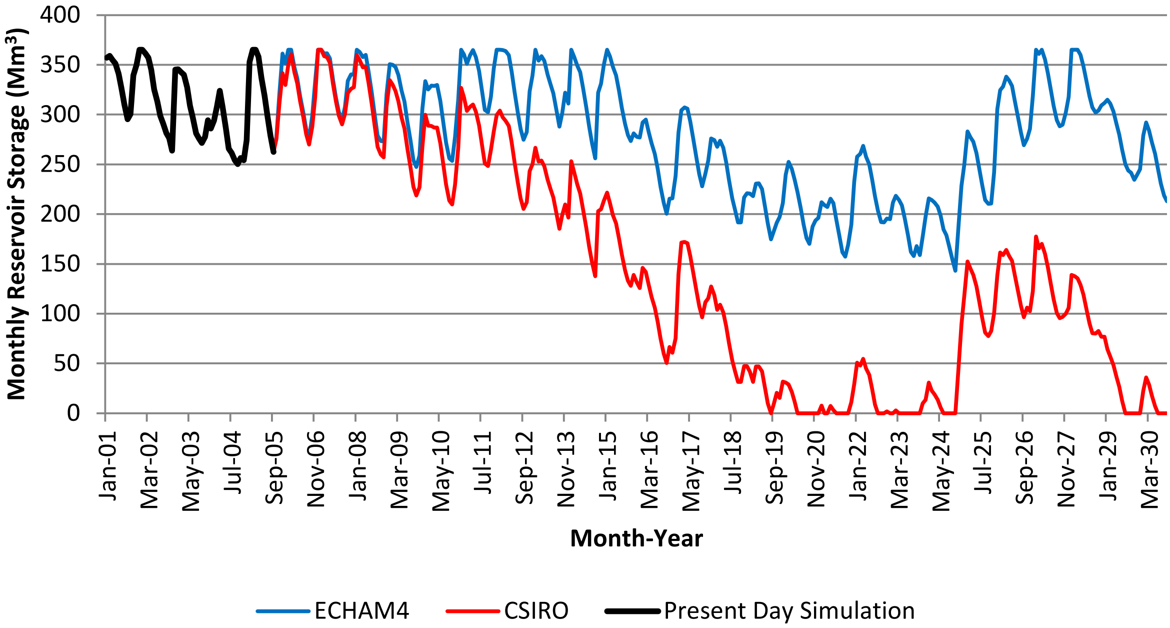

Figure 6.28: Grootdraai Dam Simulated Monthly Reservoir Storage under Scenario 1

The reservoirs show a declining trend in storage from mid 2010 to mid 2024 with both reservoirs drying up between years 2019 and 2024 under the CSIRO GCM. This can be attributed to the demand-driven set up of the model in which the reservoirs ensure all demands downstream are supplied to, irrespective of the drawdown consequences. However, the reservoirs undergo a lower draw down under the ECHAM scenario, with storage being approximately 57% for both reservoirs within the dry period.

6.5.1.3. <u>Unmet Water Demand</u>

According to the model, the main deficits in water supply occur in the irrigation sector and few small towns in the UVRB. For the case of the small towns, the deficits have not been considered significant because they also depend on groundwater for alternative supply (DWAF, 2002). The simulated deficits generally range within 50 – 60% of required demand. However, DWAF (2002) stipulates water requirements for small towns is alternatively met from small dams and alternative sources such as boreholes and wells. The alternative sources were not modelled because of unavailability of data thus the total abstraction for the towns was assigned to surface water sources only. An example is Qwa Qwa and Harrismith towns which, according to the model, experience serious deficits during the dry season. However, the surface water sources have been historically inadequate for Qwa Qwa therefore its supply being the responsibility of Sedibeng Water Company in the Middle Vaal WMA.

The areas experiencing deficits in irrigation during the dry season are mainly located in Zone 2 of UVRB as shown in Figure 6.29. A comparison of the required irrigation demand and the demand supplied (totalled over the dry season which spans the months of June, July and August JJA) is given in Figure 6.30.

The supply to Rand Water, ESKOM, SASOL and Mittal Steel are assured to the year 2030 according to the results. However, this assurance has to be viewed in relation to depleting reservoir storage. As mentioned earlier, the model has been setup to supply water to all consumers on an equal priority. Therefore, the model reservoir operation will constantly ensure all downstream demands are met irrespective of its storage. Therefore, the assurance of supply in this case would be incorrect.

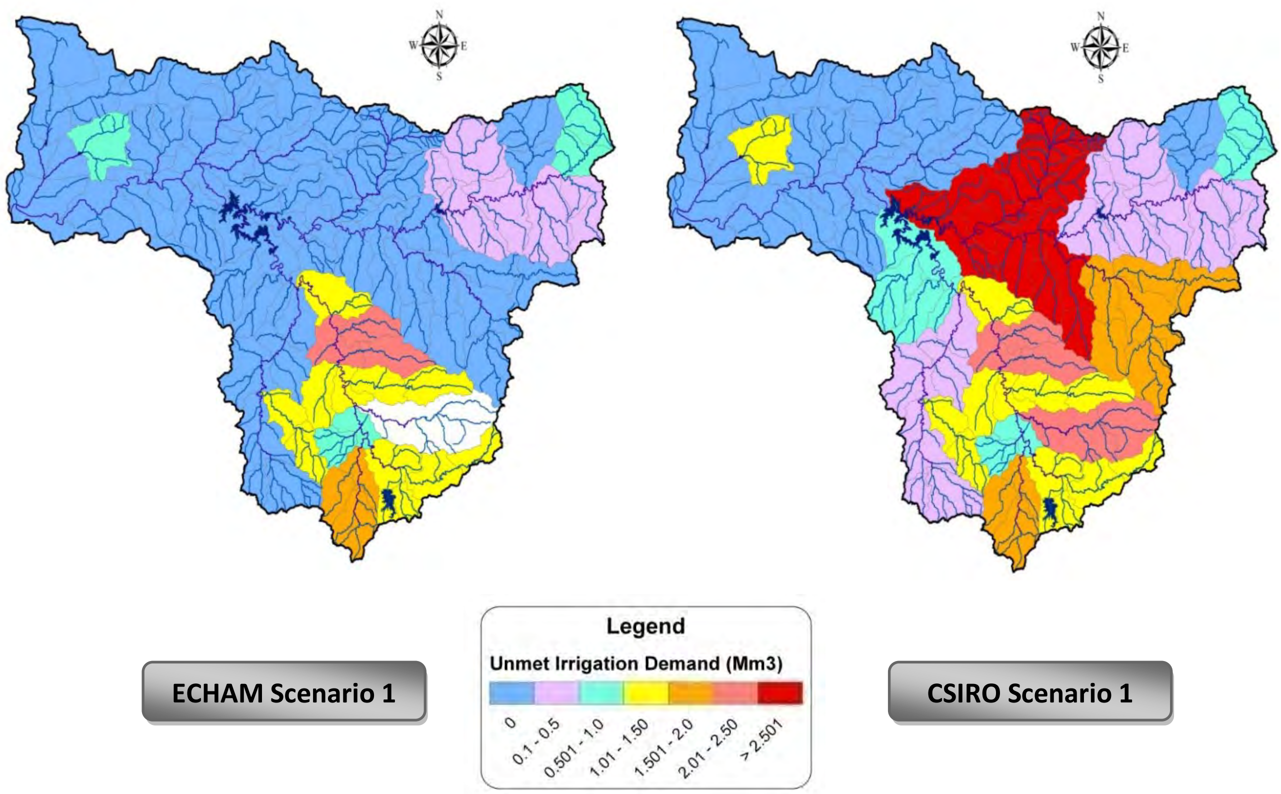

Figure 6.29: Range of Irrigation Supply Deficit in Future Dry Seasons (JJA) under Scenario 1 (Year 2005 – 2030)
(Individual monthly deficits totalled for JJA)

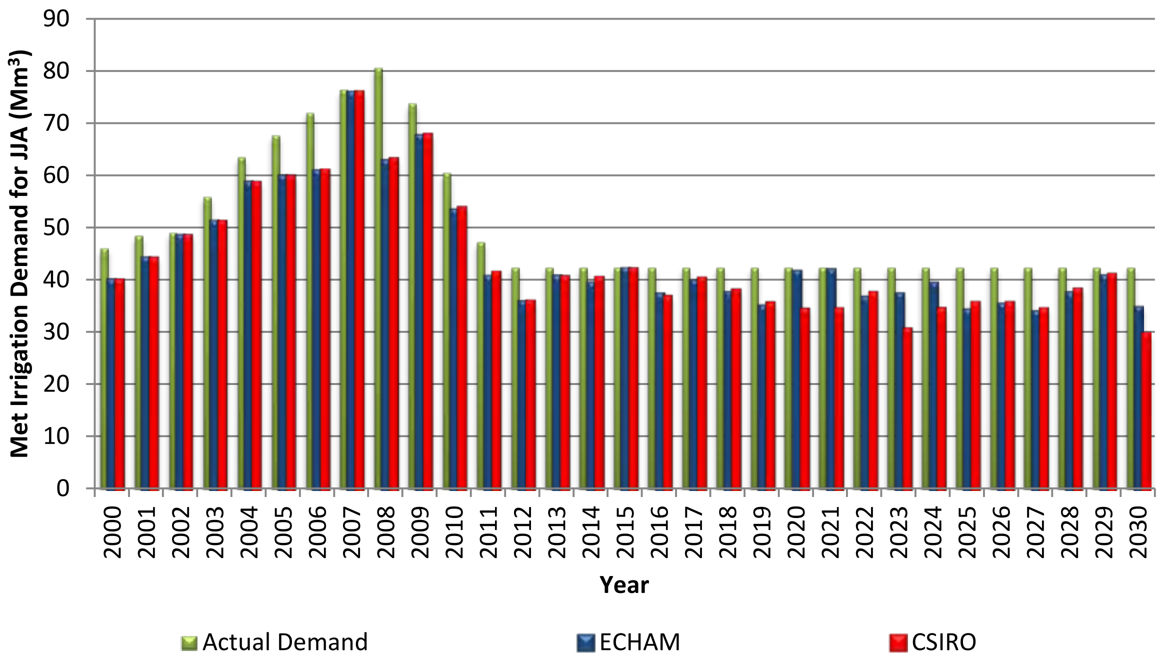

Figure 6.30: Irrigation Demands met for Dry Season (3-Month Total of JJA) (Scenario 1)

A closer inspection of Figure 6.30 shows that total unmet demands are, in 17 of the 30 years, greater using the ECHAM model than CSIRO. This concurs with the findings in Section 6.3.1.2 which outlines the lower predicted JJA rainfall by ECHAM compared to CSIRO. Consequently, the simulated stream flows are lower for ECHAM. Figure 6.31 shows the ECHAM stream flow relative to CSIRO for Zone 2. It is very clear that the ECHAM stream flows are lower in Zone 2, thus explaining the larger unmet water demands in its case. Furthermore, as from year 2012, approximately 10 and 13% of the irrigation requirement is not met using both ECHAM and CSIRO models respectively.

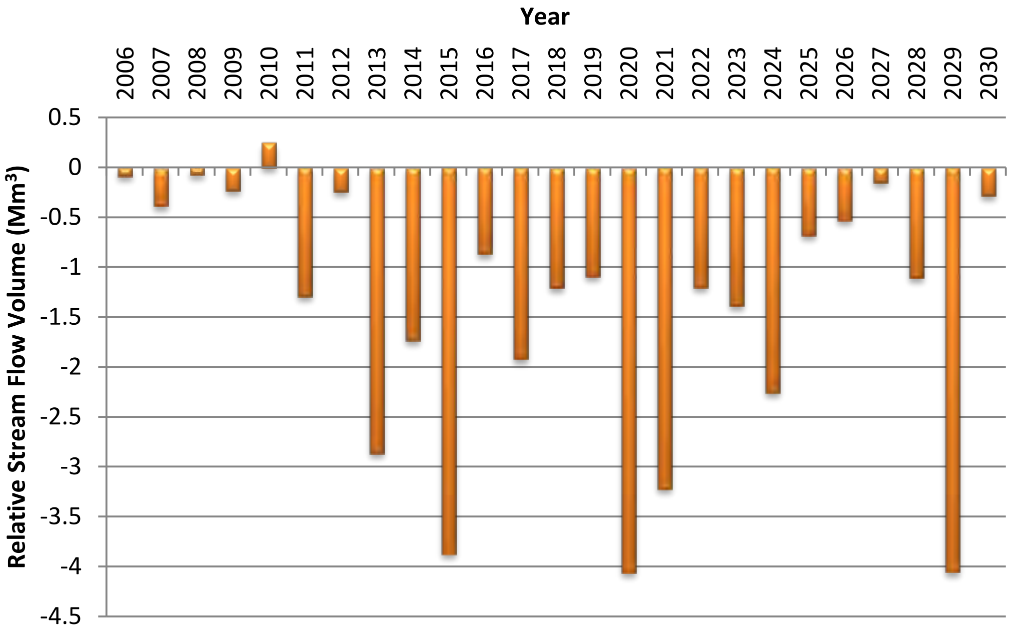

Figure 6.31: ECHAM Annual Stream Flow relative to CSIRO for JJA in Zone 2

6.5.1.4. <u>In-stream Flow Requirement</u>

The ability of the system to meet the in-stream flow requirements was analysed for the dry season (JJA) as this would represent the critical case. IFR requirements are met during the dry season for all key points except Klip River. The results of the simulation are given in Figure 6.32.

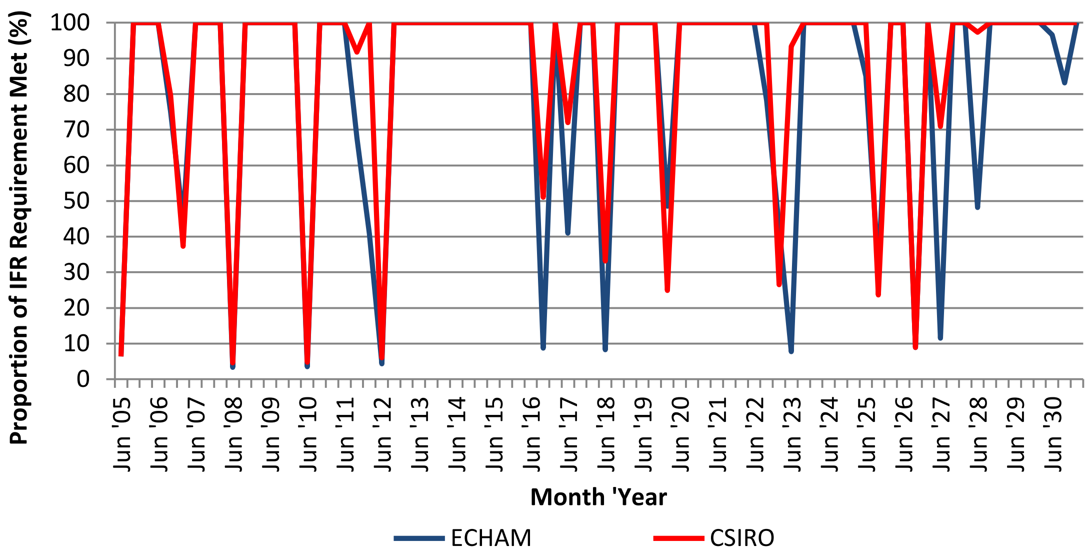

Figure 6.32: Proportion of IFR Demand Met in the Dry Season (JJA) for Scenario 1

The simulation shows that the IFR requirements are generally not met through the dry period at the Klip River key point. In some years, unmet IFR is as high as 97% of the actual requirement. The magnitude of unmet IFR under the ECHAM model is larger due to the explanation given in Section 6.3.1.2. It can be observed that dry season IFR for the years 2016 to 2028 is generally not met with only 3 years having this requirement fully supplied.

6.5.2. Scenario 2: LHWP Scenario 'A'/ Implementation of WC/WDM

This scenario assumes the same supply condition as in Scenario 1 but with implementation of WC/WDM measures. Scenario 2 goes on to depict the impacts of savings in water use (refer to Table 6.4) on the water resources.

6.5.2.1. <u>Streamflow</u>

i) Zone 1

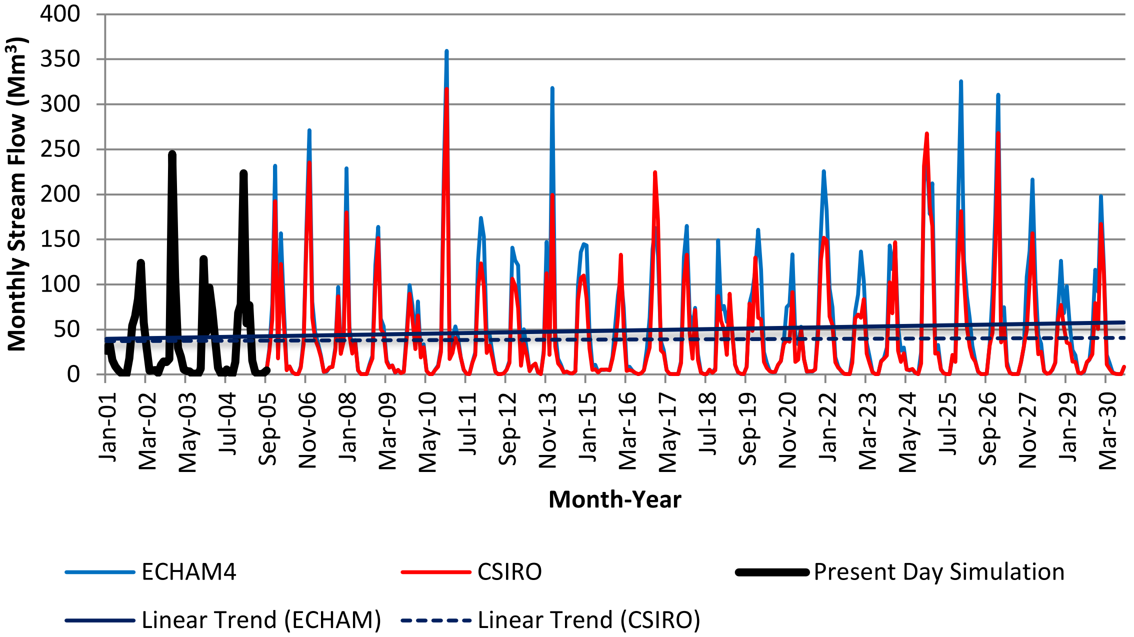

Figure 6.33: Simulated Monthly Stream Flows for Zone 1 under Scenario 2

ii) Zone 2

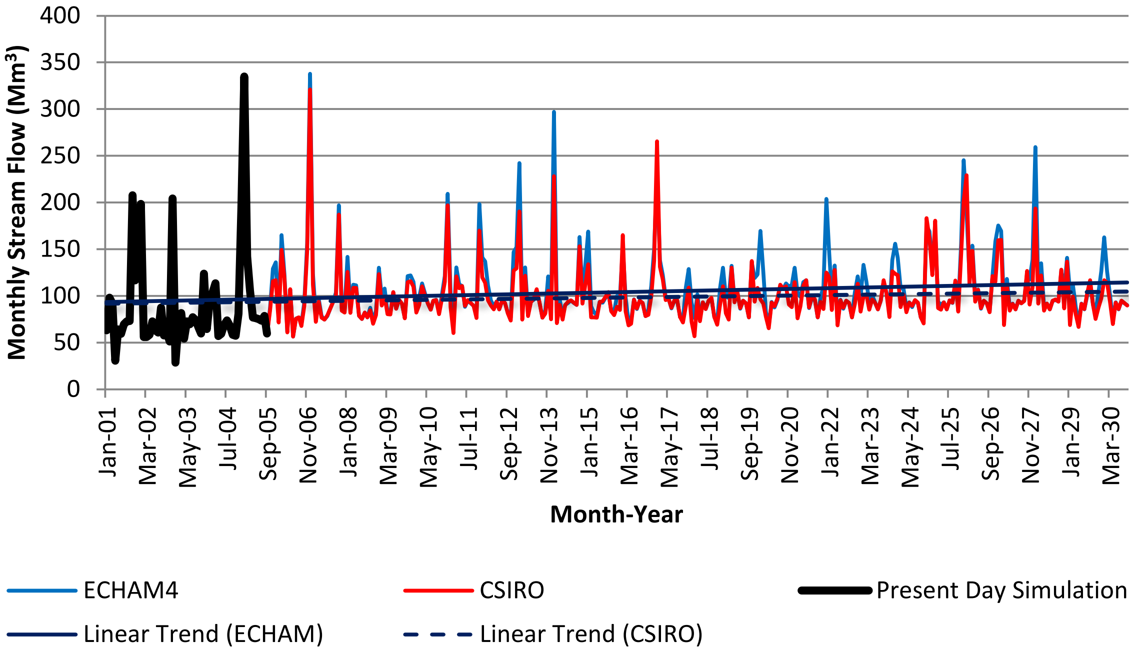

Figure 6.34: Simulated Monthly Stream Flows for Zone 2 under Scenario 2

iii) Zone 3

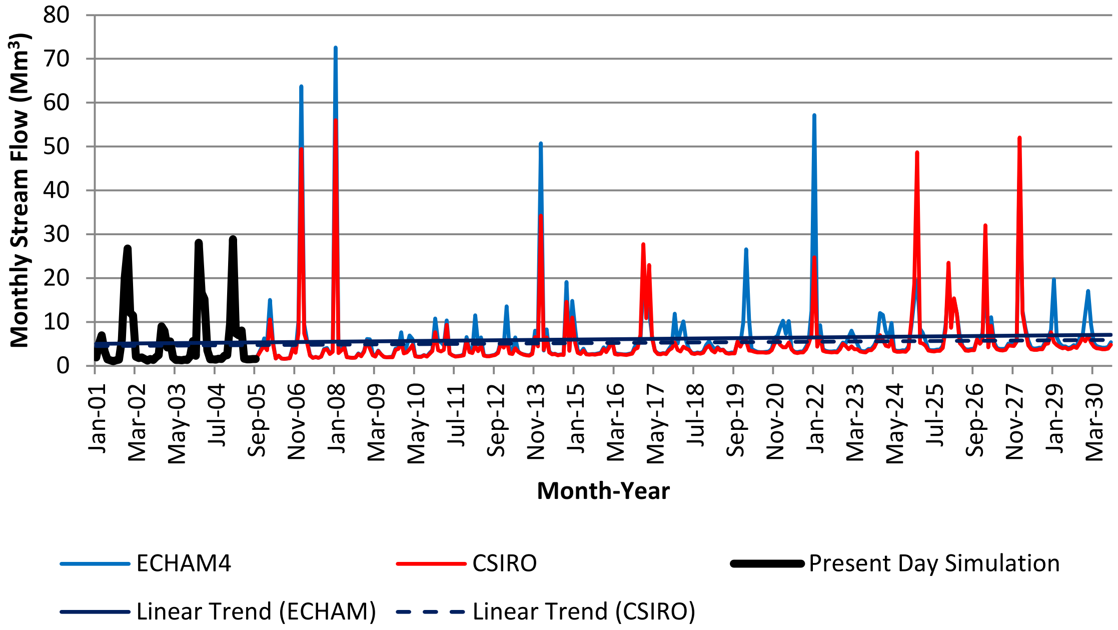

Figure 6.35: Simulated Monthly Stream Flows for Zone 3 under Scenario 2

iv) Overall Basin

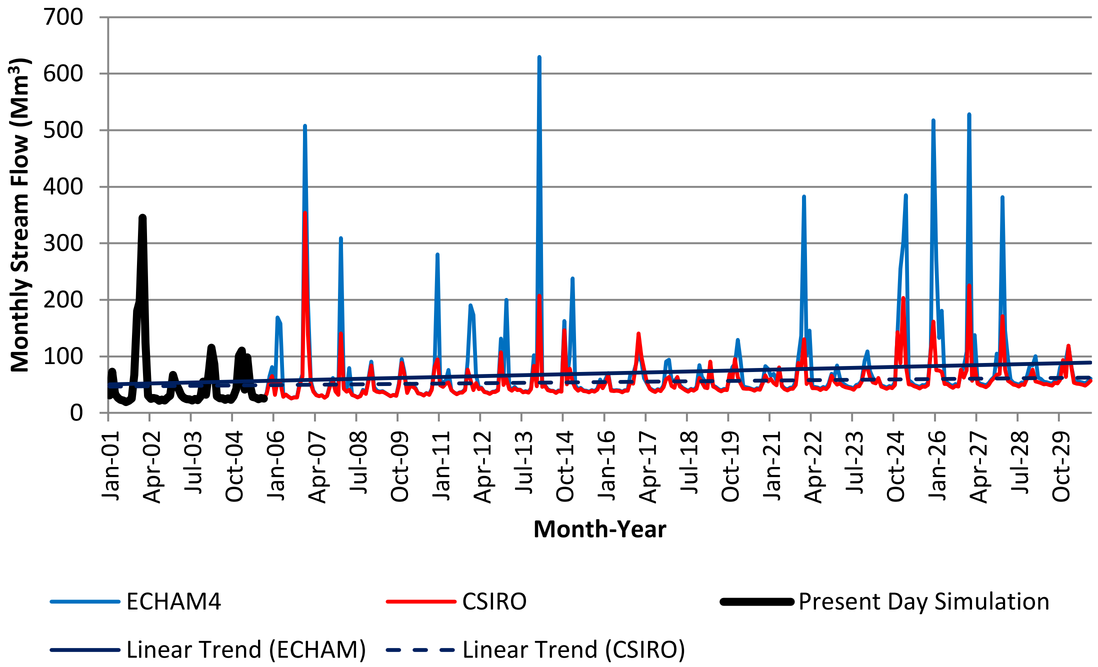

Figure 6.36: Simulated Monthly Stream Flows for Overall Basin under Scenario 2

Similar to stream flows under Scenario 1, Scenario 2 shows an increasing trend in stream flow in Zone 1. The magnitude of peaks increases towards the end of the simulation period. However, stream flows in Zone 2 and 3 show no change from Scenario 1. This was expected because the WC/ WDM measures were solely applied to demands supplied by Rand Water which abstracts water from the Vaal Dam. Therefore, any savings in water will be affected in the storage of the reservoir system which comprises of Vaal and Grootdraai dams. Zone 2 lies upstream of the Vaal Dam and Zone 3 is on the Mooi River which is a tributary of the Vaal River thus have no direct or indirect relation with the savings from the WC/ WDM measures.

The Overall Basin hydrograph shows similar increases in stream flows as Zone 1 towards the end of the simulation period. As mentioned earlier, the modelled reservoirs operate as a system. Therefore, a saving in demand abstracted from the Vaal Dam would translate to changes in released stream flows. The node used to measure stream flow for the overall basin lies on the Vaal River downstream of Vaal Dam. In addition, the increased stream flows can also be attributed to the contribution of intermediate QC's to river reaches between the two dams.

The Mann Kendall statistics were not computed for this scenario because the trend would be similar to Scenario 1 due to savings in water use consequently resulting in more storage and stream flow volumes.

6.5.2.2. <u>Reservoir Storage</u>

i) Vaal Dam

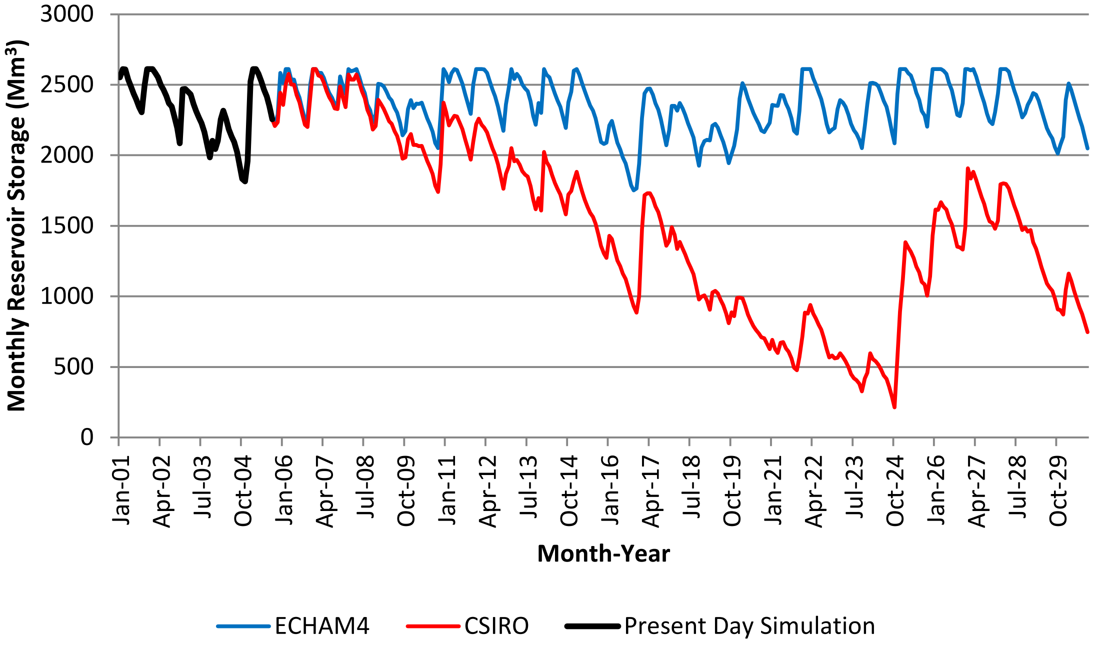

Figure 6.37: Vaal Dam Simulated Monthly Reservoir Storage under Scenario 2

ii) Grootdraai Dam

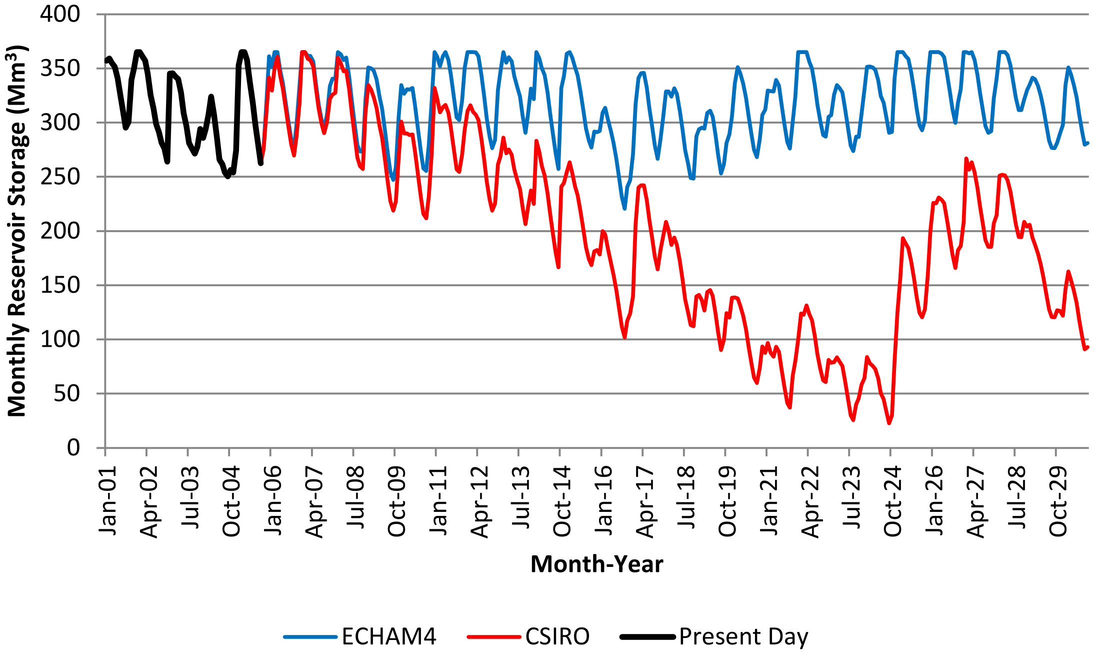

Figure 6.38: Grootdraai Dam Simulated Monthly Reservoir Storage under Scenario 2

There is a marked increase in storage as a result of the implementation of WC/ WDM measures. However, the period between years 2010 to 2024 show a significant decline in storage under CSIRO, whereas a smaller reduction is realised under the ECHAM model for the same period. This observation is characteristic of Scenario 1 as well. The WC/ WDM measures have however prevented the reservoirs from drying up thus shows that a savings in water use can result in significant increase in water resources. The ECHAM model predicts lowest storage of 68% both in Vaal and Grootdraai Dams late in year 2017 and 2024 respectively. Under the CSIRO model, the Vaal and Grootdraai Dams reach their lowest storage of 8% in mid year 2017 and 9% late in year 2024 respectively. The above translates to approximately 10% increase in storage from implementation of WC/ WDM measures for both reservoirs under ECHAM and CSIRO models.

6.5.2.3. Unmet Water Demand

The unmet demands under Scenario 2 lie within the same range as Scenario 1. Reference is made to Figure 6.29 which shows the areas whose respective irrigation requirements are not met. The explanation behind this outcome is that most of the areas experiencing deficits are located in the upstream catchments of the UVRB which rely mainly on surface runoff and small impoundments which have not been modelled. Therefore, savings from WC/ WDM measures which are applied further downstream do not result in significant benefit for these areas.

Figure 6.39 shows the proportion of irrigation demand supplied totalled over the 3 months of the dry season. The deficit in irrigation supply is now reduced to 9 and 10% for ECHAM and CSIRO respectively. This means that the WC/ WDM measures have resulted in an increase in irrigation supply by 1% and 3% for ECHAM and CSIRO models respectively.

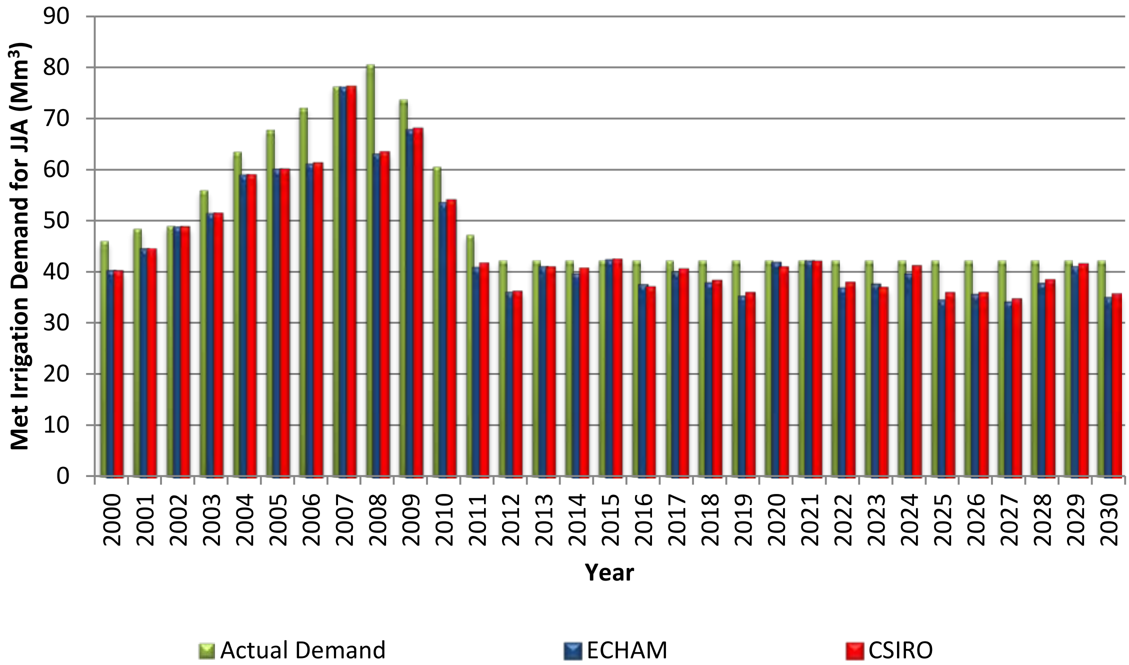

Figure 6.39: Irrigation Demands met for the Dry Season (3-Month Total of JJA) under Scenario 2

6.5.2.4. <u>Instream Flow Requirement</u>

The IFR supplied in Scenario 2 is the same as in Scenario 1 due to reasons explained in Section 6.5.2.3.

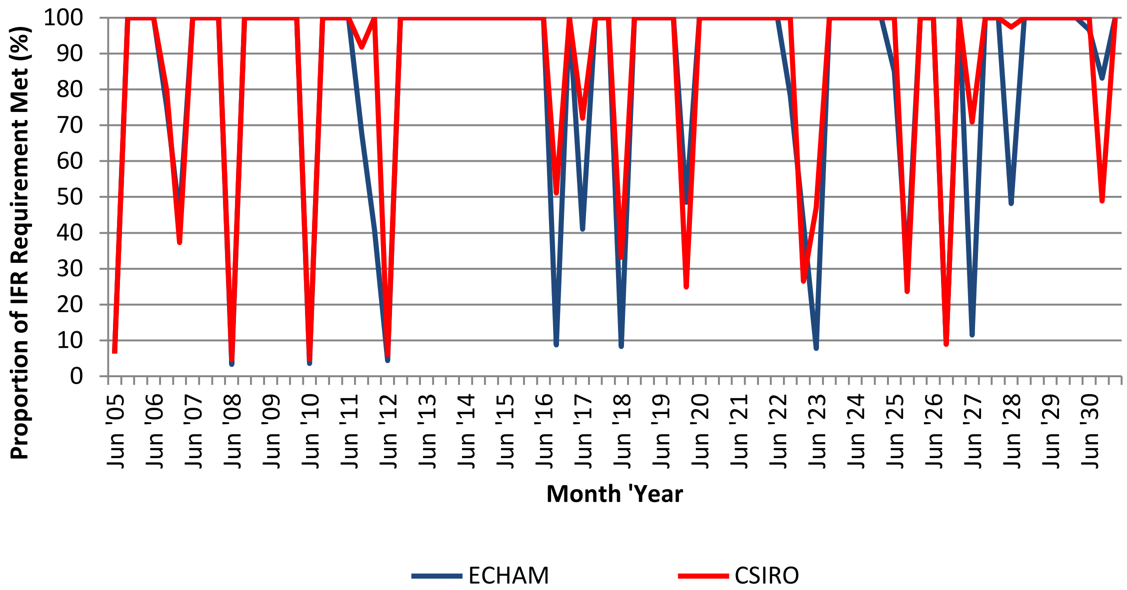

Figure 6.40: Proportion of IFR Demand Met in the Dry Season (JJA) for Klip River under Scenario 2

6.5.3. Scenario 3: LHWP Scenario 'B'/ No Implementation of WC/WDM

This scenario considers an increasing volume of water transferred from the LHWP with no implementation of WC/ WDM measures. This case portrays the best case scenario for the system because it postulates a more realistic future in terms of the increasing water transfer and the laxity in implementation of conservation measures.

The LHWP has been designed to be implemented in phases, of which phase II is near completion. There still remains 2 more phases to reach capacity as per the agreement with Lesotho. Conservation of water, on the other hand, is yet to gain adequate momentum through improvement of existing water infrastructure to reduce water losses. This measure will take time before significant results can be achieved.

Similar to previous scenario analyses, the stream flow hydrographs have been plotted for the three Zones and Overall Basin. These are given in Figure 6.41 to Figure 6.44.

6.5.3.1. <u>Streamflow</u>

i) Zone 1

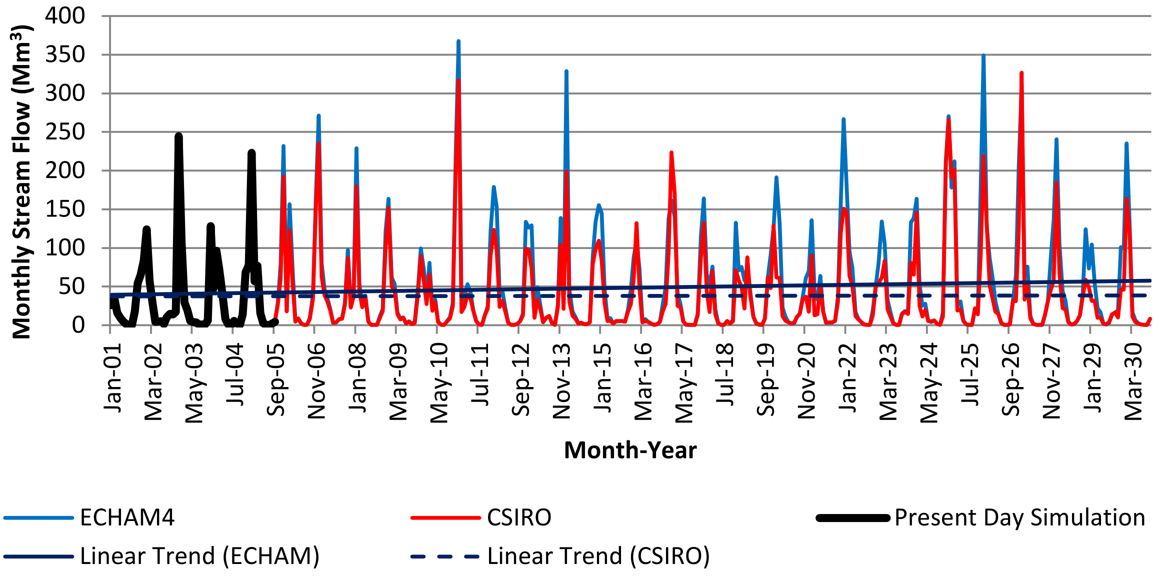

Figure 6.41: Simulated Stream Flows for Zone 1 under Scenario 3

ii) Zone 2

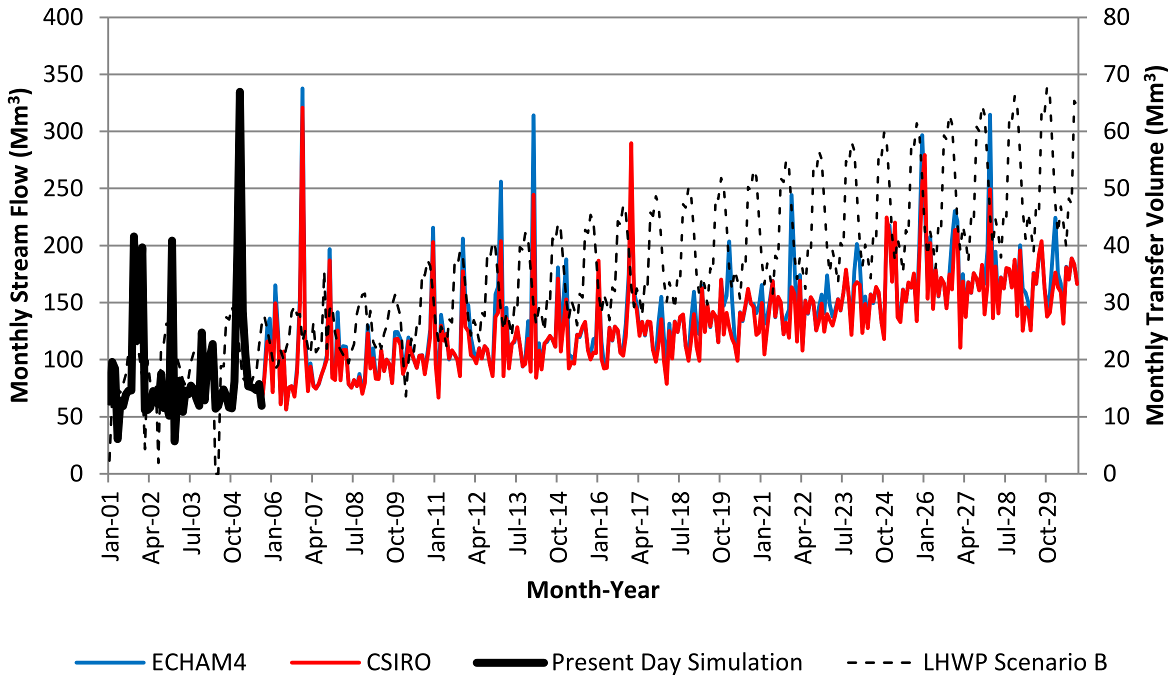

Figure 6.42: Simulated Stream Flows for Zone 2 under Scenario 3

iii) Zone 3

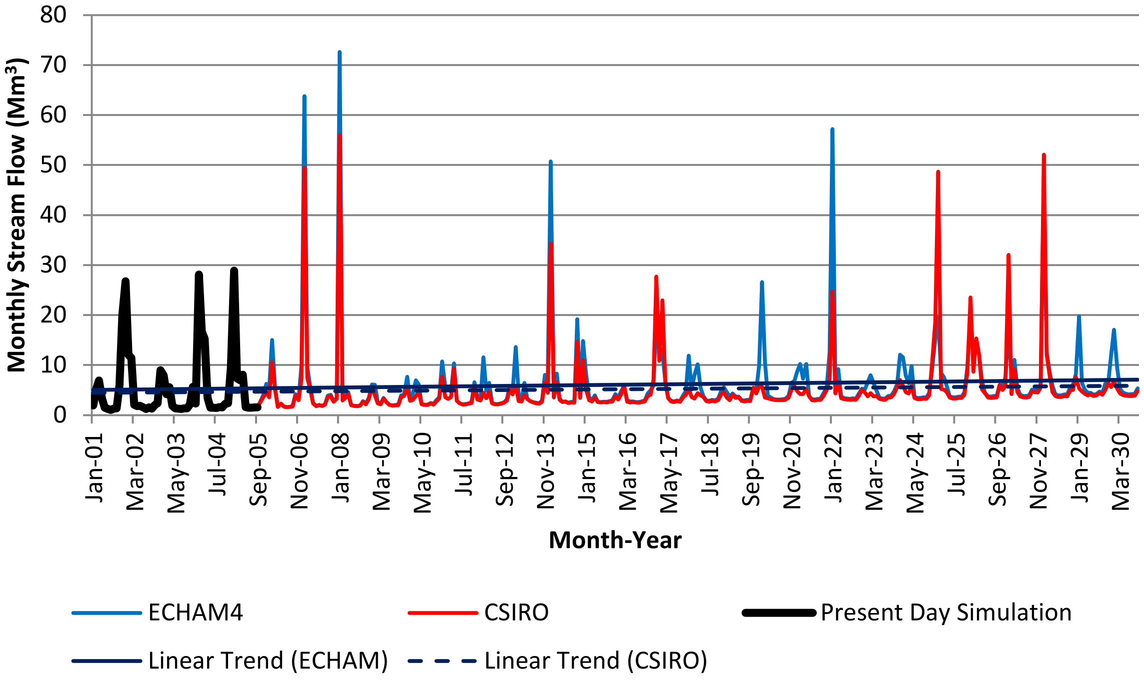

Figure 6.43: Simulated Stream Flows for Zone 3 under Scenario 3

iv) Overall Basin

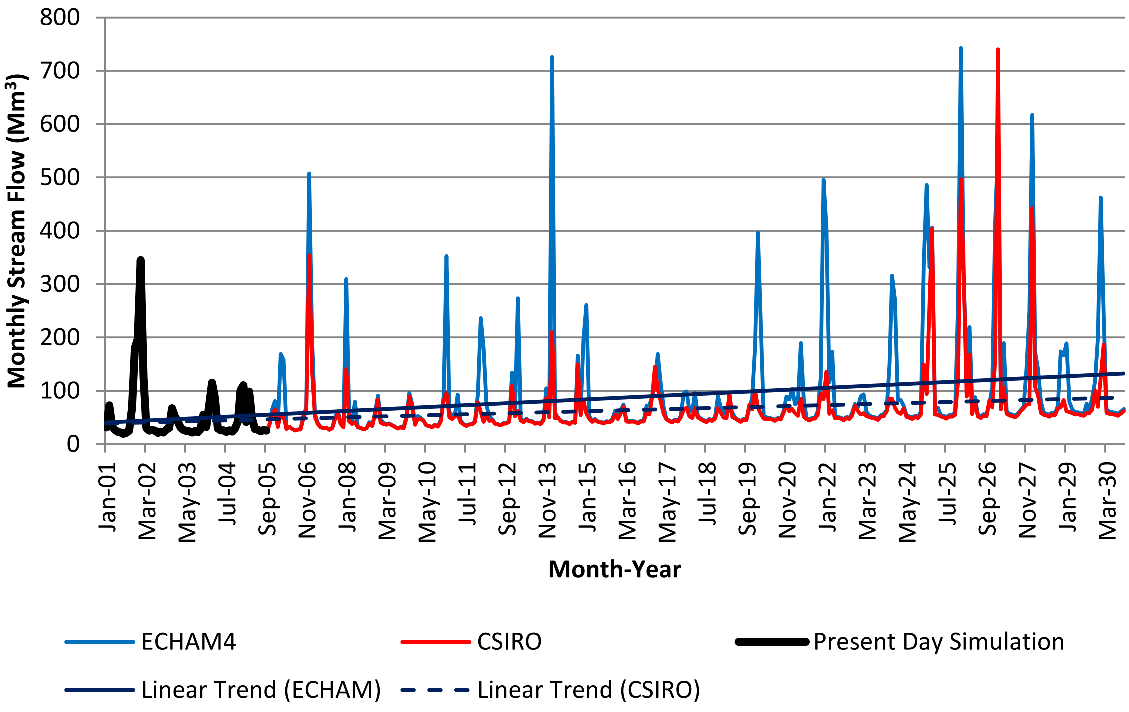

Figure 6.44: Simulated Stream Flows for Overall Basin under Scenario 3

A trend analysis was carried out on the simulated stream flows for the Overall Basin, results of which are presented in Table 6.8. At a 5% significance level (α), the null hypothesis stating there is no trend in the simulated stream flow was rejected for all scenarios. Furthermore, a trend was also detected in the time series when seasonality was considered.

Table 6.8: Results from the Mann Kendall Trend Analysis for Scenario 3

Trend Test	Climate Model	Scenario 3	
		P-Value	Kendall's Tau
General Mann Kendall	ECHAM	< 0.001	0.389
Seasonal Mann Kendall		< 0.001	0.606
General Mann Kendall	CSIRO	< 0.001	0.400
Seasonal Mann Kendall		< 0.001	0.585

The positive values of Kendall's tau indicate presence of an increasing trend over the simulation period. The very strong increasing trend in Zone 2 has been attributed to the growing volume of LHWP water transfer as indicated in the graph. The transferred water is released directly into the Liebenbergsvlei River which is the main river draining into Vaal Dam.

A mean monthly stream flow analysis was carried out on the 40 year historical stream flow recorded at the gauge used to measure overall basin performance in comparison with the simulated stream flow statistics that is the mean, minimum, maximum, mean plus one standard deviation and mean minus one standard deviation. The latter two statistics shows the stream flows occurring at least 68% of the time. The graphical plots of the above mentioned statistics for Scenario 3 are given in Figure 6.45 and Figure 6.46 for each of the GCM model. In addition, the maximum monthly observed stream flows have also been included.

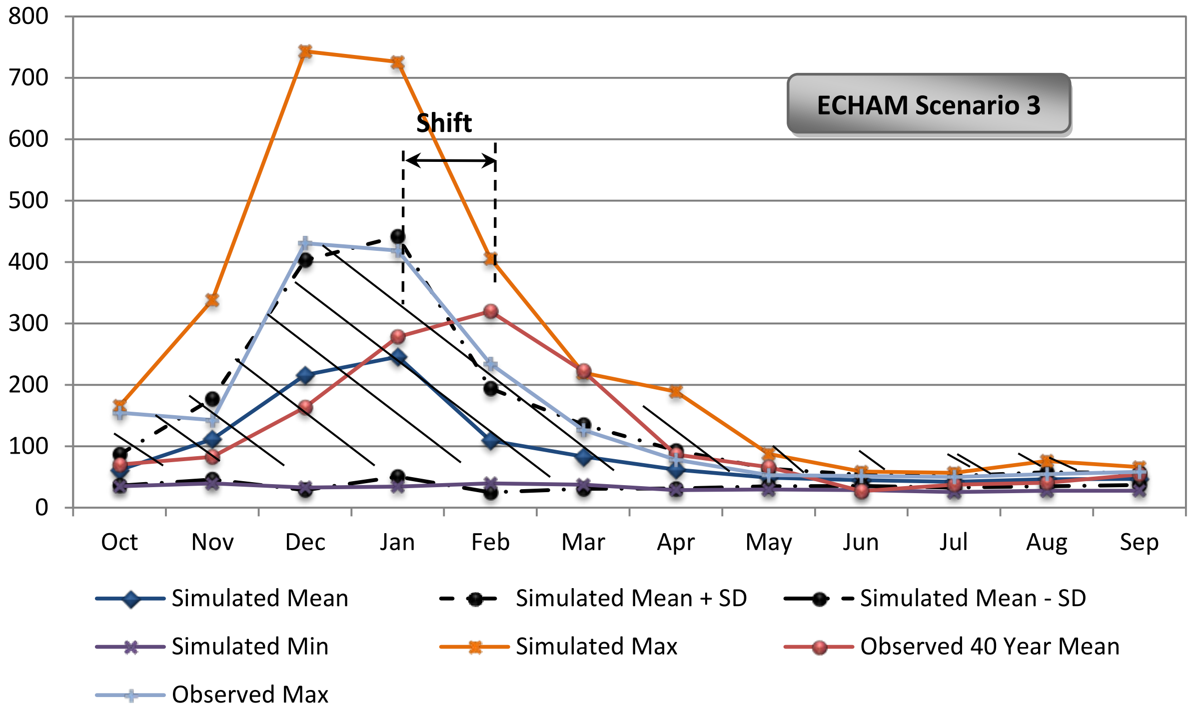

Figure 6.45: Simulated Mean, Maximum, Minimum, One Standard Deviation under ECHAM and Historical Mean and Maximum Monthly Stream Flows

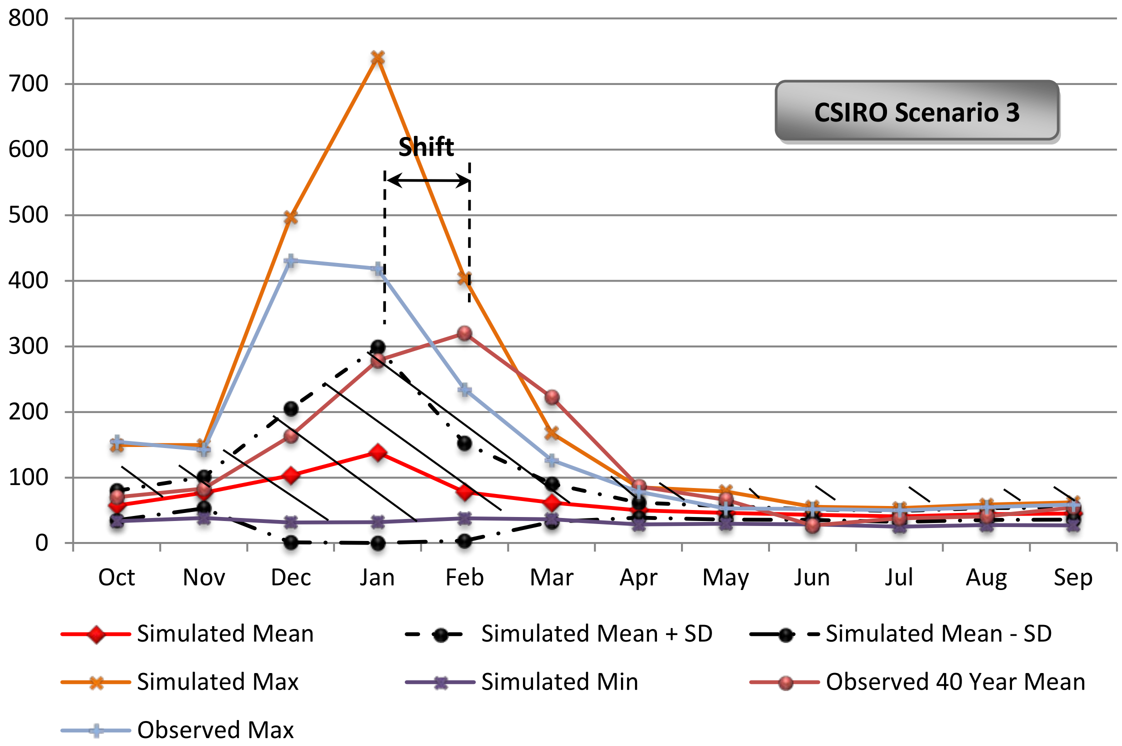

Figure 6.46: Simulated Mean, Maximum, Minimum, One Standard Deviation under CSIRO and Historical Mean and Maximum Monthly Stream Flows

The monthly mean flows are smaller for both GCMs than observed mean monthly flows. This is because of larger water abstractions in the future compared to the past. In addition, the month having the peak stream flow has shifted by a month to January from February. The maximum simulated monthly stream flows were also computed and plotted with the maximum monthly observed stream flow. This plot shows that future stream flows will be more extreme than the past.

Scenario 3 represents the best case and also is the more realistic of the other scenarios which were developed mainly for simulation of the heavy dependence of UVRB on transfer from LHWP (Scenario 1) and the impacts of WC/ WDM measures in face of constrained water resources (Scenario 2). For this reason, further analysis of the simulation results for Scenario 3 was warranted.

The magnitude of maximum stream flows in the period year 2000 – 2030 has increased compared to observed records by 91% (ECHAM) and 77% (CSIRO).

Simulated annual stream flows at the outlet of the UVRB were plotted for the two GCM models and presented in Figure 6.47. These volumes are 'released' to Middle Vaal WMA and consequently cascading to the Lower Vaal WMA for use. According to DWAF (2003), the predicted release volume in the year 2025 will be 910 Mm^3/ annum. However, both the climate models predict an ability of the basin to release a larger volume ranging from 1,400 (CSIRO) to 2070 (ECHAM) Mm^3/ annum for the same year. This means an increase of 54% and 130% from the predicted volume.

A correlation analysis of predicted annual rainfall with simulated annual stream flow for year 2005 – 2030 was also carried out and results are given in Figure 6.48.

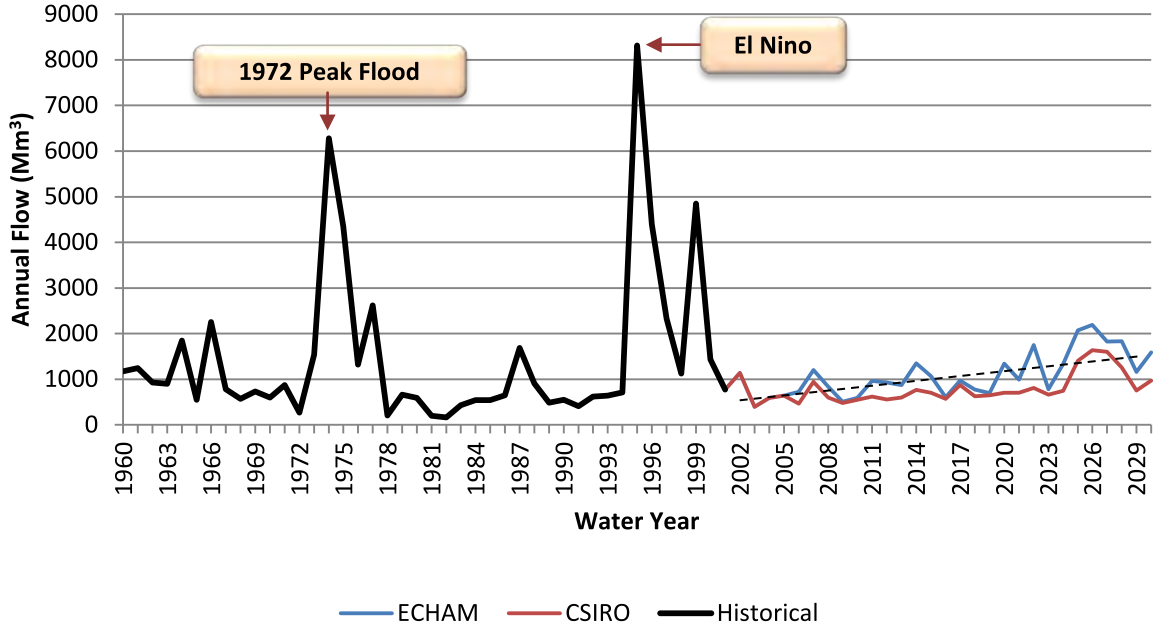

Figure 6.47: Annual Stream Flows at Basin Outlet under Scenario 3 (1960 – 2030)

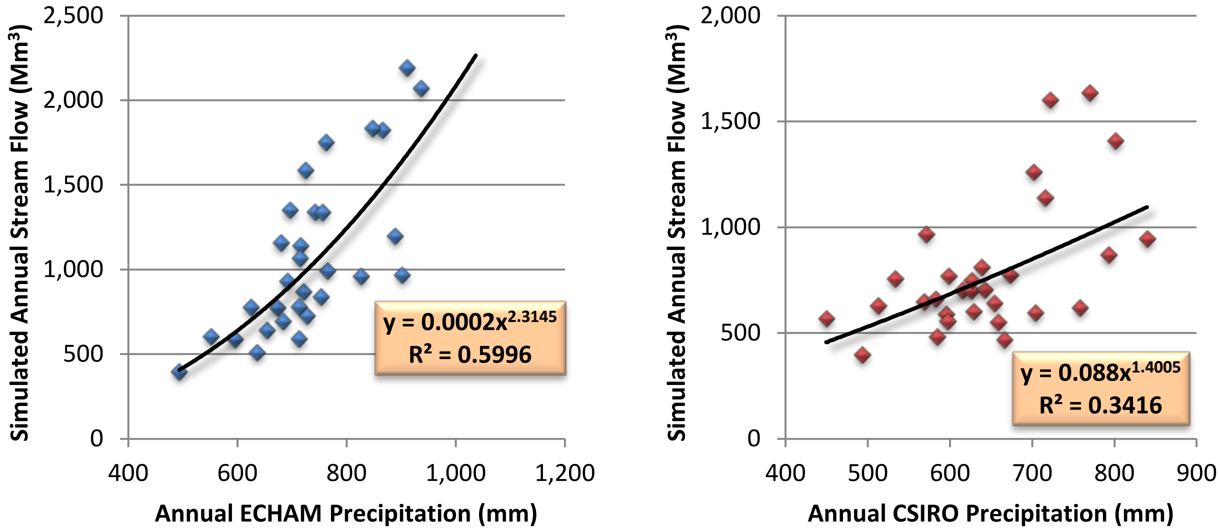

Figure 6.48: Correlation Analysis of Annual Predicted Rainfall and Simulated Stream Flows at Basin Outlet under Scenario 3

The power function resulted in the best correlation coefficient (R^2). The ECHAM correlation explains 60% of the relationship between predicted precipitation (ECHAM) and simulated stream flow. The CSIRO correlation however is weak with only 34% of the relationship being explained by the correlation equation. The power function provided the best fit because of the characteristics of rainfall – runoff relationships. Due to urbanisation and cultivation, runoff is accelerated; therefore this relationship would in most cases not be linear but rather curvilinear. Thus the results concur with this by the fact that increase in rainfall would result in a larger increase in runoff and consequently stream flow under surfaces which have been altered by human practises. In addition, any variation in inter-basin transfer volumes will also affect the correlation. However, at this stage, this has not been assessed because static volumes of inter-basin transfer have been assumed. This presents the worst case scenario in that the current volumes of water transfer will not be reduced but increase in the future.

The correlation equations presented in Figure 6.48 incorporate the assumptions made during model set up thus should be used with this consideration in mind. Any principal change to the assumptions would invalidate the equations.

6.5.3.2. Reservoir Storage

i) Vaal Dam

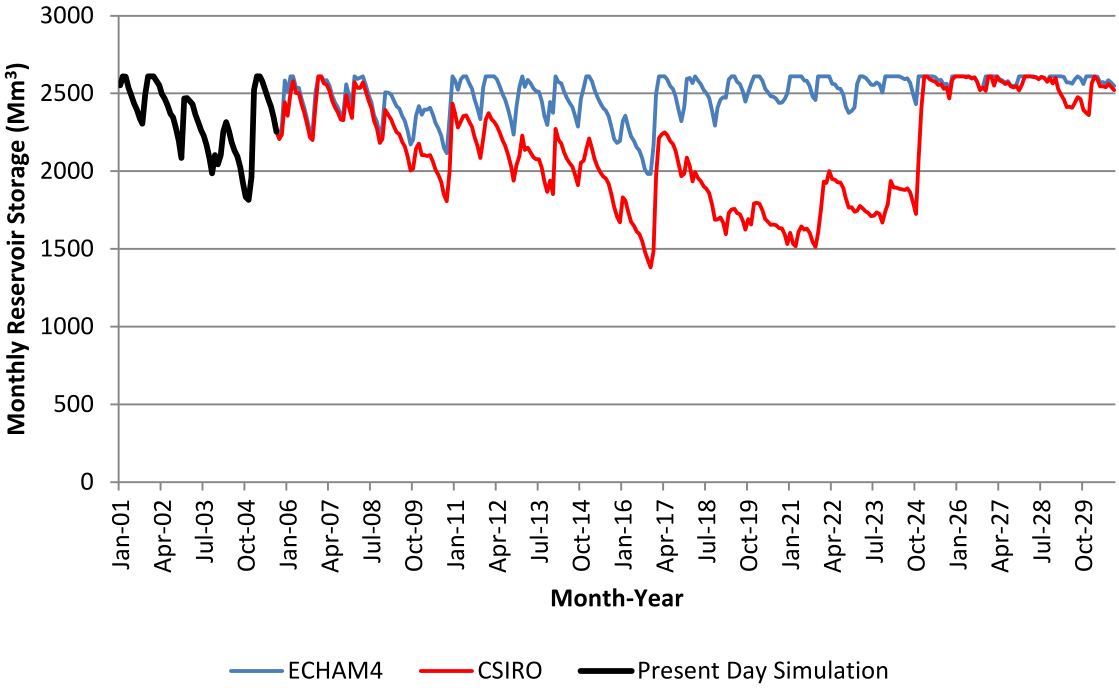

Figure 6.49: Vaal Dam Simulated Reservoir Storage under Scenario 3

ii) Grootdraai Dam

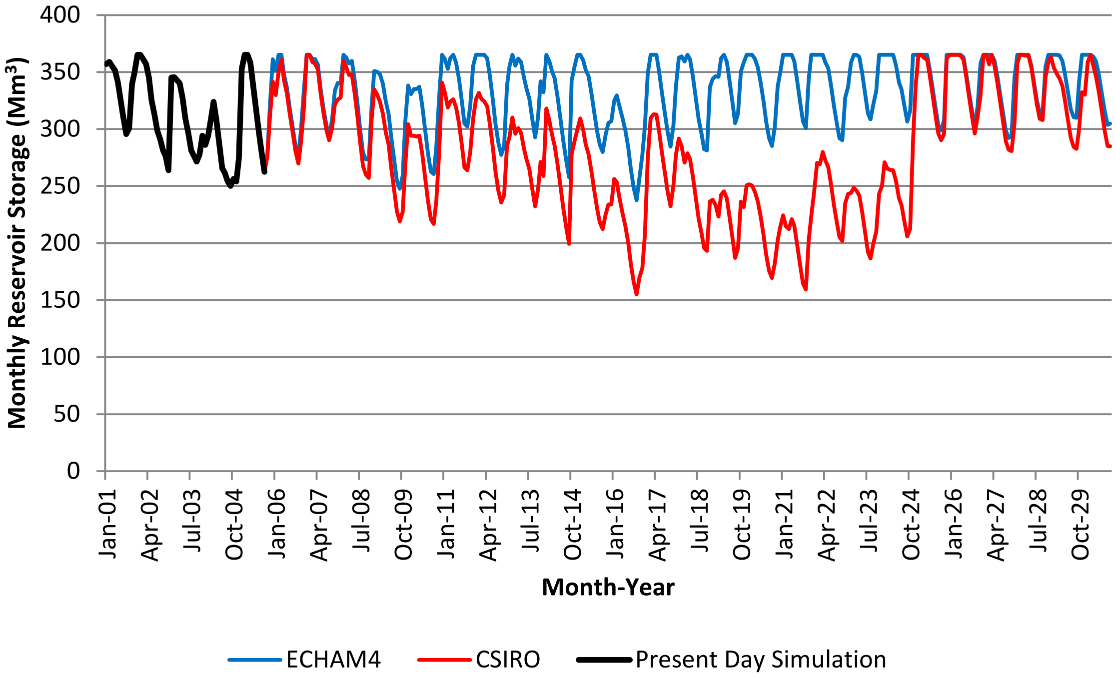

Figure 6.50: Grootdraai Dam Simulated Reservoir Storage under Scenario 3

Scenario 3 portrays a stable future with respect to reservoir storage. However, similar to the results for the other 2 scenarios, the period between years 2015 to 2024 indicates a drier period under the CSIRO model. The ECHAM model predicts storage in the Vaal and Grootdraai Dams will reach an all-time low of 75% and 66% respectively late in year 2016. Similarly, CSIRO predicts lower storages of 55% and 43% in year 2017 for the Vaal and Grootdraai Dams respectively.

6.5.3.3. <u>Unmet Water Demand</u>

There is a deficit of 10 and 9% for ECHAM and CSIRO models respectively in meeting the irrigation demands during the dry season. This is in close range to the deficits obtained in previous 2 scenarios for reasons explained earlier. Figure 6.51 shows the irrigation deficits predicted under the assumptions of Scenario 3.

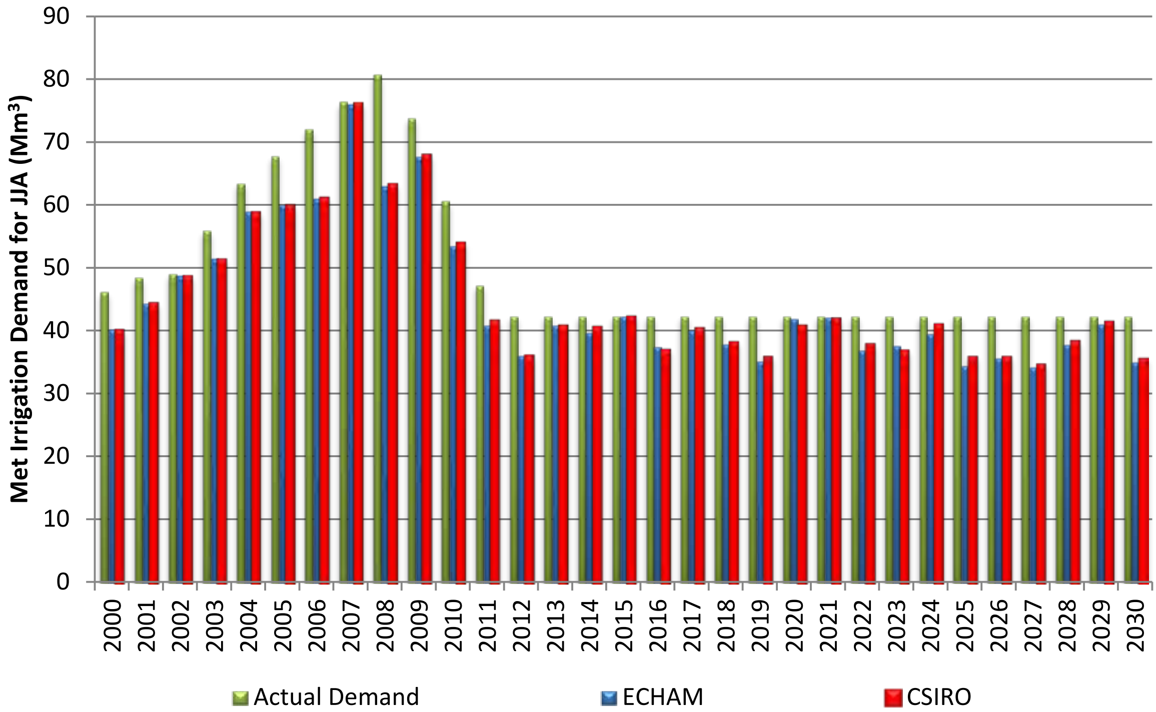

Figure 6.51: Cumulated Met Irrigation Demands for the Dry Season (Scenario 3)

6.5.3.4. Instream Flow Requirement

IFR requirements are met for all key points except Klip River during the dry season, with simulation results similar to previous scenarios because the predicted rainfall in the QCs draining into Klip River does not change across the scenarios. Furthermore, this scenario focuses on the impact of increasing volumes of water transfer without any contribution of WC/ WDM measures and the sub catchment draining into the Klip River is not affected by the above in any way.

6.6. Conclusion

6.6.1. Overview of Scenarios

Scenario 1 inspects the consequences of a constrained inter basin transfer from the LHWP. This situation may not arise considering the agreement in place with Lesotho and also the considerable investment on the project. However, the aim of this scenario was to highlight the vulnerability of the basin on the LHWP inter basin water transfer. It should be noted that there exists other inter basin transfers, volumes of which have been assumed constant at the year 2008 till year 2030. These transfers could also increase in the future and supplement the LHWP transfer and the UVRB in general.

Scenario 2 builds on Scenario 1 incorporating WC/ WDM measures expressed as a percentage saving in water used. This scenario highlights the effects of WC/ WDM management on the water resources in the basin and gives an indication of the savings which can be realised from such measures.

Scenario 3 portrays a more feasible situation whereby the LHWP transfer volume continues to grow at a rate based on historical data. WC/ WDM measures have not been included because implementation of the same normally takes a long period before significant results can be realised. Therefore, this scenario assumes no WC/ WDM measures will be implemented in the near future. It is a fact that WC/ WDM measures definitely have a positive impact on water resources, thus its exclusion from Scenario 3 can also serve a conservative approach to this scenario.

The results of the model simulation under the 3 scenarios are presented in the following sections.

6.6.2. Stream flow

Stream flows are set to increase in the future under all three scenarios. This has been verified visually from the plots and also using the Mann Kendall Test. However, the increasing trend in Scenarios 1 and 2 should be viewed in light of diminished reservoir storage. The WEAP model has been set up with equal priority to all consumers and storage being of least preference. Therefore, the model tends to satisfy all demands downstream of the dams irrespective of their storage. Thus in actual sense, scenarios 1 and 2 show that despite a major portion of total demand being met, there will not be adequate storage for sustained supply.

The UVRB suffers serious deficits in water storage with Scenario 1 showing a period where the reservoirs run dry. This result highlights the heavy dependence of the system on the LHWP inter basin transfer. Therefore, if this source of augmentation is constrained in any way in the future, the UVRB will experience significant deficits in meeting its water demands.

Scenario 2 shows the difference WC/ WDM measures can make in increasing water resources. A saving in the range of 2 -14% over 10 years applied only to the Rand Water supply region prevented the reservoirs from running dry (under CSIRO), and resulted in increased reservoir storage of nearly 10%. Therefore, savings made across the entire basin holds huge potential for increasing the water resource.

However, Scenario 3 shows a period of increasing stream flows to the year 2030 together with adequate reservoir storage. For reasons explained in Section 6.6.1, results for Scenario 3 are expounded further. A synthesis of mean monthly and annual stream flow results for Scenario 3 shows the following:

- A one/ two month shift in peak stream flow from February to January/ December when compared to mean monthly values using the historical 40 year record.

- The mean monthly stream flow for the period year 2000 – 2030 is much lower than the mean monthly stream flow for Year 1960 – 2000 despite increased precipitation under both ECHAM and CSIRO. This can be attributed to the larger water abstractions in the present and future compared to the past.
- The magnitude of maximum monthly stream flow increases by 91% (ECHAM) and 77% (CSIRO) relative to observed maximum monthly stream flow.
- A relatively strong relationship was developed between rainfall and stream flow for the UVRB under ECHAM for the simulation period (R^2 = 0.6). However, the same cannot be said for the CSIRO case which had a weak R^2 of 0.38. The correlation equation for ECHAM can further be used to obtain a preliminary indication of stream flows which can be expected, incorporating all abstractions trends assumed, for a particular value of annual precipitation.

6.6.3. Reservoir Storage

The capacities of the main reservoirs in the UVRB cannot shield the consumers from deficits if inter basin water transfer from LHWP is constrained. This is indicated by the storage running dry between years 2019 and 2024 under the drier CSIRO GCM. Despite ECHAM's predicted higher rainfall, there is a decline in storage as well between the period mentioned above although not as severe as under CSIRO.

However, the results prove the significance of WC/ WDM measures by the substantial increase in storage for relatively small savings (14%) in water use implemented in the urban setting only. Therefore, this result shows that if this saving can be achieved throughout the basin, then more stability and reliability can be achieved from the existing storage capacities.

Scenario 3 shows a stable system under both GCMs in terms of reservoir storage. However, the period between 2016 and 2024 shows significant draw downs under the CSIRO GCM. The ECHAM GCM on the other hand sustains storage beyond 80% capacity for both reservoirs throughout the simulation period.

6.6.4. Water Demand

According to the model results, the major urban water demand from Rand Water is satisfied together with industrial requirements up to the year 2030. However, demands for some smaller towns namely Harrismith, Qwa Qwa, Vrede and Warden are not met especially during the dry seasons. Some of these towns depend on alternative sources of water like groundwater. For the case of Qwa Qwa, it is also supplied by Sedibeng Water Company from the Middle Vaal WMA. The model set up only assigned the respective demands to rivers and alternative water supplies to towns was not considered. Therefore, the deficits in these towns were assumed to be met from alternative sources and considered insignificant.

Water demands are generally met across the three scenarios. However, results from Scenarios 1 and 2 should be viewed with caution because despite meeting nearly all the demands, the reservoir storage diminishes drastically. Therefore, it would be incorrect to conclude that water demands are met under these scenarios. If the LHWP transfer suffers any reduction in water volume, then there will be deficits in the UVRB in meeting its water supply obligations. Furthermore, these deficits will not be eradicated even if WC/ WDM measures are implemented because of the relatively small positive change in reservoir draw downs as a result.

However, Scenario 3 shows all demands are met except for the small towns whilst ensuring adequate reservoir storage as well. Therefore, it can be concluded that the ability of the water resources in meeting the demands within the basin up to the year 2030 is reliable under possible climate change scenarios of both ECHAM and CSIRO given unconstrained transfer from the LHWP. Irrigation demands suffer deficits in the range of 10 – 13% during the dry seasons (JJA) only and mainly for the regions in Zone 1 and 2. However, these deficits will be larger under constrained LHWP water transfer.

6.6.5. Instream Flow Requirement

The IFR was analysed for the dry season and results indicate that this requirement is met at all key points except Klip River in which case IFR is not met nearly 50% of the simulation period. IFR requirements however cannot be said to be satisfied under Scenario 1 and 2 because of diminishing storage. Conversely, Scenario 3 shows the same result as above but with adequate reservoir storage.

Therefore, it can be concluded that the basin will be able to meet the assumed IFR across Scenario 3 only for all key points except Klip River for both GCM models. Klip River key point undergoes a deficit during the dry season for 15 out of the 30 years of simulation. If continued augmentation of the UVRB water resources is constrained, then IFR requirements will be difficult to meet in the future.

CHAPTER SEVEN

CONCLUSIONS AND RECOMMENDATIONS

"When a subject is highly controversial…one cannot hope to tell the truth. One can only show how one came to hold whatever opinion one does hold. One can only give one's audience the chance of drawing their own conclusions as they observe the limitations, the prejudices, the idiosyncrasies of the speaker"

Virginia Woolf

7.1. Introduction

WEAP has been used to assess the impacts of climate change in the UVRB. The model was set up to simulate the hydrological processes of the basin. Water abstractions, storage reservoirs and inter basin transfer infrastructure were also incorporated in the model to simulate the use of resources holistically. The future surface water availability was assessed under climate change scenarios to the year 2030 to determine the basin's ability to meet projected demand obligations. This Chapter also discusses some of the pros and cons of using the WEAP model for such applications and concludes with recommendations for future work.

7.2. Summary of Results

7.2.1. Modelling the Naturalised Hydrology

The hydrology for the UVRB was set up under natural conditions to obtain optimum parameters for the model regarding climate and land use. Naturalised flow data was used in this process and the parameters calibrated by comparing the natural to modelled flows. The model performance for each of the 3 zones and for the overall basin is as follows:

- The model was able to simulate the natural flows very well for Zone 1 with R^2, E, E_{rel} and d_{rel} of 0.903, 0.728, 0.862 and 0.938 respectively.
- The simulation for Zone 2 and 3 resulted in lower but still acceptable R^2, E, E_{rel} and d_{rel} values of 0.583, 0.593, 0.576, 0.818 and 0.583, 0.479, 0.920, 0.960 respectively. However,

the E_{rel} and d_{rel} values for both zones indicated the simulation for low flows for both zones was achieved satisfactorily.

- The basin as a whole tended to distribute the error in each zone and gave an overall R^2, E, E_{rel} and d_{rel} of 0.817, 0.674, 0,843 and 0.812 respectively.

The high flows are underestimated in most cases. Nonetheless, Zone 1 performed well in capturing most of the high flow occurrences indicated by E_j and d_j of 0.613 and 0.779 respectively. However, the results were relatively low for the other Zones. In overall, the basin model performed well as a whole in simulating the high flows with values of E_j and d_j equal to 0.585 and 0.767 respectively.

All Zones exhibited good performance under prediction of low flows as seen by the d_{Rel} (> 0.75). Under E_{Rel} however, Zones 1 and 3 performed well (> 0.8) but Zone 2 had a low performance (0.576). The reason for this result could not be established at the time. In general, the performance of the basin as a whole was good under low flows with E_{Rel} and d_{Rel} equal to 0.843 and 0.812.

The performance of the model can be attributed to the following possible factors:

a) The 'zoning' of the UVRB for calibration. The re-zoning of the basin into smaller zones may result in a better model performance.

b) The manual method of calibration is inconvenient and prone to judgement errors which may have resulted in inadequate calibration.

c) The 'fixing' of all parameters except RRF and PFD may have limited the scope of calibration. It may be possible to improve the results if other input parameters were also adjusted.

7.2.2. Modelling the Present Day Hydrology

The current land use, present water abstractions and water infrastructure were superimposed on the naturalised hydrology in WEAP to simulate the basin's water resources. The model simulation was assessed against observed stream flow data for gauges located near the outlet of the three Zones.

The model performance was lower compared to the calibration stage with E values ranging from 0.2 to 0.4 for the Zonal performances. However, the basin performs well as a near whole with an E of 0.686. A similar result for R^2 was also obtained. The model overestimates most of the peaks except for the extremes.

In summary, the model performance is not very good at the zonal scale, but reasonable when considering a larger part of the basin. These results were expected because of the intrinsic uncertainties in modelling the present day situation. WEAP offers a simplified representation of the complex workings of basin hydrology and thus is much easier to model virgin conditions which are much simpler. As for the present day conditions, the system has many 'unknowns' and assumptions had to be made because determining them was beyond the scope of this Study. Some of the main reasons to explain the performance are given as follows:

a) The derivation of RRF based on land use changes may have been overestimated thus having a larger instance of overestimation of flows.
b) The demand data used in this Study was taken as is under the assumption that it is accurate. This may be partially correct because it has its own set of assumptions and possible errors which may have translated into the results obtained in this Study. In addition, the back extrapolation of the demands may not be reflecting the true situation.

c) Some of the observed stream flow data obtained from DWEA have monthly values based on estimation which may give misleading results.

d) Reservoir operating rules could not be obtained in time, thus the reservoirs have been modelled without operating rules. This may have contributed to the poor results of most dams.

7.2.3. Modelling the Future Hydrology

The impact of climate change on future availability of surface water to meet the demand obligations was assessed for the UVRB using the TYN SC 2.03 climate dataset. Three scenarios were developed using 2 climate models, ECHAM4 and CSIRO using the B2 SRES scenario, which specifically addressed the dependency of the basin on the LHWP inter basin water transfer, the measure of the impact of WC/ WDM implementation and finally the impact on the surface water resource if reliable external transfer will be guaranteed but without any conservation measures in place.

Taking into consideration the model errors, the results indicate:

a) Higher future stream flows. In addition, the mean monthly stream flow indicates a one month shift in peak flow from February to January. The magnitude of peak maximum monthly stream (year 2005 -2030) flow increases by 91% (ECHAM) and 77% (CSIRO) relative to observed maximum monthly stream flow (year 1960 – 2000).According to DWAF (2003), flow volumes released to Middle Vaal WMA and consequently cascading to the Lower Vaal WMA for use in the year 2025 will be 910 Mm^3/ annum. However, both the climate models predict an ability of the basin to release a larger volume ranging from 1,400 (CSIRO) to 2070 (ECHAM) Mm^3/ annum for the same year. This means an increase of 54% and 130% from the predicted volume.

b) The existing storage infrastructure will not be able to buffer the deficits in meeting water demand in the basin if the LHWP transfer is constrained in any way. Both climate models indicate the reservoirs having critical draw downs between years 2019 – 2024, with an instance of drying up under the CSIRO model. However, WC/ WDM measures in the range of 2 – 14% implemented over a 10 year period improves storage and prevents drying of the reservoirs. In the case of unconstrained LHWP transfer, the reservoirs are maintained at an average of 80% of storage capacity under both climate models. However, the period between years 2016 – 2024 shows significant draw downs under the CSIRO model indicating a potential dry period.

c) The major urban water demand from Rand Water is satisfied together with industrial requirements up to the year 2030. However, demands for some smaller towns namely Harrismith, Qwa Qwa, Vrede and Warden are not met during the dry seasons. Some of these towns depend on alternative sources of water like groundwater. For the case of Qwa Qwa, it is also supplied by Sedibeng Water Company from the Middle Vaal WMA. The model set up only assigned the respective demands to rivers and alternative water supplies to towns was not considered. Therefore, the deficits in these towns were assumed to be met from alternative sources and considered insignificant. On the other hand, irrigation demands constantly experience deficits during the dry season in the range of 10 – 13%. The areas having deficits lie within Zone 1 and 2 only.

d) The IFR is met at all key points across all scenarios except Klip River which undergoes a deficit during the dry season for 15 out of the 30 years of simulation. If continued augmentation of the UVRB water resources is constrained, then IFR requirements across the basin will be difficult to meet in the future.

7.3. Overall Conclusion

A model of the UVRB was successfully set up and a scenario analysis carried out under possible impact of climate change. However, despite the quality checks and justified assumptions made on the data used, errors would be inherent. Therefore, the results of this Study should be viewed with caution at this stage. Nonetheless, the results indicate a wetter and hotter climate in the near future for the UVRB. In addition, the dependency of the basin on external sources of water was highlighted which places emphasis on the wise use of water resources in the basin to ensure future sustainability. On the other hand, the ecological reserve if determined to be within the ranges used in this Study, will generally be met except for one region. This output should however be looked into and model errors ruled out before its conclusive adoption.

This Study has initiated setting up of a model for the UVRB which encompasses hydrology and some aspects of water management on a single platform. Due to time constraints, only the issue of climate change on the surface water resource was addressed, thus leaving substantial potential of the model untapped. It also presents the strong ability of WEAP in modelling complex water systems thus providing an opportunity for rapid assessment of the state of existing water resources via scenario analyses. This is ideal for water managers especially in South Africa where management of water resources holds priority.

7.4. Pros and Cons of WEAP

WEAP offers an 'under one roof' approach to modelling a river basin. This means that the model has the capability to simulate the hydrology, water demands, water quality and economics of implementing water infrastructure augmentation at a single go. Therefore, the model provides a holistic view of the entire workings of a river basin. This Section presents the strengths and weaknesses of WEAP.

Some of the advantages of WEAP are as follows:

- Is an integrated water resources planning system which incorporates the water abstractions, model the water quality and also perform economic analyses on investments carried out in the basin in relation to available water resources. Furthermore, water infrastructure like dams and inter basin transfers can simultaneously be considered.
- Built-in models for: Rainfall runoff and infiltration, evapotranspiration, crop requirements and yields, surface water/groundwater interaction, and instream water quality
- GIS-based, graphical "drag and drop" interface
- Model-building capability with a number of built-in functions
- Dynamic links to spreadsheets and other models like QUAL2E for water quality and MODFLOW for groundwater.
- Powerful reporting system including graphs, tables and maps.

However, despite the numerous advantageous features of WEAP, it has its downsides:

- Is data intensive especially for the soil moisture hydrologic module.
- The lack of an inbuilt automated calibration function. This limits the extent and quality of the calibration process to the judgement of the modeller and thus may result in inefficient calibration.
- For this study, the model setup for 30 year simulation of basin processes under climate change took considerable computation time (2 hours per scenario run) on an average computer (CORE^{TM} 2 Duo, 2.00GHz Processor with 2Gb RAM). Therefore, a faster computer would be required for an extended analysis.

7.5. Recommendations

The modelling exercise was relatively successful in setting up the complex UVRB system. However, this study can be considered as a first step in capturing the intricate workings of the basin. Therefore, to improve the results and also the use of all the model capabilities, the following is proposed for future work:

i) Automatic calibration of the model should be applied by using third party algorithms like the Parameter ESTimation (PEST) tool (Doherty, 2004) or writing a code to be applied in WEAP. This will improve the calibration process by assisting the modeller in making more informed judgements on model parameters and their optimum values. Furthermore, automated calibration will also allow calibration at the QC scale instead of the three Zones adopted in this Study which would potentially improve the results of the model.

ii) This study has used only two of WEAP’s capabilities, which are the simulation of surface water hydrology and water demand allocation. There are 3 additional capabilities which in conjunction with the above two would provide the whole picture of the water resources and their use in the UVRB. These are as follows:

    a) Water quality: WEAP can simulate the water quality of the rivers in terms of the Biological Oxygen Demand (BOD) and Dissolved Oxygen (DO). In addition, the model can be coupled with QUAL2E water quality model thus offering a wider spectrum of water quality analysis.

    b) Ground water: The groundwater component can also be incorporated in the model to simulate the hydrogeology. This will give the complete picture of water resources in the UVRB. Furthermore, the groundwater component can be set up using MODFLOW and linked to WEAP thus using the former model’s powerful features.

    c) Economics: The Costing module can also be populated to calculate the cost of new infrastructure, operating costs and resulting benefits from the water infrastructure and also maintenance of existing ones. This would be ideal for water managers as they would be able to have insight to cost benefits of proposed infrastructure and also improve on management of existing ones.

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