Catchment Hydrological Modelling Using ArcSWAT:

A study of the Ingula Pumped Storage Scheme (IPSS) Catchments, South Africa

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Submitted in Fulfillment of the Academic Requirements for the Degree of Master of Science

Discipline of Geological Sciences

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South Africa

February 2017

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

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Abstract

The Soil and Water Assessment Tool (SWAT) model and its GIS interface, ArcSWAT, were applied in the study of the Ingula Pumped Storage Scheme (IPSS) catchments, in the KwaZulu-Natal and Free State Provinces of South Africa. The objective of the study was to determine the suitability of ArcSWAT for modelling mountainous, data-scarce catchments in Southern Africa and therefore could be applicable for water resources management at catchment scale. The IPSS is one of ESKOM's hydropower stations built to supplement electrical power supply during peak power demand hours in South Africa. The IPSS comprises two dams, Braamhoek and Bedford, connected by a network of shafts and tunnels. The dams are 4.6 km apart with a 470 m head difference. The response of the IPSS catchments to climate and land use/cover changes was modelled by integrating various catchment scale land use/cover, climate, and soil information using ArcSWAT. Model calibration and validation were made against measured stream flow data downstream of the Braamhoek Dam to improve the predicting capabilities of the model. The model was run using land use/cover of 2000 and 2009 against weather data from 1990-2035 generated using the WeatherMan tool of the Decision Support System for Agrotechnology Transfer (DSSAT). The model performance was evaluated using the Standard Regression (R^2), Nash-Sutcliffe criteria (NSE), percentage of bias (PBIAS), and the ratio of the root mean square error to the standard deviation of measured data (RSR) error indices. The model performance statistics for the weather data of 1990-2035 in both land use scenarios are: $0.86 \leq R^2 \leq 0.92$, $0.85 \leq NSE \leq 0.88$, $0.03 \leq PBIAS \leq 0.24$, and $0.07 \leq RSR \leq 0.08$. The simulation results show that a 10% increase and decrease in precipitation resulted in a maximum mean monthly flow increase of 36% and decrease of 49% downstream of the Braamhoek dam. Similarly, the same changes in precipitation resulted in a modelled discharge increase of 31% and decrease of 41% downstream of the Bedford dam. The mean monthly flow volume for both catchments was found to be higher for 2009 land use/cover than for 2000 land use/cover which indicates the sensitivity of both catchments to precipitation and land use/cover changes. With the aid of DSSAT, the SWAT model has been successfully calibrated and validated to simulate the stream flow responses of the IPSS catchments on a monthly time-scale and can be applied to other catchment with limited data.

Key Words/Phrases: ArcGIS, ArcSWAT, hydrologic modelling, Ingula Pumped Storage Scheme, South Africa

Preface

The work described in this dissertation was carried out in the School of Geological Sciences, University of KwaZulu-Natal, Westville campus, from January 2014 to December 2016, under the supervision of Dr Molla Demlie.

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

Declaration 2 - Publications

Details of contributions to publications that form part and/or include research presented in this thesis are:

Ngubane, Z. and Demlie, M. (2015). Modelling the response of a catchment to land use and climate change using ArcSWAT: case study of the Ingula Pumped Storage Scheme (IPSS) catchments, South Africa. *4th YWP-ZA Biennial and 1st African YWP Conference*, Pretoria, South Africa.

Ngubane, Z. and Demlie, M. (2016). Modelling the response of a catchment to land use and climate change using ArcSWAT: case study of the Ingula Pumped Storage Scheme (IPSS) catchments, South Africa (under review). *Submitted to Journal of Water Resources Management.*

Declaration

This research has not been previously accepted for any degree and is not being currently considered for any other degree at any other university.

I declare that this Dissertation contains my own work except where specifically acknowledged.

Student Name and Number: Zesizwe Ngubane 203511606

Signed………………………………………..

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Plagiarism Declaration

I, Zesizwe Ngubane, declare that:

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

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Acknowledgements

I would like to express my sincere gratitude to my former employers; CMC *di Ravenna*, PG Mavundla Projects and Impregilo SA - Joint Venture (CMIJV) for the financial support towards this research.

I am deeply grateful to my supervisor, Dr. Demlie, who has been quite patient in reviewing and improving my work, giving constructive and invaluable comments for the success of this study.

I would like to express my appreciation to the School of Geological Sciences at UKZN, to my colleagues for the support given.

I would like to thank the Eskom Environmental teams led by both Mr Peter Nelson and Mr Calvin Teffo for letting me be part of the team, for the data, and the constant support before and during my fieldwork.

I would like to express my deepest gratitude to my family, my colleagues at DUT, my mentor, and my friends for the unlimited support and encouragement.

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List of Abbreviations and Acronyms

ACRU	Agricultural Catchments Research Unit
ARCU	Agricultural Research Council
ArcSWAT	ArcGIS graphical user interface for SWAT
ARIMA	Autoregressive Integrated Moving Average
CEC	Cation Exchange Capacity
CFRD	Concrete Faced Rock Fill Dam
CN2	Curve Number
CRD	Cumulative Rainfall Departure
CREAMS	Chemicals Runoff and Erosion from Agricultural Management Systems
DEEPST	Initial Depth of Water in the Deepest Aquifer
DEM	Digital Elevation Model
DSS	Decision Support Systems
DSSAT	Decision Support System for Agrotechnology Transfer
DWA	Department of Water Affairs (South Africa)
EPIC	Erosion Productivity Impact Calculator
ESCO	Evaporation Compensation Factor
ESKOM	Electrical Supply Commission
GIS	Geographic Information Systems
GLEAMS	Groundwater Loading Effects on Agricultural Management Systems
GPS	Geographical Positioning Systems
GW_DELAY	Groundwater Recession Coefficient
HRU	Hydrological Response Unit
ICASA	International Consortium for Agricultural Systems Application
IPSS	Ingula Pumped Storage Scheme
IWUL	Ingula Water Usage License

LH-OAT	Latin Hypercube One-Factor-at-a-Time
m amsl	metres above mean sea level
m bgl	metres below ground level
MW	Monitoring Wells
NSE	Nat-Sutcliffe Error Criteria
RMSE	Root Mean Square Error
ROTO	Routing Outputs to Outlets
RSR	Root Mean Square Error to observations standard deviation ratio
SHALLST	Initial Depth of Water in the Shallowest Aquifer
SOL-AWC	Soil Available Water Capacity
SURLAG	Surface Runoff Lag Coefficient
SWAT	Soil and Water Assessment Tool
SWRBB	Simulator of Water Resources in Rural Basins (SWRBB or SWRRB)
WMA	Water Management Area
USDA-ARS	United States Department of Agriculture-Agricultural Research Services
USGS	United States Geographical Survey

CHAPTER 1 INTRODUCTION

1.1 Background

The limited availability of water resources for different water use sectors presents one of the most contentious and challenging issues to the implementation of effective management and future development of South Africa's catchment areas (Taylor *et al.*, 2001). According to Daniel *et al*. (2011), current patterns in societal advances are associated with an array of interlinked factors that affect the availability and quality of water. These factors enlist population growth, increased urbanisation and industrialisation, increased energy use, desertification, global warming, and poor water quality (Daniel *et al.*, 2011). To meet the water demands of a growing society in a balanced fashion, a means of evaluating the country's meagre water resource is essential to planners with the prime objective of managing catchments to maintain a sustained yield of water supply for the country (Everson *et al*., 1998; Pitman, 2011). Furthermore, the South African National Water Act (Act No. 36 of 1998) requires that the national water resources be developed and allocated in an equitable and conservative manner (NWA, 1998).

Daniel *et al*. (2011) state that an improved understanding of how each of the factors that affect water availability at the catchment scale influences water supply, demand, and quality that requires improved abilities to understand the underlying processes and their impact on water availability and use. This, according to Brooks *et al*. (2013), entails employing a holistic approach that integrates hydrological processes at the watershed scale to determine an overall watershed response to both user demands and climate change. Computer-based hydrologic simulation models, remote sensing technologies, Geographic Information Systems (GIS), global positioning systems (GPS), decision-support systems (DSS), internet applications, and isotope technologies are amongst the tools available to hydrologists and watershed managers to model and quantify water resources. According to Everson *et al*. (1998), management tools and models are used to make long term predictions, select the best alternative that fits the desired requirements, determine production functions to evaluate the impact of management practices, and assess the risk to allow the choice of management decisions at different probabilities of occurrence.

South Africa's continued development and resulting energy demand has put tremendous strains to the country's electrical power supply. The need to satisfy the nations' need for electrical power whilst sustaining a "green" environment has been exerting pressure on the Electrical Supply Commission (ESKOM), the national power utility company, to come up with power sources such as wind farms and hydropower stations as a supplement to the traditional coal-fired stations. With that backdrop, the Ingula Pumped Storage Scheme (IPSS) is one of the hydropower stations that have been built by ESKOM to generate electricity.

The Ingula Pumped Storage Scheme has two dams constructed in two catchments. These are an upper Bedford Dam constructed on the Bedfordspruit in the headwaters of Wilge River, located within the Upper Vaal Water Management Area (WMA) and a lower Braamhoek Dam constructed on the Braamhoekspruit located in the Upper uThukela River basin or WMA. The IPSS was constructed to generate hydropower and supply it into the national grid during peak electricity demand periods from the Braamhoek Dam. During low demand hours, water will be pumped from the Braamhoek Dam into the upper dam, the Bedford Dam, for storage. An understanding of the impact of climate and land use/cover change to water availability in these catchments has not been established.

In this M.Sc. study, the overall watershed response of the IPSS catchments to changes in land use/cover and climate is simulated using ArcSWAT version SWAT2012 (a tool developed by the United States Geological Survey, USGS). ArcSWAT is an ArcGIS extension and a graphical user interface of the Soil and Water Assessment Tool (SWAT) model. ArcSWAT integrates catchment-scale geological, hydrological, meteorological, and environmental information to better understand the dynamics of the hydrology of a catchment. The SWAT model has been applied extensively in many parts of the world including Africa (Abdulla and Eshwati, 2007) to make watershed management decisions and has also been coupled successfully with other modelling applications, such as in-stream and riparian models and geospatial and optimisation tools (Moriasi *et al.*, 2007).

1.2 Research Questions

- How does the outflow downstream Ingula dams respond to change in climate and land use/cover?
- Is ArcSWAT suitable for use in relating land use/cover changes, climate changes, and the IPSS hydrology as well as make future predictions?

1.3 Research Aims and Objectives

This study seeks to assess the applicability of ArcSWAT to simulate hydrological conditions of the Southern African hydrological landscapes.

The specific objectives of the study are:

- To determine the suitability of ArcSWAT for modelling mountainous, data-scarce catchments in Southern Africa and assess its applicability for water resources management at a catchment scale.
- To apply ArcSWAT in modelling the impact of land use/cover and climate change on water availability at a catchment scale using the IPSS catchments as a case study.

1.4 Structure of the Dissertation

This dissertation is comprised of six (6) chapters and structured as follows:

Chapter one is the introductory chapter. It outlines the study background, research rationale, aims and objectives of the research.

Chapter two presents an overview of the study area in terms of geology, hydrogeology, soils, land use/cover, physiography and drainage, and hydro-meteorological aspects.

Chapter three provides literature review, discussing different tools and methods applied in hydrological watershed modelling including the application of ArcSWAT.

Chapter four outlines the research methodology followed and the materials used.

Chapter five presents the main results, its interpretation and discussion.

Chapter six consists of the main conclusions drawn from the study and the recommendations emerging from this research.

References used and cited within the dissertation are listed in the list of references.

CHAPTER 2 OVERVIEW OF THE STUDY AREA

2.1 Location

The Ingula Pumped Storage Scheme (IPSS) is a 1332 MW ESKOM Holdings Limited hydropower station built 23 km north-east of Van Reenen's Pass and 55 km north-west of Ladysmith in the uThukela Regional District. The IPSS site straddles the escarpment of the Little Drakensberg Mountain Range and the provincial boundary of the Free State and KwaZulu-Natal Provinces in South Africa (Figure 2-1). The provincial boundary is also a watershed between the Vaal River basin draining west towards the Pacific Ocean and the uThukela River basin draining east towards the Indian Ocean. The upper part of the catchment (Bedford catchment) drains in a northerly direction via Wilge River and its tributaries in the headwaters of the Vaal River and the lower catchment (the Braamhoek catchment) drains in a southerly direction via Braamhoekspruit and its tributaries all the way into the Klip River that is situated in the headwaters of the uThukela River.

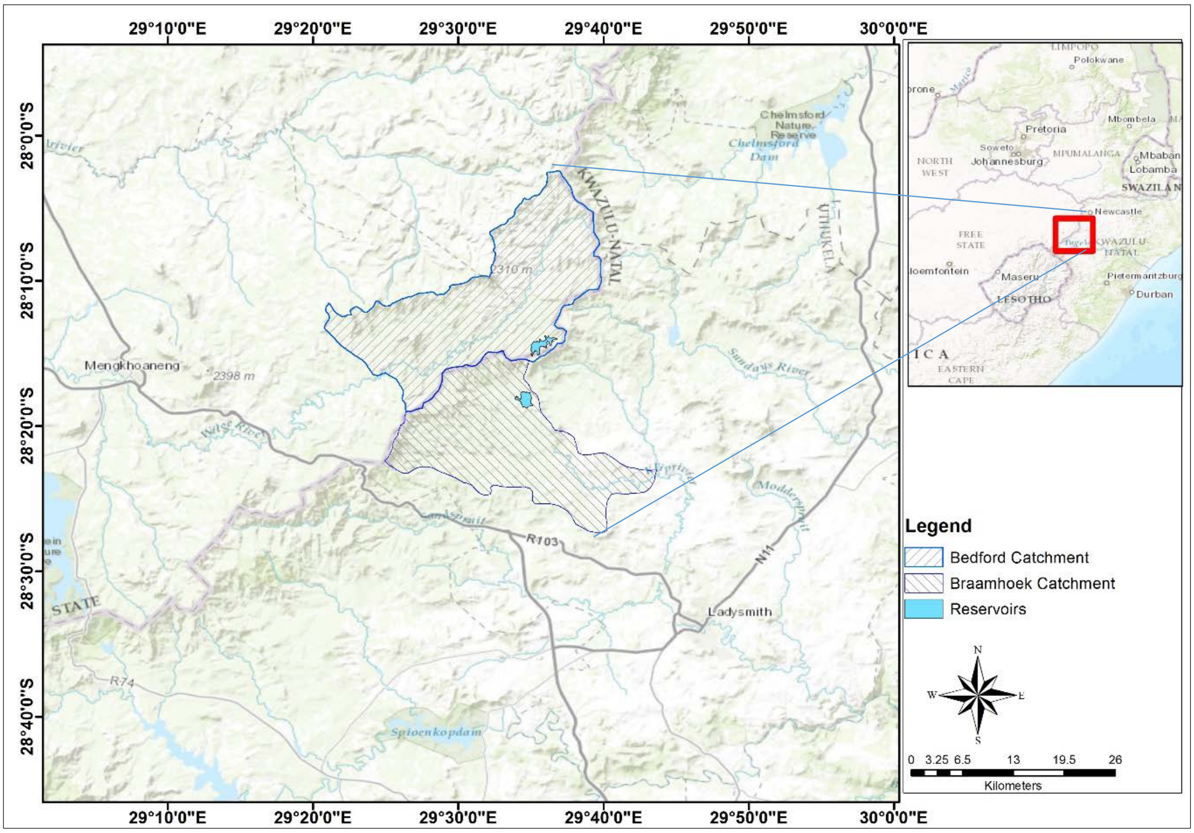


Figure 2-1: Location map of the Ingula Pumped Storage Scheme (IPSS) catchments.

2.2 Climate

The IPSS catchments fall within the “cold interior zone” in reference to the climatic zone map of South Africa described in SANS 204-2 (SANS, 2008). According to Köppen-Geiger classification (Conradie, 2012), the Braamhoek and Bedford catchments fall within the Cwa and the Cwb regions, respectively (Figure 2-2). Cwa represents the warm temperate climate with dry, cold winter and hot summer; and Cwb represents the warm temperate climate with dry, cold winter and warm summer (Conradie, 2012).

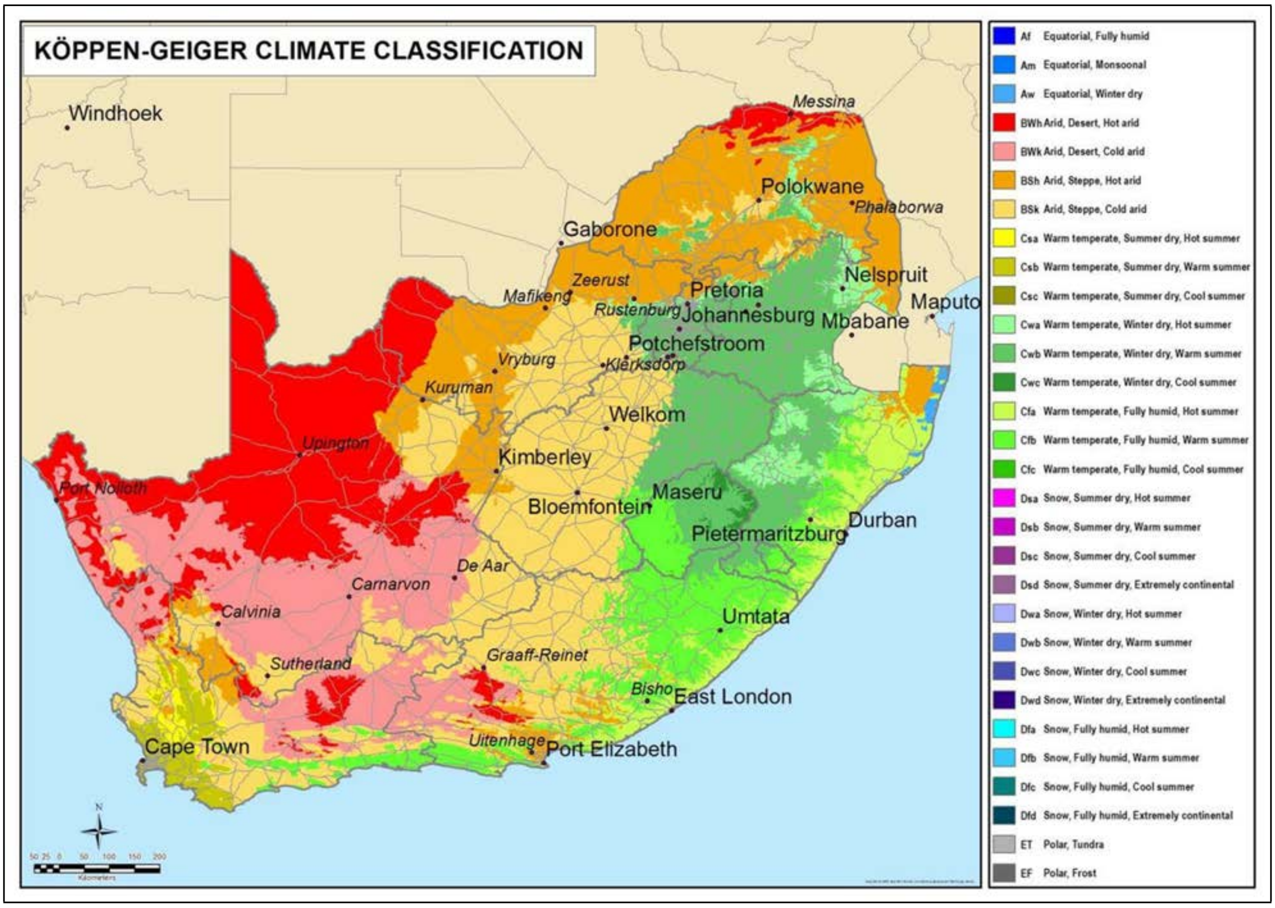


Figure 2-2: Köppen-Geiger climate classification map for South Africa (adapted from Conradie, 2012).

The Braamhoek and Bedford catchments are each equipped with a weather station in full operation since September and June 2008, respectively. The stations gauge daily rainfall, minimum and maximum temperature, and average wind speed and wind direction. The Bedford weather station is located at an altitude of 1745 m amsl, at coordinates 28°15'00"S and 29°32'00"E. The Braamhoek weather station is located at an altitude of 1290 m amsl and at coordinates of 28°20'00"S 29°30'00"E. The rainfall and temperature of the IPSS show seasonal variation. Figure 2-3 and Figure 2-4 show mean monthly rainfall, in millimetres, and mean monthly temperature, in degrees Celsius, comparison from the two catchment weather stations for the period between Spring 2008 to end of October 2016. The Bedford station was, however, damaged in 2014 and has not been replaced. Graphical comparisons of the two catchments' weather attributes was performed using data supplied by the Eskom onsite Environmental Office (Nelson, 2014 pers. comm.).

Table 2-1 shows annual rainfall for the two stations for the period 2009 to 2014. The Bedford catchment is generally characterised by cooler temperature compared to the Braamhoek catchment, commensurate with its altitude. Figure 2-5 shows wind speed from both catchments in km/hr where, in accordance with the altitude, Bedford catchment has higher wind speeds compared to the Braamhoek catchment.

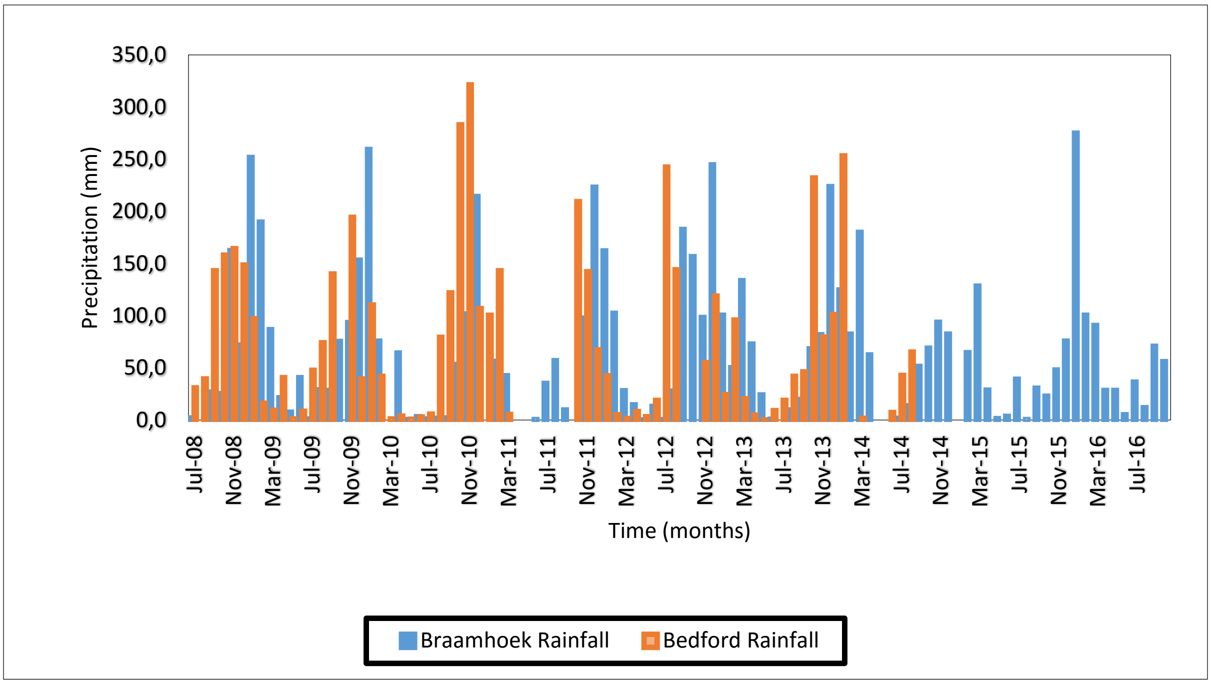


Figure 2-3: Mean monthly rainfall (mm) from the two weather stations located within the study catchment (Data from Nelson, 2014).

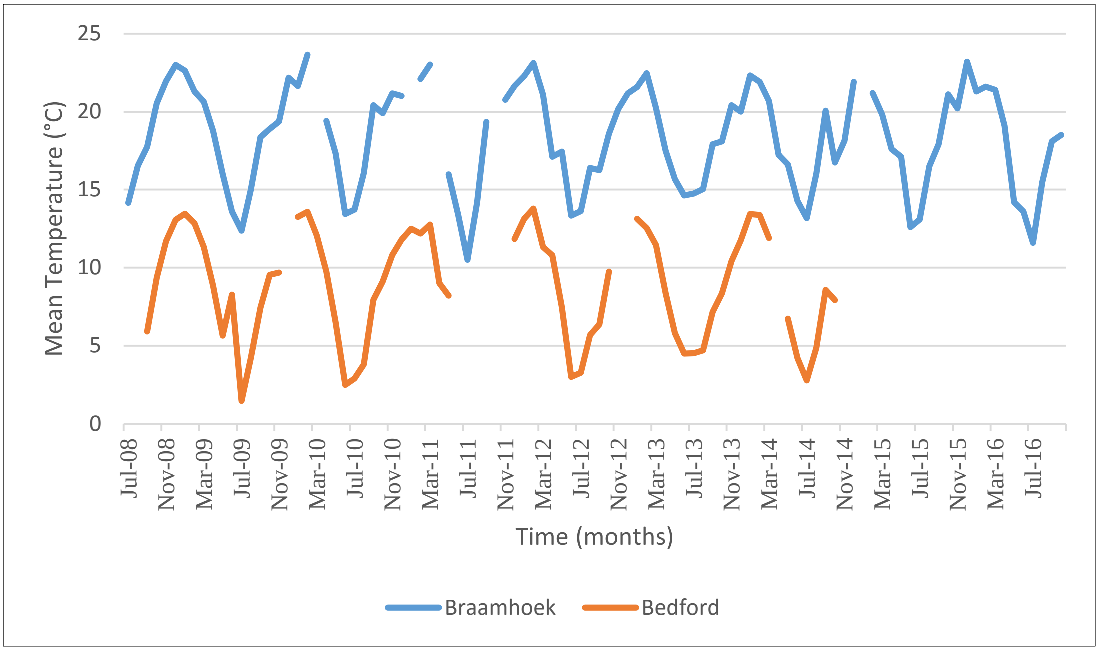


Figure 2-4: Mean monthly temperature (°C) from the two weather stations (Data from Nelson, 2014).

Table 2-1: Annual rainfall at the two weather stations within the study area (Data from Nelson, 2014).

Year	Braamhoek Gauge (mm)	Bedford Gauge (mm)
2009	978.40	747.20
2010	777.00	884.20
2011	522.10	886.50
2012	1031.40	675.40
2013	785.50	667.30
2014	761.00	550.60

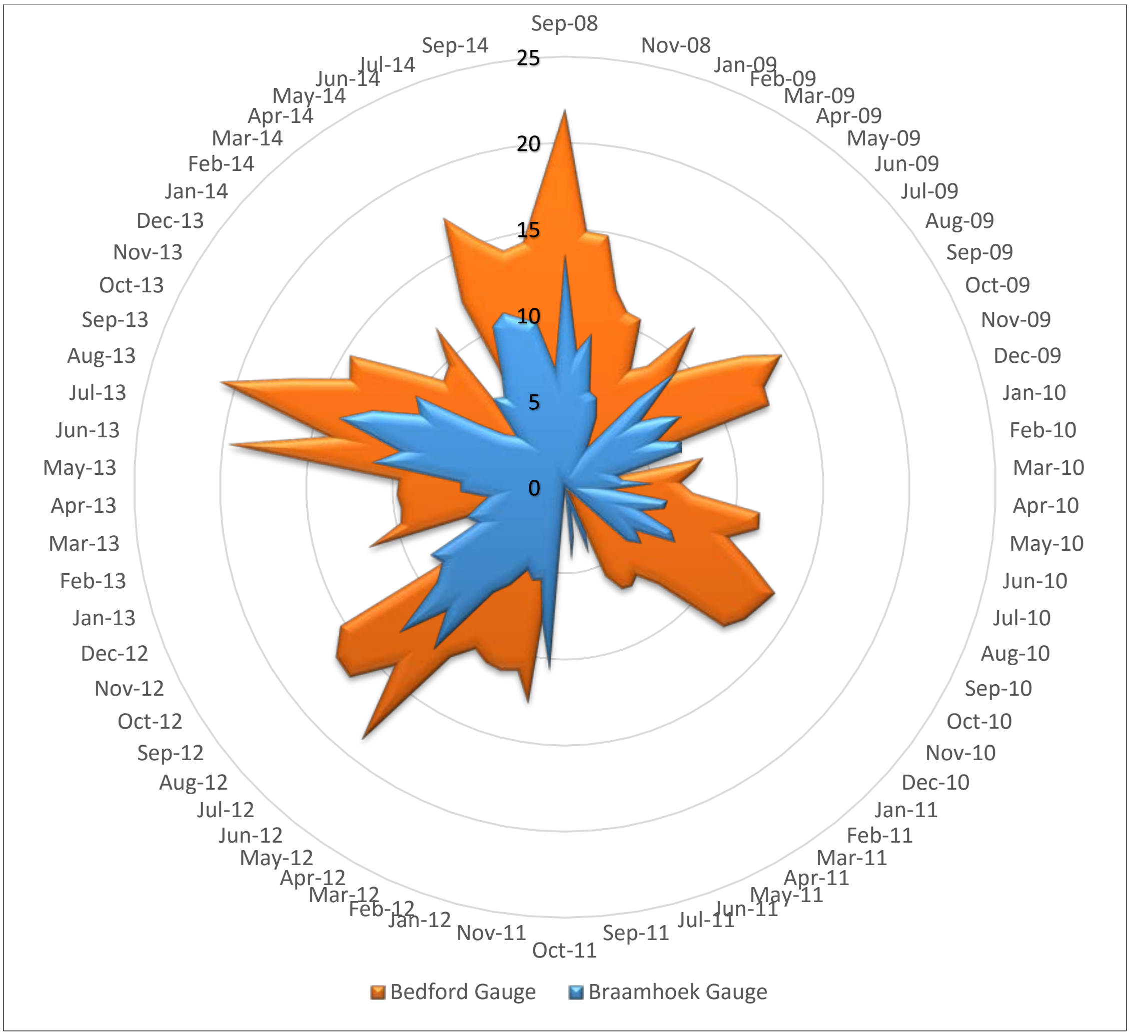


Figure 2-5: Wind speed recorded at the IPSS weather stations (Data from Nelson, 2014).

2.3 Topography, drainage and catchment area

The topography of the study catchments ranges from elevated plateau areas to steep mountains along the escarpment to undulating topography at the base of the escarpment. Figure 2-6 shows a processed Digital Elevation Model (DEM) of the study area showing the significant difference in relief between the two catchments. The overall altitude difference between the two catchments is 1277 m amsl.

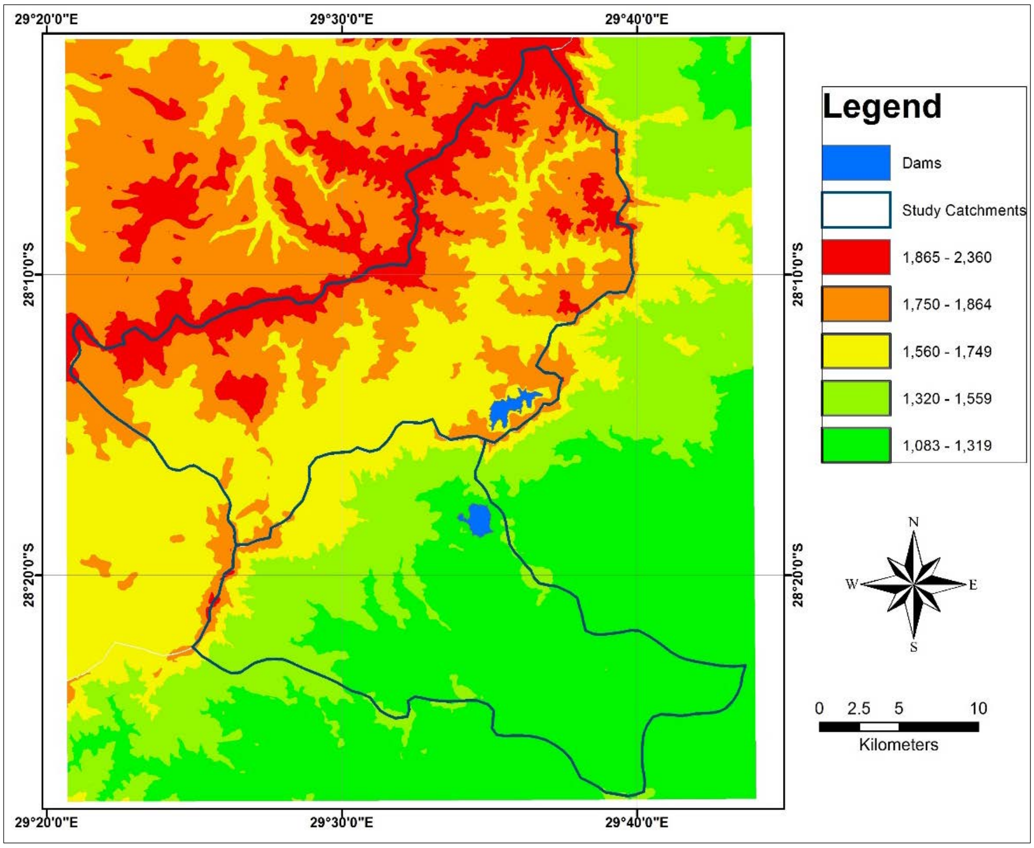


Figure 2-6: Digital elevation model of the study area.

The main requirements for a pumped scheme enlist, among other things, favourable geology, hydrology (both surface and groundwater), and two reservoirs where one is located at a significantly higher elevation than the other. The IPSS's two reservoirs are connected by a network of tunnels and shafts (Figure 2-7). The two reservoirs are 4.6 km apart with a head difference of 470 m, separated by the Great Escarpment, a giant horseshoe-shaped feature peculiar to the southern Africa, where it separates an elevated interior plateau from a coastal hinterland at lower attitude (Partridge and Maud, 2004).

The Bedford catchment is regulated by the Bedford Dam and reservoir, a concrete faced rock fill dam (CFRD), creating the upper reservoir at an altitude of 1700 m amsl. The Bedford reservoir area sits at 11.5 km^2 with 25.5 km^2 impounded area at full supply level. The volume of the reservoir at supply level is 22.56 Mm^3 with a minimum operating level of 3.24 Mm^3 and live storage of 19.32 Mm^3 (BCJV, 2006).

The Bedford catchment is located in the Free State Province. Its main stream is the Bedfordspruit that flows into the Wilge River located within the C81A Quaternary Catchment of the Upper Vaal WMA (Terrel *et al.*, 2012). The Wilge River forms an important part of the Vaal River catchment, which is of high importance as a water supply source for the Greater Tshwane-Johannesburg Metropolitan Area (the industrial heartland of South Africa) and a large part of the Free State province. The industrial areas that are supplied by the Vaal River produce more than 50% of South Africa's industrial produce and consumes more than 80% of the country's electricity requirements (Provincial Spatial Development Framework, 2013).

The Bedford-Chatsworth Wetland is located downstream of the Bedford Dam (Plate 2-1) which is of profound importance from a conservation and environmental point of view, because of its flora, fauna, and bird population. It has a high structural diversity supporting a unique assemblage of plants and invertebrates giving it a high sensitivity and conservation value (Terrel *et al*., 2012). Partridge and Maud (2004) reported that its peat content is recognised as an unusual habitat. This wetland is home to the White-winged Flufftail (*Sarothrura ayresi*) in summer which is classified in the Eskom Red Data Book of Birds of South Africa, Lesotho, and Swaziland as one of the critically endangered birds (Barnes, 2000). These wetlands at the Bedford Farm straddle the continental watershed and serve as a continual water source to the Wilge and Thukela Rivers, with springs flowing throughout the year.

Plate 2-1: Downstream view of the Bedford catchment showing the Bedford-Chatsworth wetlands.

The Braamhoek catchment lies within the upper part of the Ladysmith Basin formed by the erosion along headwater tributaries of the Thukela River (Partridge and Maud, 2004). The Braamhoek Dam and reservoir is a roller compacted concrete dam with a single gallery. The Braamhoek reservoir area sits at 60.11 km^2 with 24 km^2 impounded area at full supply level. The volume of the reservoir at supply level is 26.26 Mm^3 with a minimum operating level of 3.34 Mm^3 and live storage of 19.32 Mm^3 (BCJV, 2006).

The hills surrounding the lower reservoir are gently undulating. Steeper reliefs are evident where dolerite intrusions occur. The extent of this catchment is about 66 km^2 and its main tributary is the Braamhoekspruit, a headwater stream of the Klip River, which forms part of the V12A quaternary catchment located within the Thukela River WMA. The lower Braamhoek catchment is located in a narrow valley between two such dolerite-capped ridges. The dam lies on sedimentary rocks with perennial wetlands. One of these wetlands is the Trekboer Wetland and is mostly wetted by runoff from the surrounding landscapes (Mentis, 2005).

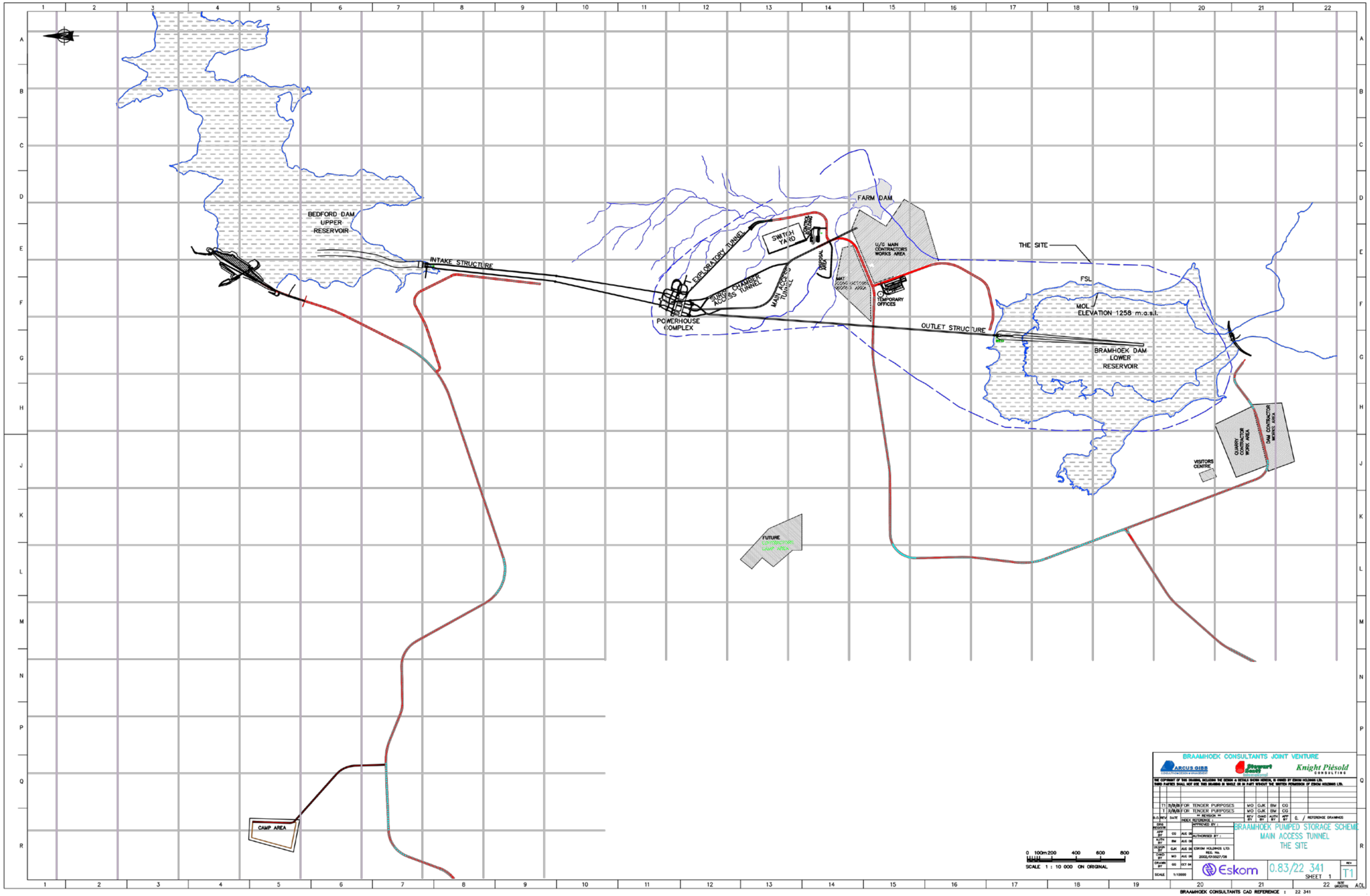


Figure 2-7: Schematic layout of the IPSS (Braamhoek Consultants Joint Venture, 2006).

The Braamhoekspruit, as seen in Figure 2-8 below, originates in a hilly area previously populated by rural villages with the surrounding areas used for subsistence farming and cattle grazing. According to Van Staden (2008), the stream can be ecologically classified as a moderately sensitive system and is considered to be a Class B stream (largely natural). During the assessment of stream during the Braamhoekspruit Bridge construction (Van Staden, 2008), the stream was found to have very good water quality, fairly neutral pH and favourable to aquatic life with a good concentration of dissolved oxygen.

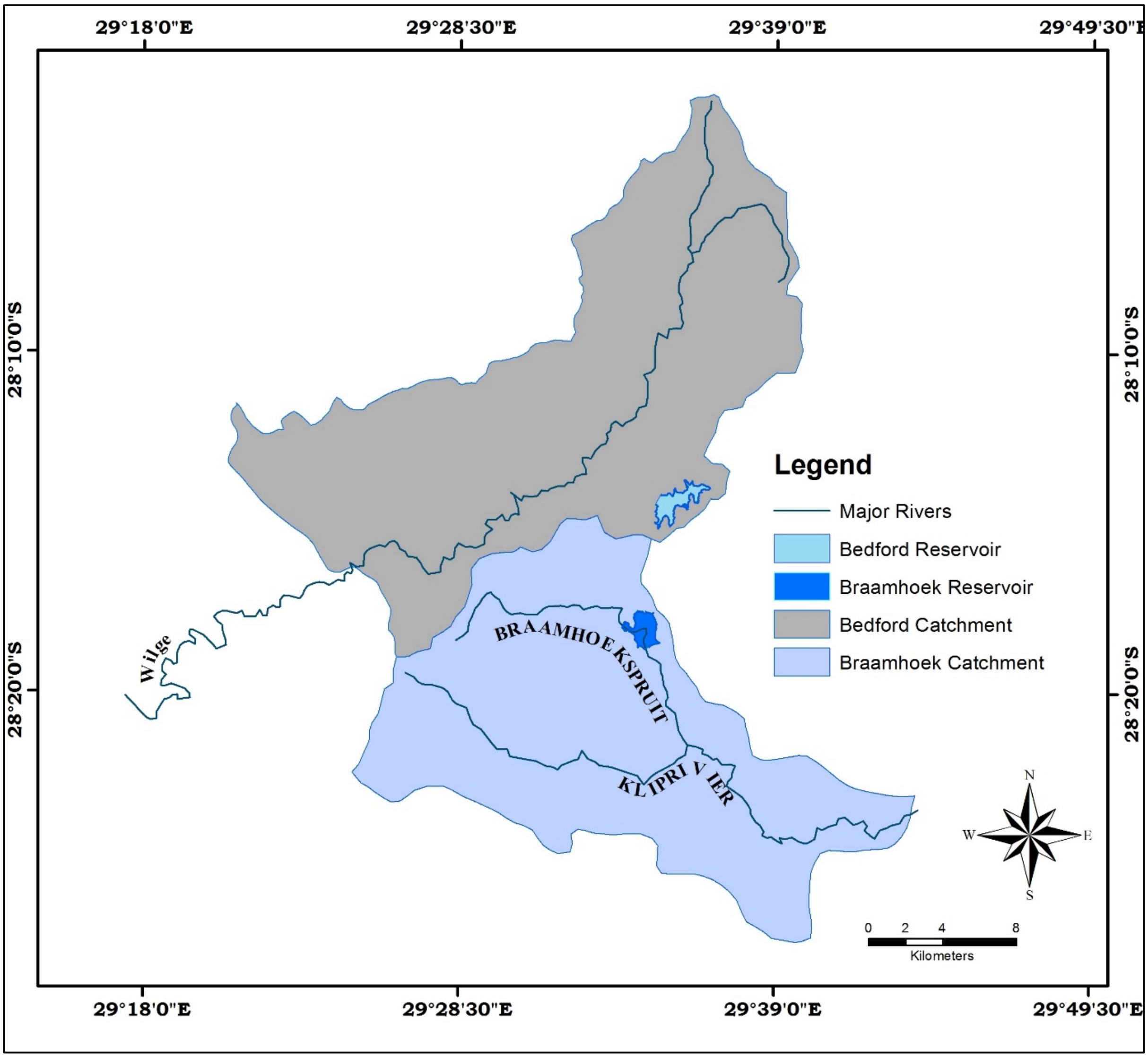


Figure 2-8: Drainage map of the IPSS.

2.4 Land use and land cover

According to Mucina and Rutherford (2006), the Bedford catchment falls within the Mesic Highveld Grassland Bioregion (Gm) and the Braamhoek catchment within the Sub-escarpment Grassland Bioregion (Gs) as shown in Figure 2-9. The catchments are covered by natural grasslands. In spite of the lumped nature of some maps and classifications, land use/cover has shifted from mostly grassland in 2000 to mining areas (quarries, open casts) and villages/townships (labour camps) in 2013 (Nelson, 2014 pers comm).

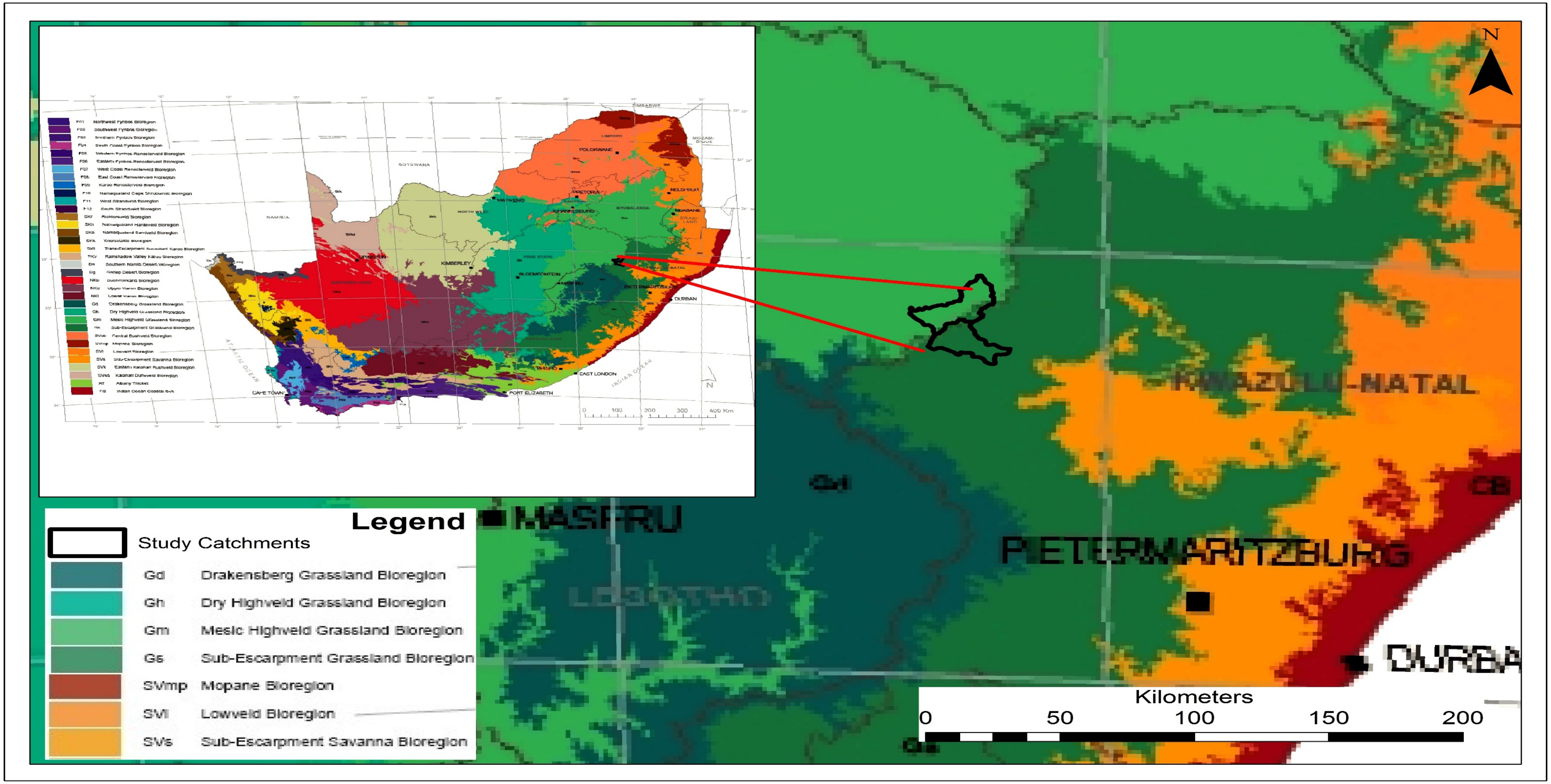


Figure 2-9: Bioregions map of South Africa according to Mucina and Rutherford (2006).

Mentis (2006) performed a dry land vegetation mapping of the study area and the findings are summarised:

- At the foot of the escarpment, on the dolerite outcrops scattered trees and shrubs grow. Typical species found in these parts are *Acacia sieberiana*, *Asparagus* sp, *Celtis Africana*, *Maytenus Buxifolia*, *Myrsine Africana*, *Rhus bicolor*, *R dentana*, *R montana*, and *Ziziphus mucronata*.
- Along the Braamhoekspruit, on the alluvia, *Acacia siberiana* creates an acacia savannah.
- The native *Salix mucronata* occurs on the banks of the Wilge River and also below the escarpment on the Braamhoekspruit with *Calpurnia sericea* and *Rhus gerrardii*.

Alien invaders include silver wattle, *Acacia dealbata* the more common of the two, and black wattle *Acacia mearnsii* both of which are classed as Category 2 plants in terms of Agricultural Resources Act 43 of 1983 (Conservation Of Agricultural Resources Act, 1984). These invaders have certain useful qualities, such as commercial use for woodlots, animal fodder, and soil stabilization. These plants are therefore allowed in demarcated areas under controlled conditions and in bio-control reserves. Silver wattle is a threat to biodiversity in that it displaces native vegetation, reduces streamflow, and aggravates soil erosion. Other invaders with light infestation and localised occurrences include gum *Eucalyptus* spp, pines *Pinus* spp, poplars *Populus* spp, and American bramble *Rubus cuneifolius*. Forbs (non-herbaceous herbs) are the main food source to rhebuck and many insects, and are reputed to have medicinal properties. As a group, forbs are geophytes.

Terrel *et al*. (2012) reported that the grassland vegetation cover and high organic matter increases water infiltration and reduces surface runoff. High organic matter and clay content lead to high water holding capacity of the soil. The upper soils are saturated after heavy rains and excess water drains via gravitational force to the lower soils.

2.5 Geological Setting

The study area is characterised by the Karoo Supergroup rocks. Figure 2-10 shows the geology of the study area based on the 1:250 000 2828 Harrismith Sheet of the South African geological series (Council for Geoscience, 1998). The tunnels, caverns and shafts are located within the

Volksrust Formation of the upper Ecca Group rocks. The Volksrust Formation is a predominantly argillaceous unit which interfingers within the overlying Beaufort Group and the underlying Vryheid Formation (Johnson *et al.*, 2006). These rocks are a series of dark greyish-blue silty, carbonaceous Mudstones and siltstones, which have an approximate thickness of 200 m (Figure 2-11). These rocks exhibit typical Karoo mudrocks' characteristics, including expansion on exposure to air and significant free swells on prolonged immersion in water (Partridge and Maud, 2004).

Volksrust Formation is overlain conformably by the Beaufort Group which forms the escarpment face with the Adelaide Subgroup (previously known as the Normandien Formation) (Figure 2-11). The basal Frankfurt Member forms a succession of interbedded greyish-white to greyish-blue siltstone and sandstone layers including the carbonaceous lenses, and often abundant mica along bedding planes. Above the Frankfurt Member is a series of carbonaceous mudstones, typical of the Karoo mudrocks. The upper edge of the escarpment is covered by the Rooinek Member; a horizon of pale grey-white to olive coloured sandstone with quartz and quartzose fragments, with feldspar, mica, and clay clasts. The Rooinek Member sandstones are lenticular and pinch out over short distances, leading to more than one unit of sandstone to be present within the Member resulting in variable thicknesses, as pointed out by Groenewald (1989). Substantial conglomerate horizons were encountered during geotechnical investigations for the upper reservoir. According to Stephenson (2005), the Rooinek member is particularly impervious; with the Bedford-Chatsworth wetland below, it acts like a geological roof with a sponge over it (Plate 2-2).

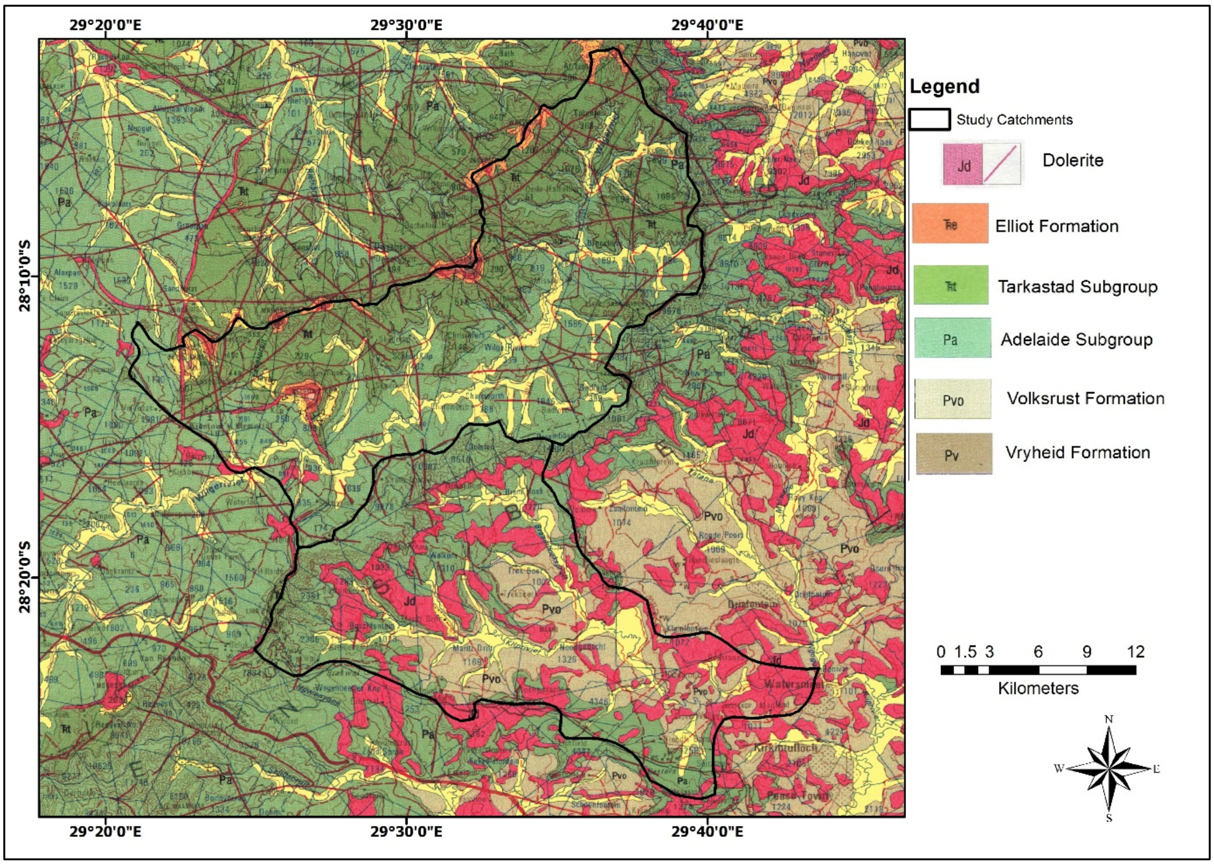


Figure 2-10: Geological map of the study area showing the main Formations (modified from Council for Geoscience, 1998).

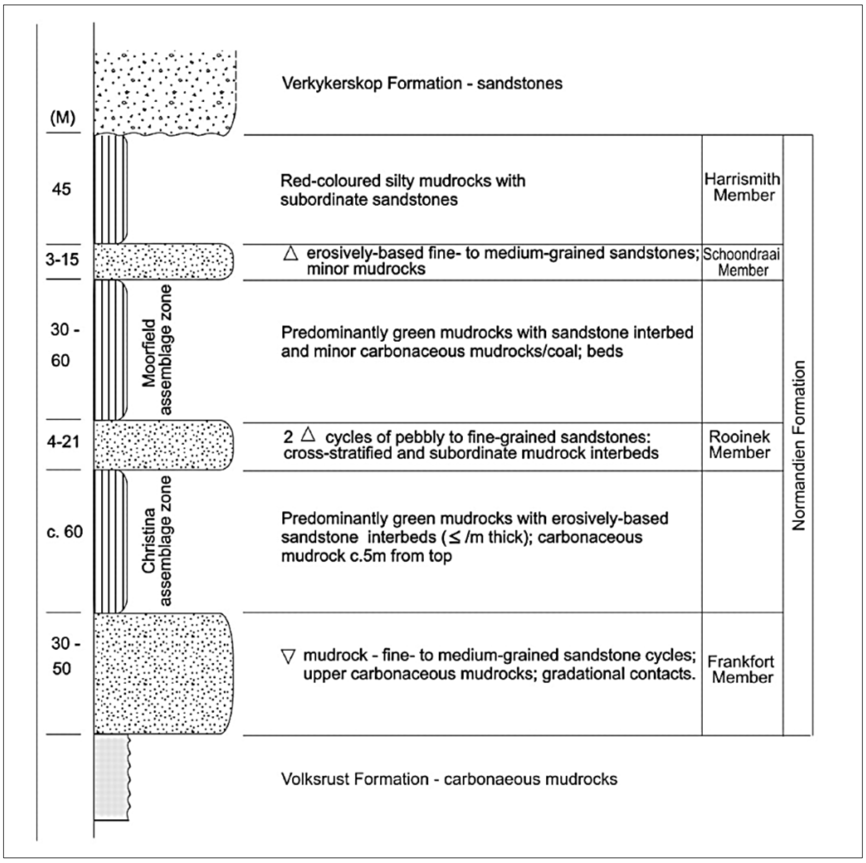


Figure 2-11: Stratigraphic successions in the study area (after Groenewald, 1989).

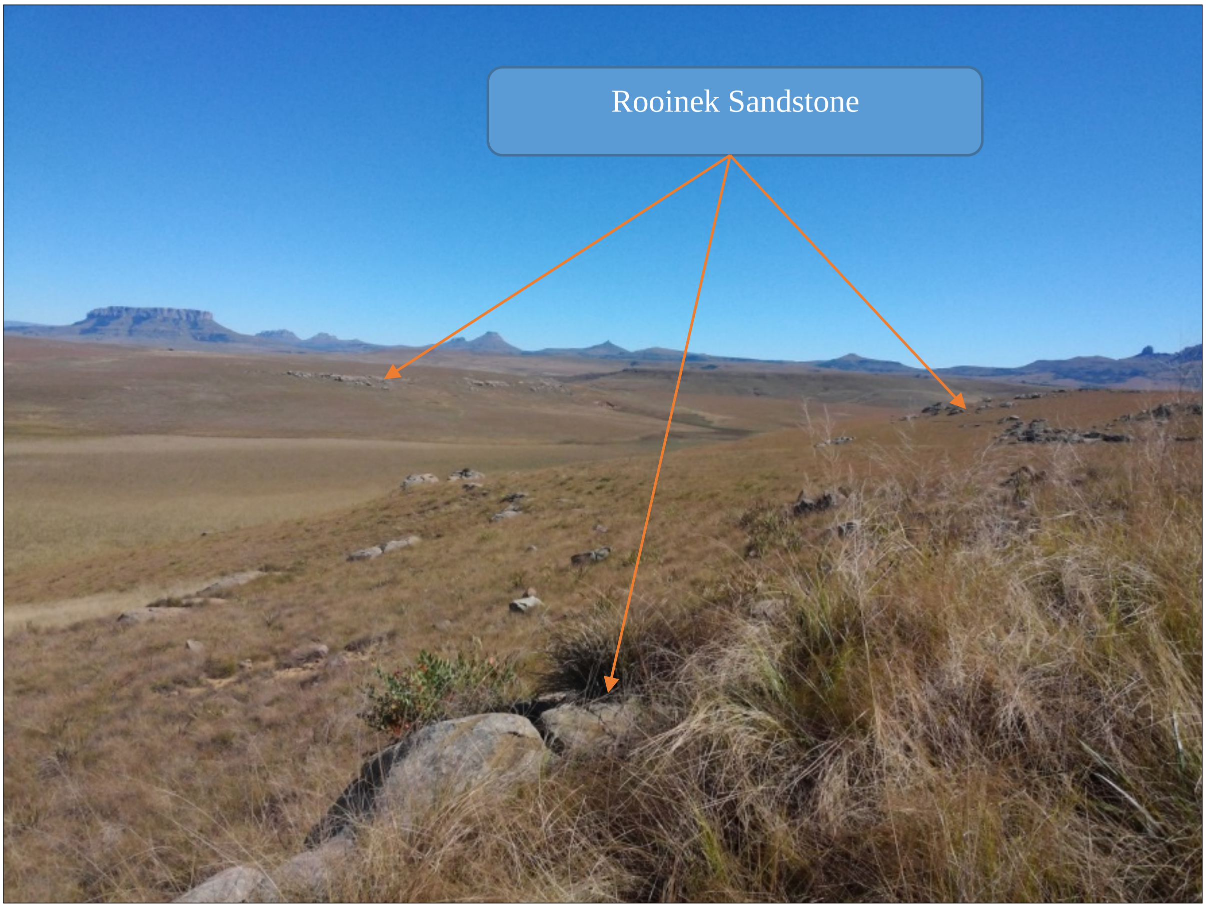


Plate 2-2: Exposure of the sandstones of the Rooinek Member in the Bedford catchment.

These sedimentary rocks are intruded by sills and dykes (Plate 2-3) of the Karoo Dolerite Suite. Numerous, narrow (1-8 m) and SE/NW trending dykes traverse the area including several conformable sills within both the Adelaide Subgroup and Volksrust Formations (Partridge and Maud, 2004). The lower reservoir basin is surrounded by sills, one of which flanks the western part of the Braamhoek Dam. Fresh dolerites that occur in the study area are generally highly jointed, especially at contacts with sedimentary rocks. These contacts are also characterised by groundwater occurrences. At the mudstone-dolerite contacts (chill zones), mudstones appear indurated, indicating that these mudstones seem to be stronger and less susceptible to slaking and expansion. The units are, however, heavily jointed.

Faults in this area are generally of small (<50 m) displacements with East/West or East South East/West North West trends (Partridge and Maud, 2004). The faults generally post-date the intrusions although there is some evidence suggesting they may have occurred contemporaneously on occasion (Keyter *et al*., 2008). Shear beds of varying thickness were observed in the sedimentary rocks mainly in-filled with argillaceous and calcareous minerals.

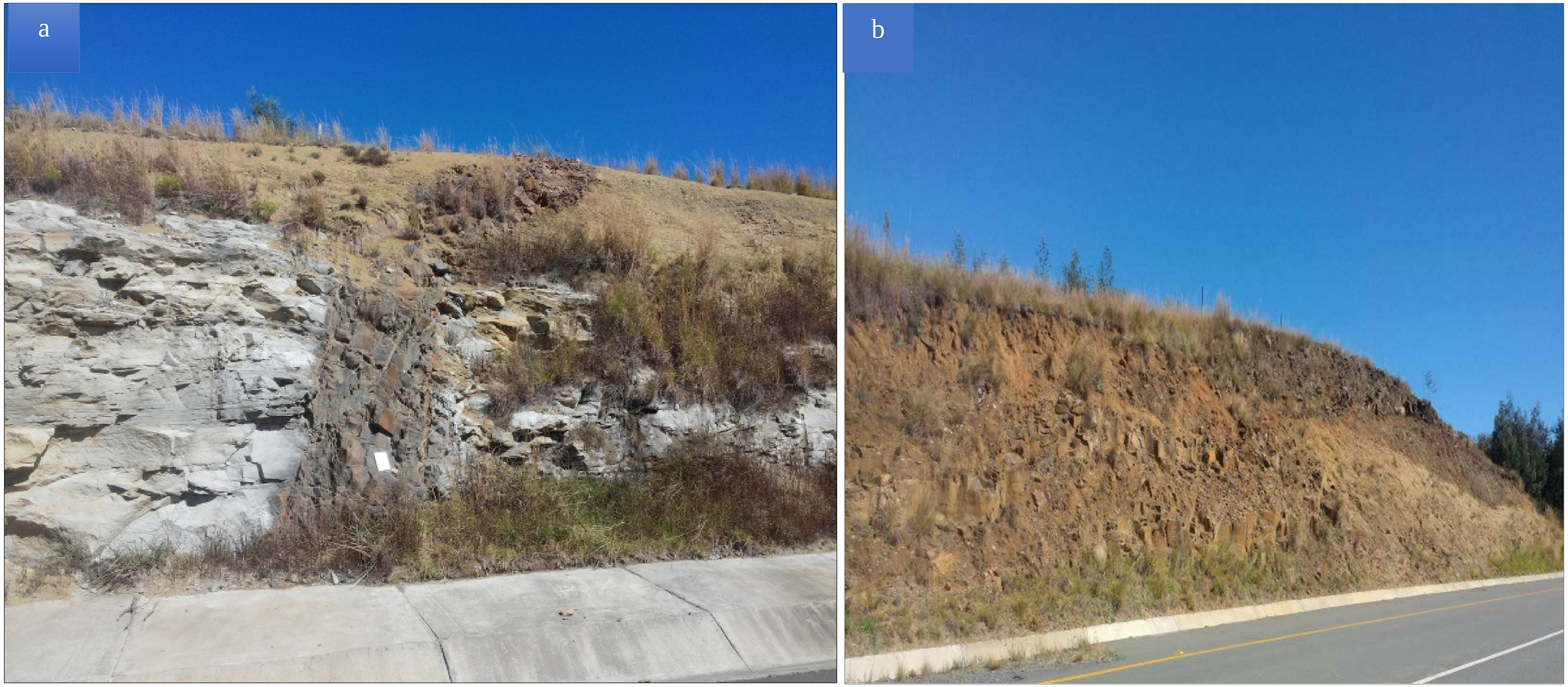


Plate 2-3: Dolerite dyke (a) and sill (b) intrusions on the De Beers Pass road cutting.

2.6 Soils

The soils of the IPSS catchment are complex and as a result Partridge and Maud (2004) put them into associations according to their topographic locations as summarised in Table 2-2:

- Association A is restricted to steeper slopes and outcrop zones. It is basically skeletal soils belonging to the Mispah and Glenrosa forms, characterised by hard rock at shallow depths in profile (less than 30 cm). This association falls into the Lithic group of soils. Mispah form (typical of Fa land type) is lithic, orthic, chromic, acalcic, fine sandy clay with the parent material being Ecca Shale (Fey, 2010) and is acidic with high infiltration rates (Van der Eyk *et al.*, 1969). Glenrosa is lithic, glossic, chromic, orthocaprolitic, aeromorphobic, acalcic, fine sandy loam; in the Fb land type (Fey, 2010).
- Association B, representing mostly Clovelly and Glenrosa forms, is typical of the rolling spurs and side slopes of the area above and inland the escarpment. The soft-xanthic Avalon form (also known as “ouklip” or umgubane) of the Plinthic soil group, contains soft plinthite in the subsoil and occurs mostly in the lower slope environment while Hutton and Griffin forms are restricted to areas in the vicinity of dolerite intrusions. This association is mostly sandy loam with high silt content and low in extractable cations (K^+, Na^+, Ca^{2+} and Mg^{2+}) hence its strongly acidic nature. The Clovelly form is the main organic soil and well-drained. Avalon is characterised by segregated iron oxides that could be mottled or cemented, indicative of limits of a fluctuating water table and low CEC (high kaolinite percentage).
- Association C has the same topographic setting and pH as B but has humic A-horizons of the Magwa and Nomanci forms; with more clay in the topsoils than in the subsoils. This association is indicative of high annual rainfall (approximately 1 200 mm p.a.) with strong subsoil leaching and preservation of organic matter in the topsoil. Subsoils of Association C are highly erodible, hence the presence of sinkholes and pipes. Humic soils are a xanthic Magwa form and lithocutanic Nomanci form both falling into category S1 in Table 2-3.

- The term “humic soils” was reserved by Van der Eyk *et al*., (1969) for soils in an advanced stage of weathering in the Tugela Basin. Humic soils are generally characterised by low cation exchange capacity (CEC), low pH, and zinc shortage.
- Association D, limited to the smaller drainage depressions, is dominated by the Katspruit form. It is also characterised by subsurface piping, sinkholes and dongas. On the wetland areas in the lower slope environments and along the floors of tributary valleys is Association E. This association is dominated by Willowbrook and Katspruit forms and is sensitive to changes in soil moisture regime caused by draining or disruption of surface runoff. Association F is strongly acidic, organic-rich soils of the Champagne form which conform to the accepted definition of peat found within the Bedford-Chatsworth wetland.
- Association G is a substrate of Rooinek sandstone with the Willowbrook and Katspruit forms predominating, Kroonstad form in the pans, and Champagne form where perennial water favours reed sedges. In the Gleyic soil group are an orthic Katspruit form and an eluvic Kroonstad form. These soils form from reduction (redox) in wetland soils. They are greyish in colour due to water saturation for long periods. They are normally found in bottomlands (vleis), have a high pH, CEC, plasticity index, and organic matter.
- Association H dominates the floodplains of the Wilge River and Braamhoekspruit. The Oakleaf form, with light to intermediate texture, is found in the levees and behind these in the back-swamp are heavier textured soils of the Willowbrook and Katspruit forms which are sensitive to disturbance. Melanic soil group is represented by acalcic, hydromorphic, gleyic Willowbrook form. These are characterised by dark colours even when dry. They’re strong with a well-developed blocky structure.
- Association I is found on the escarpment zone as Mispah and Glenrosa forms. On the flatter gradients (spurs and slump lobes), Nomanci form can be found. The soils in this association are vulnerable to erosion. Association J is located in the foothill zone flanking the Braamhoekspruit. In this association Clovelly, Griffin, and Avalon forms predominate; with Hutton, and Shortlands forms in proximity to dolerite intrusions. This association is characterised by intermediate to heavy texture in the subsoils with the rest strongly acidic. The clay content in these soils increases with depth (luvic). Oxidic soils in the study area are represented by a xanthic Clovelly form, rhodic Hutton form, xanthorrodic Griffin form, a xanthic-hydromorphic Pinedene, and a pedorhodic Shortlands from. These are characterised by free drainage in the upper solum and a relatively low CEC.

- The final association, K, is relatively recent in origin. It attests to the extent of erosion due to poor management practices and is called Dundee form. It is characterised by the coarse, stratified alluvium. In the Cumulic group are a neocutanic Oakleaf form and a fluvic Dundee form. These are immature soils of unconsolidated deposits. The Dundee form is negligibly altered while the Oakleaf form is altered in a luvic direction (increase of clay content with depth). These are normally found in gentle concave footslopes and valley basins.

The soils could also be grouped following Fey (2010) as in Figure 2-12 and into: 1) Humic soils, 2) Melanic soils, 3) Plinthic soils, 4) Oxidic soils, 5) Gleyic soils, 6) Cumulic soils, 7) Lithic soils, and 8) Organic soils. According to Kuenene and le Roux (2012), the soil distribution of "Ingula Soilscape" is about the same as the parent material.

The study done by Terrel *et al*. (2012) shows that the upper site lies within the Bb 122 land type (Figure 2-12) described as a "Plinthic catena: upland duplex" characterised by a grading of soils from red through yellow to grey soils down the slope. The catena is represented by Clovelly, Mispah, Pinedene/Clovelly and Dundee soil forms in the valley bottom. Here the clay layer is yellowish in colour and is expected to limit or slow downward movement of water through soils. Clovelly form in the midslopes has a clay content that increases down the profile with the hydraulic conductivity (K) of Apedal B being the highest at 87 mm/h; followed by Orthic A at 45 mm/h; then the saprolite at approximately12 mm/h where ponding is expected. The Griffin form in the midslope position has the following K values and arrangements: Orthic A equals to 40 mm/h; Apedal B equalts to 90 mm/h and saprolite equals to 38 mm/h. The Pinedene soils in the lower foot slopes are as follows: Orthic A equals to 35 mm/h and Apedal B equals to 30 mm/h; along dolerite dyke intrusions K equals to 2.4 m/day.

Erosion classes assigned to soil forms in Table 2-2 are defined by Partridge and Maud (2004) as follows:

- G3 is the intricate pattern of deep gullies (1-3 m) exposing the entire soil profile
- G4 is where the landscape is dissected and truncated by large (3-5 m deep) gullies with 25-50 % of the area being unproductive
- R2 represents small, shallow (less than 0.1 m) rills
- R3 represents rills of considerate depth (0.1-0.3 m) and intensity usually observed on air photos

- S1 represents areas where there are no visible signs of erosion showing on aerial photos showing high management
- S2 represents surface erosion deduced from poor cover, sediments deposits, and plant pedestals

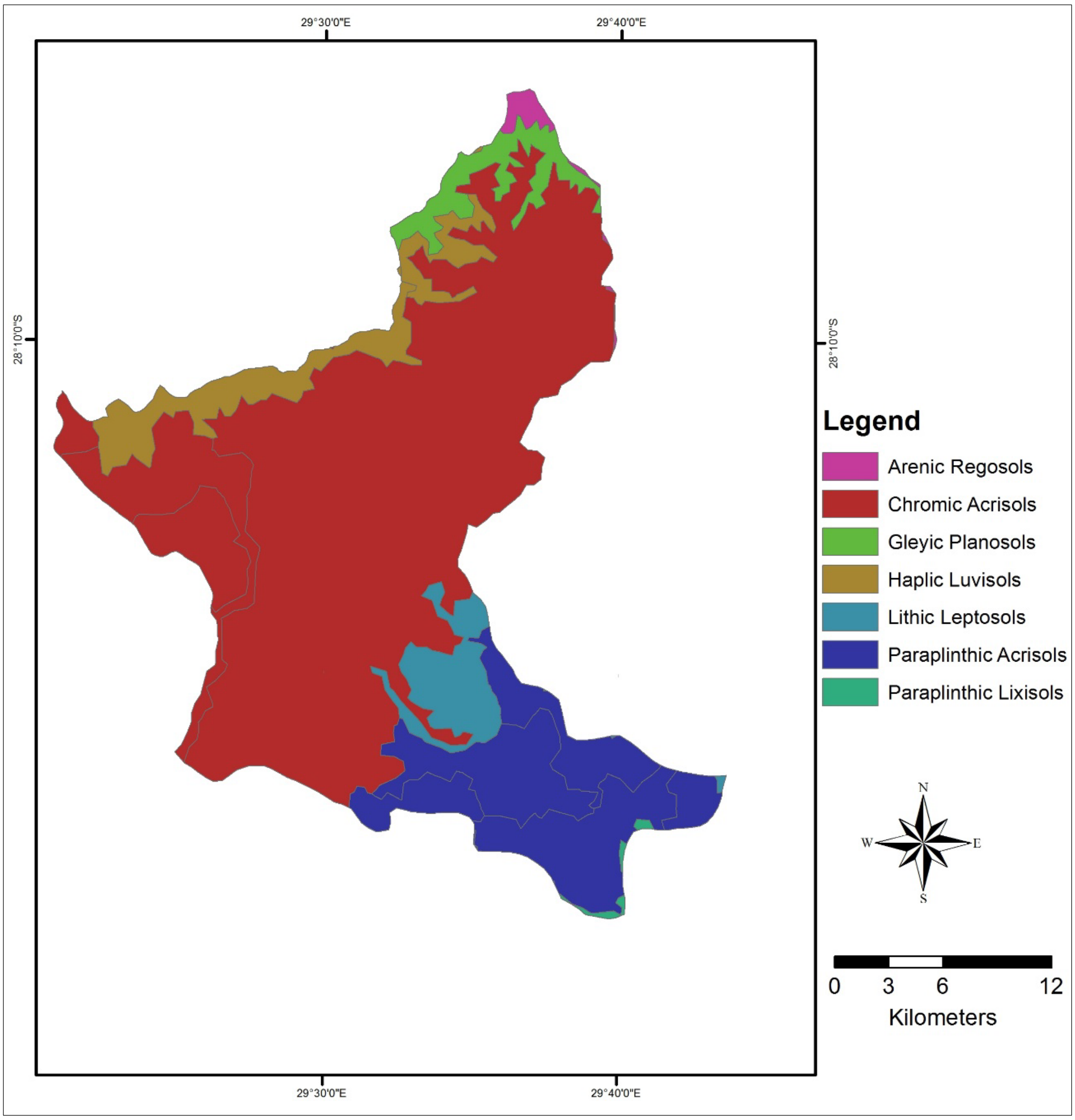


Figure 2-12: Soil map of the IPSS catchments (modified from Landtype Staff, 2006).

Table 2-2: Summary of soil attributes within the study catchments (adapted from Partridge and Maud, 2004).

Soil Form	Association(s)	Vegetation/ Land use/ Landform	Parent Material	Erosion Class	Horizons	Permeability	Extractable Cations	Resistance (ohms)/pH
Mispah	A, I							
Glenrosa	A, B, I	Grassland/ Grazing/Upper slope depression	Colluvium	R3	Orthic A1 and Lithocutanic B2 weathered shale	Rapid	Mg^{2+}, Ca^{2+}, K^{+}, Na^{+}	2000/3.7
Clovelly	B, J	Grassland/ Grazing/Mid slope	Colluvium	G3	Orthic A1 and Apedal A2	Rapid	Ca^{2+}, Na^{+}, Mg^{2+}, K^{+}	1400-2750/4.3-4.5
Avalon	B, J	Grassland/ Grazing/Mid slope		S2	Orthic A1, Apedal B21, and Soft Plinthite B22	Moderate	Mg^{2+}, Ca^{2+}, K^{+}, Na^{+} (A1 and B21) Ca^{2+}, Mg^{2+}, K^{+}, Na^{+}	2300-9000/4.2-4.5
Hutton	B, J	Grassland/ Grazing/Mid slope	Colluvium	G3	Orthic A1 and Red Apedal B2	Rapid	Mg^{2+}, Ca^{2+}, K^{+}, Na^{+}	1900-4600/4.2-4.1
Griffin	B, J	Grassland/ Grazing/Crest	Colluvium	S1	Orthic A1 and Apedal B1 and Reddish brown B2	Slow-moderate	Ca^{2+}, Mg^{2+}, K^{+}, Na^{+}	1850-6000/3.8-3.9
Magwa	C	Grassland/ Grazing/ Ridgecrest	Colluvium	S1	Humic A1, Yellow brown Apedal B21 and Yellow brown Apedal B22	Rapid	Ca^{2+}, Mg^{2+}, K^{+}, Na^{+}	2250-8000/4.3-4.6
Nomanci	C, I	Grassland/Grazing/Upper slope	Colluvium	R2	Humic A and Lithocutanic B2	Rapid	Ca^{2+}, Mg^{2+}, K^{+}, Na^{+}	1700/4.5
Katspruit	D, E, G, H	Grassland/Grazing/Valley bottom on river bank	Alluvium	G3	Orthic A1 and G	Rapid on A1 and slow on G	Ca^{2+}, Mg^{2+}, K^{+}, Na^{+}	1900-4800/4.4-4.5
Willowbrook	E, G, H	Grassland/Grazing/Floodplain	Colluvium/Alluvium	S1	Melanic A1, G1 and G2	Very slow	Ca^{2+}, Mg^{2+}, K^{+}, Na^{+}	700-720-900/5.0-4.5-4.9
Champagne	F, G	Grassland/Grazing/Floodplain	Colluvium/Alluvium	G4	Orthic A1 and Red Structured B2	Slow to very slow	Ca^{2+}, Mg^{2+}, K^{+}, Na^{+}	1100-2000/3.7-3.5
Kroonstad	G	Grassland/Grazing/Valley Bottom	Alluvium	S1/G3	Orthic A1, E and G	Slow to very slow (G)	Ca^{2+}, Mg^{2+}, K^{+}, Na^{+}	2200-3700-300/4.1-3.7-4.0
Oakleaf	H	Grassland/Grazing/Floodplain-Levee	Alluvium	G4	Orthic A and Neocutanic B2	Rapid	Ca^{2+}, Mg^{2+}, K^{+}, Na^{+}	1100-2250-4400/3.4-3.4-3.5
Shortlands	J	Grassland/Grazing/Upper slope	Colluvium	R2	Orthic A1 and Red Structured B2	Slow to moderate	Ca^{2+}, Mg^{2+}, K^{+}, Na^{+}	1100-2000/3.7-3.5
Dundee	K	Grassland/Grazing/Gully mouth	Alluvium	S2	Orthic A1, Stratified Alluvium and Buried Melanic A of Willowbrook	Rapid	Ca^{2+}, Mg^{2+}, K^{+}, Na^{+}	

Table 2-3: Soil categories mapped in the study area and used for modelling (edited from Land Type Survey Staff, 2006).

Category	Description	Form
S1	Soils with humic topsoil horizons	Magwa, Nomanci
S2	Freely drained, structureless soils	Hutton, Clovelly, Griffin, Shortlands, Oakleaf
S3	Red or yellow structureless soils with a plinthic horizon	Avalon, Pinedene
S4	Excessively drained sandy soils	Dundee,
S5	Dark clay soils which are not strongly swelling	Arcadia
S6	Swelling clay soils	(Willowbrook)
S7	Soils with a pedocutanic (blocky structured) horizon	Estcourt
S8	Imperfectly drained soils, often shallow and often with a plinthic horizon	Kroonstad
S10	Poorly-drained dark clay soils which are not strongly swelling	Willowbrook
S12	Dark clay soils, often shallow, on hard or weathering rock	(Willowbrook)
S13	Lithosols (shallow soils on hard of weathering rock)	Mispah, Glenrosa
S14	Duplex soils (a sandy topsoil abruptly overlying a clayey, structured subsoil), often poorly drained	Kroonstad
S15	Wetlands	Champagne, Katspruit,
S16	Non-soil land classes (Pans, rivers, stream beds, erosion, marshes, reclaimed land, dunes, gravel, etc	
S17	Rock (surface outcrops)	

2.7 Hydrogeological Conditions

According to the 1:500,000 Kroonstad 2726 Hydrogeological Map Series (DWA, 2000) shown in Figure 2-14, the main aquifer type within the IPSS catchment is intergranular and fractured with median borehole yield that ranges from 0.1 to 0.5 l/s. This aquifer system is developed as a result of fracturing and subsequent weathering processes. According to DWA (2000), these processes created two hydraulically interconnected vertical aquifer zones that occur in a vertical profile namely:

- A shallower, weathered zone, where the original rock structure has been changed to a mass of more or less loose rock fragments, in a matrix of fine products of weathering, mostly sand, silt and clay, and
- A fractured zone, down to a depth where the rock is becoming solid and fresh in appearance. The transition to this deeper zone is usually gradual. The lateral movement of groundwater in the top zone is very slow and boreholes tapping this zone have low yields.

The fracturing and, to a lesser degree, the weathering processes have produced a network of fractures in the highly competent mainly quartzitic rock formations (DWA, 2000). The volume of groundwater stored in this type of aquifer is therefore limited, much lower than in other aquifer types.

The Geomeasure Group (2008) reported that the sedimentary rocks of the area generally represent poorly productive secondary aquifers. Primary storage and permeability are negligible and groundwater storage and movement is confined to fractures and bedding planes within the rock mass. The indurated zones (chill zones) at the contact with dolerite and displacement faults are however often highly fractured and enhance groundwater storage and permeability. Blow yields of boreholes located in these contact zones ranged between 0.5 and 6 l/s (Geomeasure Group, 2008).The depth of weathered rock/soil, and the depth, frequency and width of fracture systems varies from place to place. Regional aquifer recharge is between 15 mm and 25 mm annually with an annual contribution to baseflow in the range of 10 mm and 25 mm (DWA, 2000).

In the Bedford catchment, sandstone is the dominant lithology. Dolerite dykes and sills have been identified in tunnels, shafts, and boreholes. In the shallow aquifer, groundwater occurs in pore spaces between grains in the soil and weathered bedrock. Generally, this aquifer is expected to be poorly-developed as rapid erosion along the escarpment will limit the development of thick soil and weathering deposits. This aquifer can be categorised as perched since the regional groundwater occurs at a relatively deeper level (Mentis, 2005). The shallow aquifer is recharged by rainfall and discharges rapidly into local watercourses and water bodies (Mentis, 2005).

The fracture system in the deeper aquifer is recharged from the perched aquifer. However, not all fracture systems will be water-bearing (Mentis, 2005). Groundwater is also expected to circulate on contact zones between sandstone/mudstone, and perhaps on bedding planes within these units. Groundwater was observed to seep along bedding plane and dolerite sill contacts and discharges as springs on steep slopes.

Site-specific information is limited but the fractured sandstone aquifer is generally expected to have higher hydraulic conductivity than fractured mudstone. This is because sandstone tends to be more brittle. Included in the fractured aquifer are the fractured and weathered margins of dolerite dykes and sills. The shallow weathered aquifer within the Braamhoek catchment is likely to include talus material. Groundwater occurrence in the deeper weathered aquifer will occur on contacts between mudstone/shale and dolerite, and on shear planes, fractures and joints in mudstone/shale. Hydraulic conductivity values range from 0.1 to 0.2 m/day (Kuenene and le Roux, 2012). This is consistent with the observed low seepage volumes into tunnels and other excavations.

The groundwater level is expected to follow the local topography as see in Figure 2-13. Measured groundwater levels suggest a range of depths from 2 m to 20 m below ground level (bgl) (Geomeasure Group, 2008). Seasonal rainfall and associated changes in the level of the reservoirs may create a hydraulic gradient into the surrounding aquifers, as indicated by tunnel inflows at the Tailrace Tunnel Outlet side noted after the rise in water level in the Braamhoek Dam.

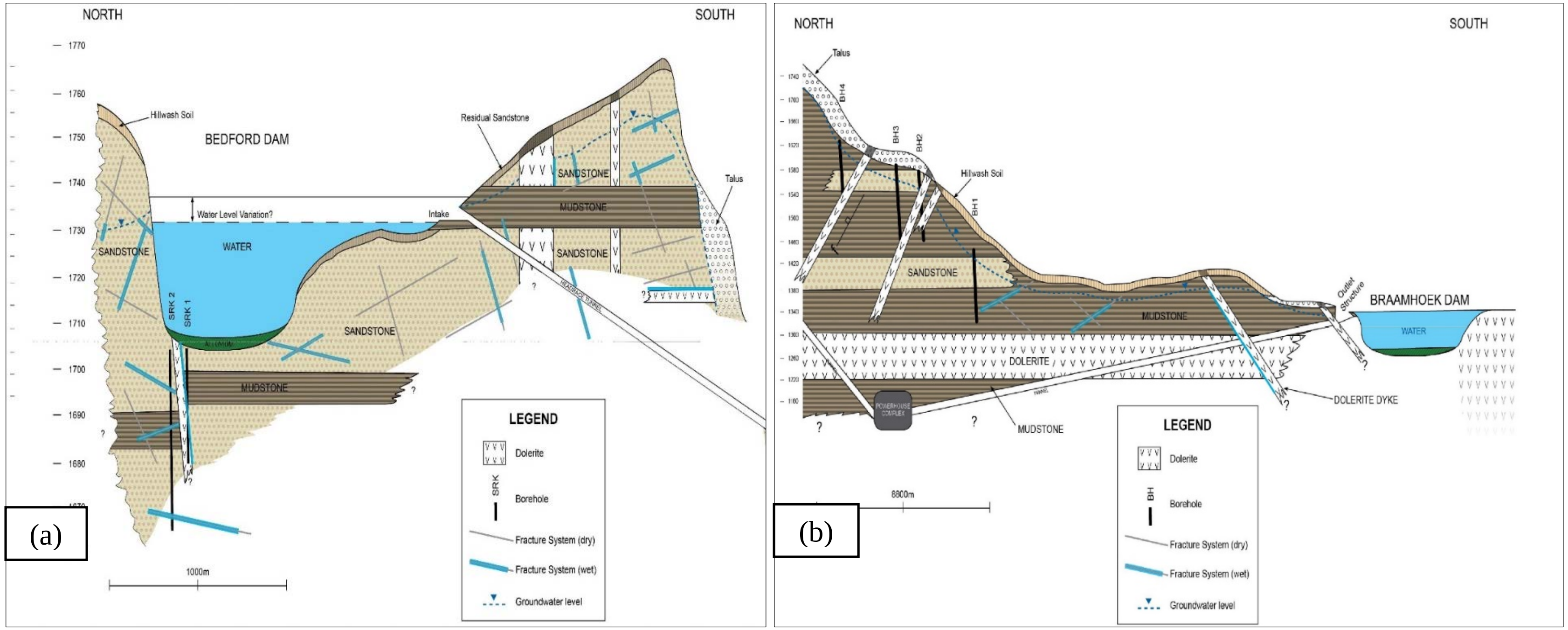


Figure 2-13: IPSS hydrogeological conceptual model for Bedford catchment (a) and Braamhoek catchment (b) (Teffo, 2015)

The annual groundwater recharge in the Braamhoek catchment ranges from 10 to 25 mm/year. This is likely to be driven by rainfall and associated changes in water level which create a hydraulic gradient into the surrounding aquifers. The groundwater component of river base flow in the Braamhoek catchment ranges from 25 to 50 mm/year (DWA, 2000).

The specific electric conductivity (EC) values range between 10 and 100 mS/m and the total dissolved solids (TDS) of groundwater within the study area is typically less than 300 mg/L (DWA, 2000). Groundwater quality in this region is generally very good (Logan, 2006; Murray *et al.*, 2012).

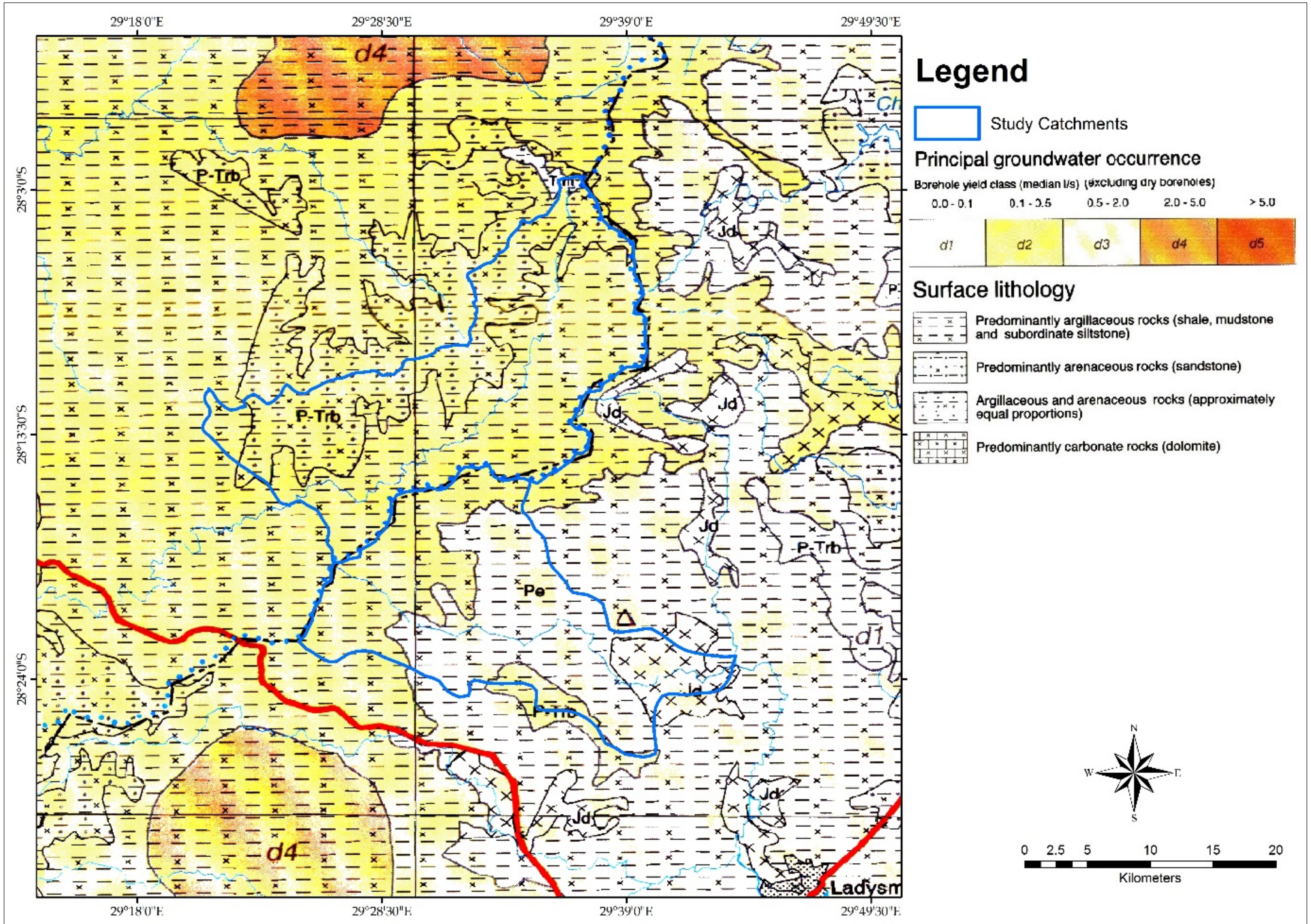


Figure 2-14: A simplified hydrogeological map of the study area (modified from the Kroonstad 2726 Hydrogeological Map Series of DWA, 2000)

CHAPTER 3 LITERATURE REVIEW

3.1 Overview

Owing to the semi-arid nature of the climate, South African rainfall and other hydrological parameters are highly variable which makes water a conceivably most precious natural resource in the country (Pitman, 2011). The uneven distribution of the water resources, both in time and space, is limiting the optimal development of the country and thus needs careful management to ensure maximum benefits (Wijers, 1993). According to Jain and Singh (2003), the elements of a water resources system can either be natural (for instance, rivers, lakes, and groundwater) or artificial (for instance reservoirs and canals). Aquatic and water-dependent ecosystems which are repositories of bio-diversity are crucial to the functioning of the hydrological cycle (Jain and Singh, 2003). Many of these aquatic habitats support communities and species of high conservation value and need careful management (Wood *et al*., 2007). However, water resources management in semi-arid, industrialised, and multi-cultural countries is challenging.

One of the most strategically important catchment areas of South Africa is the KwaZulu-Natal Drakensberg mountain range. According to Schulze (1979), the Drakensberg is South Africa's major inland source of water supply, including the uThukela River draining east into the Indian Ocean and Vaal River draining west towards the Pacific Ocean. The Drakensberg marks a continental watershed of rivers that are important to the economy of South Africa. Natural grasslands occupy, on average, 29% (350 000 km^2) of the country major catchment areas with rainfall averaging between 600 and 1200 mm per annum (Everson *et al*., 1998).

Watersheds, as defined by Brooks *et al*. (2013), are biophysical systems that define the land surface that drains water and water-borne sediments, nutrients, and chemical constituents to a point in a stream, channel or a river defined by topographic boundaries. Black (1996) classified the functions of a watershed according to hydrology and ecology. Hydrologically, there are three fundamental functions of watersheds (Black, 1996): 1) collection of the water that becomes runoff, 2) storage of various amounts of water for various durations, and 3) discharge of the water as runoff. Ecologically, they function in two additional ways (Black, 1996): 1) to provide pathways along which environmental chemicals are processed in numerous reactions of different types, and 2) to provide a habitat for the flora and fauna that constitute biological elements of ecosystems.

These functions give rise to the critically important linkage between hydrology and water quality and quantity inherent in characterisation of watershed functions. These systems can be used to study the hydrological cycle and help in understanding of how its components can be influenced by human activities and climate change, which aids in water management (Black, 1996). Managing water resources is mostly required at watershed scale given that is the basic hydrologic unit where the heterogeneity and complexity of processes and interactions linking land surface, climatic factors, and human activities can be studied (Fadil *et al*., 2011).

Watershed modelling is an important tool for management of water resources (Singh and Frevert, 2006). Anderson and Woerssner (2002) defined a model as any device that represents an approximation of a field situation. Hydrological models are an assemblage of mathematical descriptions of components of the hydrological cycle and they are employed to understand dynamic interactions between climate and land surface hydrology (Singh and Woolhiser, 2002). Hydrological models provide a framework to conceptualise and investigate the relationships between climate and water resources (Vansteenkiste *et al*., 2011). Dzwairo and Otieno (2014) pointed out that understanding complex systems involves constructing models, comparing their predictions with observations, and improving them by using feedback mechanisms from the continuous assessments.

Many models were developed for watershed hydrology but the availability of temporal and spatial data is the main constraint hindering the implementation of these models, especially in developing countries. However, the development of remote sensing techniques and GIS capabilities have encouraged and improved the use of these models worldwide.

3.2 Hydrological Models and Modelling Procedures

Hydrological models can be basically classified as either deterministic or stochastic (Vansteenkiste *et al*., 2011). Deterministic models only permit one possible outcome from a simulation with one set of inputs and parameter values; whereas stochastic models allow for an element of randomness in the outcomes due to uncertainties associated with the input and parameter variables (Vansteekiste *et al*., 2011). Most hydrological models are deterministic, but some consist of one or more stochastic components (Singh and Woolhiser, 2002).

Within deterministic models, two main approaches to modelling may be adopted; namely, lumped hydrologic models that simulate a spatially averaged hydrologic system, and distributed models that involve a more accurate representation of the hydrologic system by considering the spatial variability of model parameters and inputs (Chow *et al*., 1988).

Based on the spatial variability and the presentation of the physical processes, four main hydrological model types are distinguished as conceptualised in Figure 3-1 (Vansteenkiste *et al*., 2011). These are: a) empirical models, (b) lumped conceptual models, (c) semi-distributed and fully distributed conceptual models, and (d) physically-based models. The physically-based, distributed models give a detailed and potentially more correct description of the hydrological processes in the catchment than do the empirical and conceptual model types.

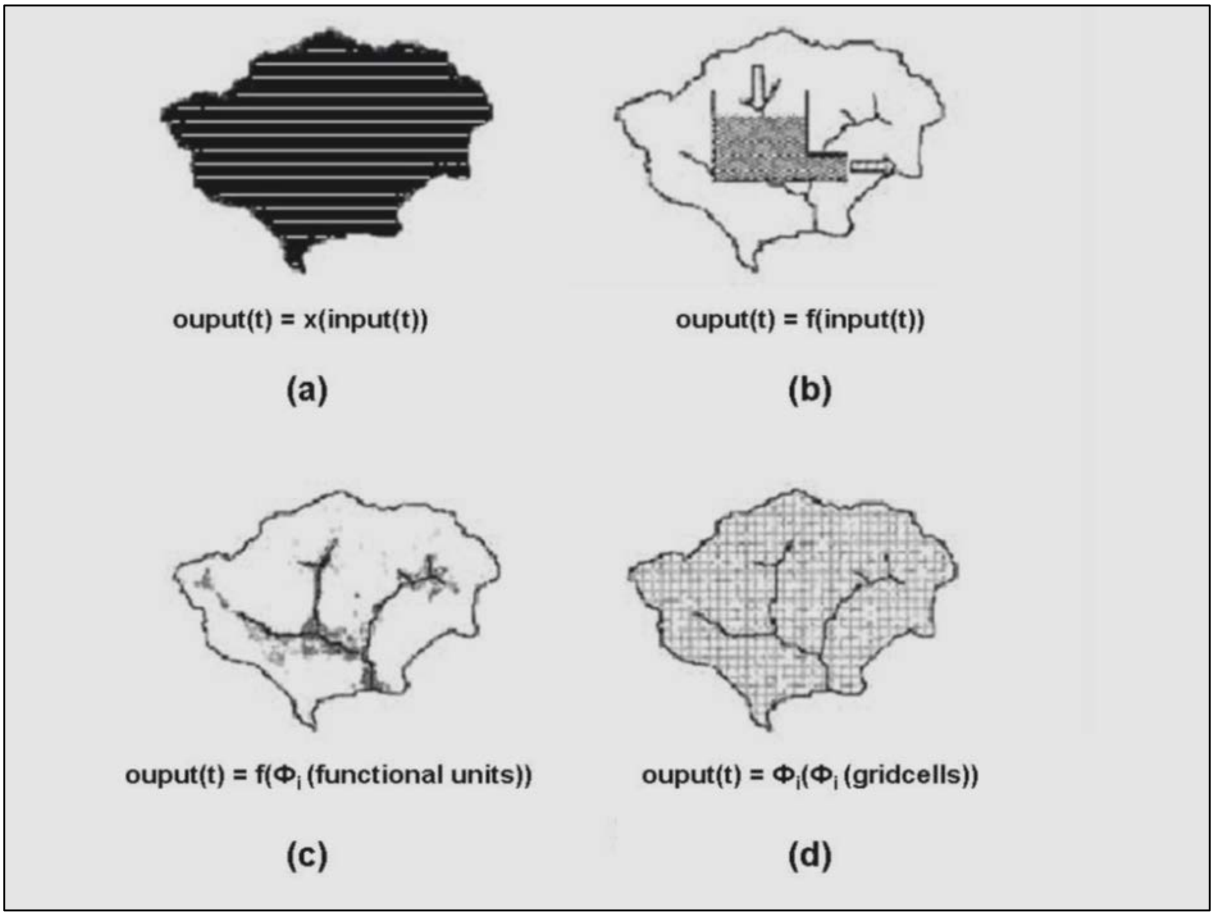


Figure 3-1: Main hydrological model types (adapted from Vansteenkiste *et al.*, 2011).

Lumped hydrological models consider the whole system (catchment, sub-catchment, aquifer, for instance) as a single unit and typically represent state variables, such as average storage in the saturated zone, as an average over the entire catchment (Chow *et al*., 1988).

Lumped models are generally expressed using ordinary differential equations and therefore do not take into account spatial variability in watershed processes, input data, boundary conditions, watershed geometry, and output (Singh, 1995). A limitation of the lumped approach is that these models are not able to consider the spatial diversity of hydrological processes over large spatial domains, associated with heterogeneity in land cover/use and soil properties (Chow *et al*., 1988). The parameters used in the lumped models represent spatially averaged characteristics of the hydrological system and are often unable to be directly compared with field measurements.

On the other hand, distributed models use partial differential equations, thereby explicitly accounting for the spatial and temporal variability in watershed processes, input data, boundary conditions, watershed geometry, and model output (Chow *et al*., 1988). Distributed hydrological models typically incorporate spatially variable datasets (for instance land use, land cover and soil characteristics). They are able to represent spatial heterogeneity of catchments and to generate outputs at interior locations (Singh and Woolhiser, 2002), which then allows them to provide a more representative description of catchment-scale processes than lumped models. The main challenge with distributed models is with the calibration process (Singh and Woolhiser, 2002). Distributed models typically discretize the catchment into sub-units (for example grid cells). Fully-distributed models divide the catchment into a uniform grid and are the most complex (Vansteenkiste *et al*., 2011).

There are also less-complicated models which do not consider every individual point separately. These simplified or semi-distributed models offer an intermediate way between lumped and fully distributed models (Vansteekinste *et al*., 2011). This separate aspect of models attempts to maintain a distributed description of catchment responses in a much simpler way. Simplified or semi-distributed models define the spatial resolution based on a distribution of functional hydrological responses in the catchment. The distribution function component in these models attempts to make allowance for the fact that not all of the catchment can be expected to respond in a similar way (Chow *et al*., 1988). In this case, points in the catchment need to be classified in terms of their hydrological similarity.

There are different approaches that have been used in attempting to make use of such a distribution of different responses in the catchment to model rainfall-runoff processes (Beven, 2001):

- The first is a statistical approach, based on the idea that the range of responses in a catchment area can be represented as a probability distribution of conceptual stores without any explicit consideration of the physical characteristics that control the distribution of responses. This is purely statistical and does not require any formal definition of similarity for different points in the catchment.
- A second type of distribution function model that attempts to define similarity more explicitly is that based on the idea of hydrological response units (HRUs). These are parcels of the landscape differentiated by overlaying maps of different characteristics, such as slope, soil, and land use. Models of this type differ in the type of conceptualisation used for each HRU.
- The third approach is based on an attempt to define the hydrological similarity of different points in a catchment based on simple theories.

One of the main advantages of the semi-distribution function approach is that some important non-linearities of the runoff generation process can be reflected in the distribution function but without introducing the large numbers of parameters values needed for fully distributed models (Beven, 2001) thus making the calibration process easier.

Hydrological models are also often classified according to their representation of catchment water processes (Vansteenkiste *et al.*, 2011). Empirical or black box models use simple empirical equations such as linear regression equations (response function models) between input and output variables. They are developed using the measured time series instead of utilising mathematical expressions describing the physical processes. They do not explicitly take into account physical processes. Several types of empirical models are observed in Govindaraju and Rao (2000):

- models using statistical methods such as Autoregressive Integrated Moving Average (ARIMA);
- models based on the unit hydrograph (or applying its principles); and
- models using data-driven methods such as artificial neural networks, model trees, nearest neighbour, and evolutionary algorithms.

An alternative to these empirical models are the conceptual models. Conceptual models describe the transformation of rainfall to runoff by means of rather simple concepts and parameters that need to be calibrated (Chow, 1988; Beven, 2001). The equations used are semi-empirical, but still with a physical basis (Vansteekinste *et al*., 2011). The structure of conceptual models is often based on several but interrelated storages representing physical elements in the catchment. The different reservoirs are linked to each other by these semi-empirical laws (Varado *et al*., 2005). The mode of operation may be characterised as a system that is continuously accounting for the moisture content in the storages.

Conceptual models usually treat the entire catchment or sub-catchment as one unit (spatially lumped); although they can be also partially distributed (semi-distributed) in case the models are related and form a collection of units (Chow, 1988). The main data to run conceptual models are the precipitation and potential evapotranspiration. The advantage of these models is that the parameterisation of the models is simple and computation is efficient (Beven, 2001). Parameters of such models are defined at catchment scale by calibration but are not easily linked to measured physical properties (Vansteekinste *et al*., 2011). The predictive power of these models is questionable in case of climate or catchment changes (Vansteekinste *et al*., 2011). Nevertheless, these kinds of models have been widely used to model hydrological processes in climate and meteorological impact studies. Other disadvantage is that these models cannot be easily applied on ungauged catchments (Varado *et al.*, 2005). They are generally valuable and employed for operational water management such as flood forecasting or dam management (Varado *et al*., 2005).

An additional approach to represent the catchment hydrological processes is given by physically-based models (Vansteekinste *et al*., 2011). Contrary to the empirical and conceptual models, these physical models use theoretical concepts in terms of sets of complex differential equations derived from fundamental physics and usually represent the characteristics in a catchment in a spatially-explicit way (Vansteenkiste *et al*., 2011). The individual components of the hydrological cycle are dealt with on a physical basis. Model parameters and variables are distributed in time and space and have a physical meaning. They are directly related to observable characteristics and can be measured in the field, which makes the calibration of these models redundant (Varado *et al.*, 2005). However, it will never in practice be possible to obtain sufficient data to give a fully correct description in all details. The representation of physical processes in the model is often too crude and the scales of measurement for many hydrological parameters are incompatible with the scales used in the models. Calibration will be crucial. It will not be a straightforward task due to high amount of parameters. MIKE SHE is an example of this kind of models (Vansteenkiste *et al*., 2011).

Watershed models are also classified based upon the simulation time-scale and can be either event-based or continuous-time simulation. According to Varado *et al*. (2005), event simulation models are applied in developing a flood hydrograph for a given precipitation event (with a duration on the order of days). Thus, these models do not address evapotranspiration, soil moisture accounting, and base flow processes. On the other hand, continuous simulation models account in time for all precipitation that falls on a watershed and the movement of water through the basin to its outlet (Varado *et al*., 2005). These models, therefore, take into account all hydrologic processes, including evapotranspiration, soil moisture accounting, and subsurface flow in the unsaturated and saturated zones.

Assessing the effects of variability in climate, biota, geology, and human activities on water variability and flow regimes requires the development of models that couple two or more components of the hydrologic cycle (Markstrom *et al*., 2008). Engman and Gurney (1991) point out that the nature of GIS and remote sensing has moved from a relatively qualitative "art", relying on inference for information to a quantitative "science" capable of measuring states of a system. With respect to hydrologic applications, unique aspects of GIS and remote sensing include: i) the ability to measure spatial information instead of point data; ii) the ability to measure actual state variables (for instance soil moisture, surface temperature) over drainage basin, and iii) the potential ability to assemble long term (years to decades) temporal data sets (Engman and Gurney, 1991).

ArcSWAT is an ArcGIS extension and a graphical user interface for the SWAT (Soil and Water Assessment Tool) model (Arnold *et al*., 1998). SWAT was developed by the United States Department of Agriculture-Agricultural Research Service (USDA-ARS) at the Grassland, Soil, and Water Research Laboratory in Texas, USA. SWAT model was tested and used in many regions of Africa especially in West Africa (Fadil *et al*., 2011).

SWAT is a river-basin or watershed-scale model developed to predict the impact of land management practices on water, sediment and agricultural chemical yields on large, complex watersheds with varying soils, land use, and management conditions over long periods (Arnold *et al*., 1994). It combines these loadings with point source contributions, and performs flow and water quality routing in stream reaches. SWAT simulates watershed hydrology, channel erosion, pesticide fate and transport, and water quality (Arnold *et al*., 2012). SWAT uses a combination of empirical and physically-based equations that use readily available inputs, and enables users to study long term impacts (Miller *et al*., 200).

According to Neitsch *et al*. (2011), SWAT incorporates features of several USDA-ARS models and is a direct outgrowth of the Simulator for Water Resources in Rural Basins (SWRBB). SWRBB is a continuous time step model that was developed to simulate nonpoint source loadings from watersheds (Neitsch *et al*., 2011). SWRRB can only be used on watersheds with areas that are a few hundred square kilometres and has a limitation of 10 subbasins (Gassman *et al*., 2007). According to Knisel (1980), other models such as Chemicals Runoff and Erosion from Agricultural Management Systems (CREAMS), Groundwater Loading Effects on Agricultural Management Systems (GLEAMS), and Erosion-Productivity Impact Calculator (EPIC) contributed significantly to the development of SWAT. CREAMS is a field scale model designed to simulate the impact of land management on water, sediments, nutrients, pesticides, leaving the edge of the field.

Watershed division in SWRRB was limited to ten subbasins and the model routed water and sediment transported out of the subbasins directly to the watershed outlet. These limitations led to the development of the Routing Outputs to Outlet (ROTO) which took outputs from multiple SWRRB runs and routed the flows through channels and reservoirs (Neitsch, 2011). ROTO provided a reach routing approach and overcame the SWRRB subbasin limitation to "linking" multiple SWRRB together (Neitsch, 2011). The linkage worked but problems with the cumbersome SWRRB files brought about the merging of ROTO and SWRRB, which then gave rise to SWAT (Neitsch, 2011).

The SWAT model is process-based and its major components include surface hydrology, weather, sedimentation, soil temperature, crop growth, nutrients, pesticides, groundwater, and lateral flow (Abdulla and Eshwati, 2007). Processes and algorithms used in SWAT can be listed after (Arnold *et al*., 1994) as follows: 1) Climate; 2) Hydrology (includes canopy interception, runoff, infiltration, and evapotranspiration; 3) Land cover/ plant growth; 4) Erosion (derived from peak runoff rate); 5) Nutrients (Nitrogen and Phosphorus cycles); 6) Agricultural (Planting, tillage, irrigation, fertilization, pesticide management, grazing, and harvesting); Stream routing using the variable storage routing method (flow continuity equation) and Muskingum routing method (wedge and prism storage); 7) Sediment transport as related to the stream flow rate. The model calculates the maximum sediment that can be transported, compares the maximum sediment concentration to the actual sediment concentration, and the extra sediment is deposited. If the actual sediment is less than the maximum, settled sediment will be re-suspended and enter the water; 8) Simulation of in-stream biology and nutrient processes including algal growth, death and settling, oxygen in water, aeration and photosynthesis, and change in water temperature; 9) Simulates sediment settling and mass balance, pesticide transport and fate, nutrient and settling and lake chlorophyll production.

The strength of SWAT is its ability to simulate continuous phenomena, with less emphasis on event-based, short-term rainfall-runoff simulations. Water balance is the driving force behind all the processes in SWAT, because it impacts plant growth and movement of sediments, nutrients, pesticides, and pathogens (Arnold *et al*., 2012). Empirically-based models, such as SWAT, provide the benefit of decreased computation time and continuous simulation of large watersheds. However, as Arnold *et al.* (2012) reported, estimating changes in nutrient loading to streams as a result of changes in land use necessitates accurate surface and subsurface flow path simulation and requires distinction of streamflow generating processes and spatial representation of land use features.

Data including land use/cover, soils, river reach data, meteorological data, and pollutants are used in SWAT models (Singh and Frevert, 2006) as well as topography, flow data, and water quality data (Arnold *et al.*, 2012). The input of these datasets can be modified to site-specific conditions and data sources. Meteorological data include: daily precipitation, maximum and minimum temperature, solar radiation, relative humidity, and wind speed. Customised climatic input data include (Gassman *et al.*, 2007): 1) simulation of up to ten elevation bands to account for orographic precipitation and/or for snow melt calculations, 2) adjustments to climate inputs to simulate climate changes, and 3) forecasting of future weather patterns which is a new feature in SWAT2012. Crop yields and/or biomass outputs can be established for a wide range of crop rotations, grassland/pasture systems, and trees. New routines in SWAT2012 allow for simulation of forest growth from seedling to full maturity (Arnold *et al.* (2012).

In SWAT, the watershed of interest is divided into subbasins, which gives the model the strength to represent the properties of land uses and/or soils of each sub-basin that have a significant effect on its hydrology better. Two options are available to discretise the watershed into simulation elements (Grunewald and Qi, 2005). These are a single hydrological response unit (HRU) based on dominant land use and soil classes within a subbasin and multiple HRUs for each subbasin considering the percentages of the land use and the soil class within the subbasin. Subbasins are grouped based on HRUs and other watershed characteristics.

SWAT is designed to simulate long-term, continuous processes of flow, sediment yields, and nutrient transport in ungauged watersheds of diverse hydrologic, geologic, and climate conditions (Borah and Bera, 2003), using daily time steps. According to Arnold *et al*. (2012), watershed hydrological simulation is separated into the land phase (controls amount of water, sediments, nutrients, and pesticide loadings to the main channel) and in-stream phase (movement of water and sediments through the channel network of the watershed outlet).

The SWAT hydrological compartment in a watershed consists of a land phase and a water-routing phase (Arnold *et al*., 2012). The land phase of the hydrologic cycle controls the amount of water, sediment and pesticide loadings to the main channel in each sub-basin, whereas the routing phase of the hydrologic cycle shows the movement of water, sediment, and nutrients,., through the channel network of the water of the watershed and then to the outlet. According to The water balance of each HRU is represented by four storage volumes; namely, snow, soil profile, shallow aquifer, and deep aquifer. The water balance and hydrologic cycle in SWAT are defined by equation 3-1 (Arnold *et al*., 2012):

$$SW_t = SW_0 + \sum_{i=1}^{t}(R_{day} - Q_{surf} - E_a - W_{seep} - Q_{gw}) \qquad 3\text{-}1$$

Where:

- SW_t is the final soil water content (mm)
- SW_o is the initial soil water content on day i (mm)
- t is the time (days)
- R_{day} is the amount of precipitation on day i (mm)
- Q_{surf} is the amount of surface runoff on day i (mm)
- E_a is the amount of evapotranspiration on day i (mm)
- W_{seep} is the amount of water entering the vadose zone from the soil profile on day i (mm)
- Q_{gw} is the amount of return flow on day i (mm)

SWAT requires long running weather data to quantify the hydrologic aspects of a catchment. The WeatherMan program was designed to simplify or automate many of the tasks associated with handling, analysing, and preparing weather data for use with simulation software (Hoogenboom *et al*., 2003). WeatherMan is part of the tools in the Decision Support System for Agrotechnology Transfer (DSSAT) version 4.5 developed through collaboration between scientists at the University of Florida, the University of Georgia, University of Guelph, University of Hawaii, the International Centre for Soil Fertility and Agricultural Development, Iowa State University and other scientists associated with the International Consortium for Agricultural Systems Applications (ICASA).

WeatherMan has the ability to translate both the format and units of daily weather data files, check for errors on import, and fill-in missing or suspicious values on export (Hoogenboom *et al*., 2003). WeatherMan can also generate complete sets of weather data comprising rainfall, maximum and minimum temperature, solar radiation, and photosynthetically active radiation. The required data for DSSAT, can be filled using either: 1) monthly means and stochastic rain, 2) just the monthly means, or 3) calibrated means and variances.

3.3 Model Calibration and Validation

Model calibration and validation are critical to the accuracy and reliability of a hydrologic model (Wu and Xu, 2006) whereby simulated and observed values are compared, evaluated and refined in the process. The model is thereafter validated using parameters and datasets from different periods. Model calibration is a process of estimating model parameters by comparing model outputs for a given set of assumed conditions with observed data (Moriasi *et al.*, 2007). Ideally, calibration should use three to five years of data that includes average wet and dry years. However, such data needs make the model calibration and validation challenging in poorly gauged and ungauged basins (Guo *et al*., 2008).

To assess model performance, graphical comparison and numerical criteria are used. Moriasi *et al*. (2007) have suggested model evaluation guidelines for accuracy of system quantification. These model output evaluation guidelines classify the criteria into Standard Regression Statistics, Nash-Sutcliffe error criteria (NSE), and the Error Index Statistics. The Standard Regression Statistics determine the strength of the linear relationship between simulated resulted and observed data. The coefficient of determination (R^2) describes the proportion of the variance of measured data explained by the model. Values above 0.5 are rendered acceptable (Moriasi *et al*, 2007).

The NSE is a dimensionless statistic that provides a relative model evaluation assessment. NSE is a normalised statistic that determines the relative magnitude of the residual variance in simulated data (Q^{sim}) compared to measured data (Q^{o}) variance. Equation 3-2 is used to calculate NSE whereby, the range between 0 and 1 is reviewed as acceptable; whereas if it is ≤ 0 then it means the observed data is a better predictor.

$$NSE = 1 - \left[\frac{\sum_i^n \left(Q_i^o - Q_i^{sim}\right)^2}{\sum_i^n (Q_i^o - \bar{Q})^2}\right] \qquad 3\text{-}2$$

Percent BIAS (PBIAS) and the ratio of the root mean square error to the standard deviation of measured data (RSR) are error indices in the evaluation process to quantify the deviation in the units of simulated data. Calculated by equation 3-3, PBIAS measures the average tendency of the simulated data to be larger than their observed counterparts. The optimal value is 0 with low magnitude values indicating accurate simulation.

$$PBIAS = \left[\frac{\sum_i^n \left(Q_i^o - Q_i^{sim}\right) \times 100}{\sum_i^n Q_i^o}\right] \qquad 3\text{-}3$$

RSR was calculated using equation 3-4. The lower the RSR, the lower the RMSE and the better the model simulation performance.

$$RSR = \frac{\sum_i^n \left(Q_i^o - Q_i^{sim}\right)^2}{\sum_i^n (Q_i^o - \bar{Q})^2} \qquad 3\text{-}4$$

Table 3-1 provides the threshold evaluation and the level of acceptability of the various calibration criteria.

Table 3-1: Indices used to assess the manual calibration for subbasins output (after Moriasi *et al*., 2007).

	NSE	RSR	PBIAS
Very Good	0.75 – 1	0-0.5	< 0.25
Good	0.65 - 0.75	0.5-0.6	0.25–0.45
Satisfactory	0.65-0.5	0.6-0.7	0.45 -0. 65
Unsatisfactory	≤ 0.5	>0.7	>0.65

CHAPTER 4 MATERIALS AND METHODS

The efficacy and the performance of ArcSWAT to model the hydrological functioning of a South African catchment was done through the application of the model to the IPSS catchments. ArcSWAT version SWAT2012 was used to model the IPSS catchments.

4.1 Materials

Input data was collected from various sources and pre-processed using ArcGIS 10.1, Microsoft Office Suite, and Apache Open Office version 4.13 to fit the modelling software's specifications. Digital Elevation Model (DEM), weather data, Braamhoek reservoir outflow data, and land use/cover of 2000 and 2009 data were obtained from the IPSS Environmental Science office (Nelson, 2014). The resolution of the DEM is 20 m × 20 m, and the geographic coordinate system was converted and redefined to Transverse Mercator Projection LO29.

Hydrological, hydrometeorological, and hydrogeological data analysis and pre-processing were performed using various software:

- The ArcSWAT version SWAT2012 was used as the modelling tool in this study.
- ArcGIS 10.1 which provides spatial and temporal analysis in spatial studies. GIS stores data as layers and these layers may be manipulated and visually accessed as output data.
- WeatherMan is part of the tools in the DSSAT version 4.5. WeatherMan has the ability to translate both the format and units of daily weather data files, check for errors on import, and fill-in missing or suspicious values on export. It can also generate complete sets of weather data comprising solar radiation, maximum and minimum temperature, rainfall, and photosynthetically active radiation.

A groundwater recharge estimate is required in the model as an input. Groundwater recharge for model input was estimated using conceptual deterministic modelling (Kirchner *et al*., 1991; Bredenkamp *et al*., 1995). Kirchner *et al*. (1991) and Bredenkamp *et al*. (1995) proposed expert opinions and general equations from which the qualified guesses for recharge from the soil/vegetation and geology were created. The Microsoft Excel-based "RECHARGE" spreadsheet software was developed by Van Tonder and Xu (2000) based on the qualified guesses. The soil/vegetation information uses a map to estimate the percentage coverage of area with soil material (% clay content) and also estimates land cover based on area of woods/trees, grass lands and bare soil. The estimations are done using Figure 4-1 in conjunction with Table 4-1 and Table 4-2. A correction of 40% is made if the surface slope is more than 5% (van Tonder and Xu, 2000).

Table 4-1: Percentage of clay content in different soil types (after Van Tonder and Xu, 2000).

Percentage of Clay content	Soil Type
0 – 10	sand (50)
10 – 20	sandy loam (20)
20 – 35	sandy clay loam (5)
>35	clayey loam, clay (3)

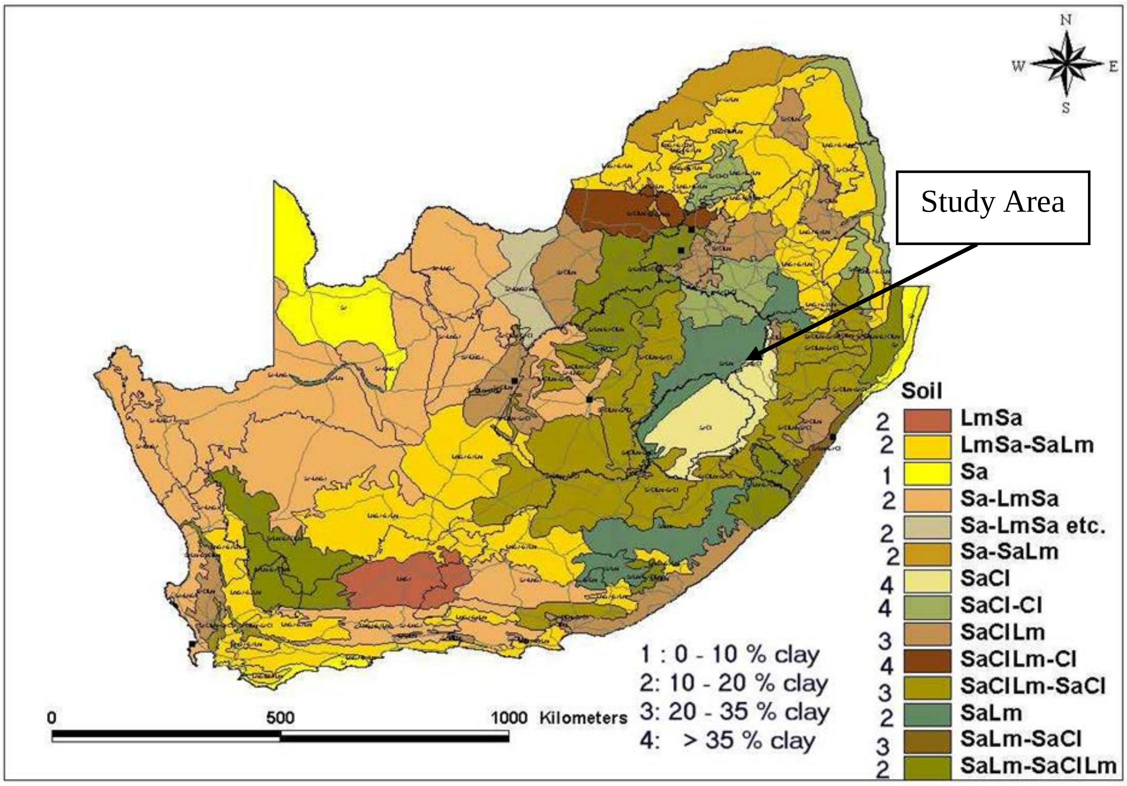


Figure 4-1: Soil map used for reference in estimation of recharge using the qualified guesses method (adapted from Xu and Van Tonder, 2001).

Table 4-2: Geology used in the qualified guess method (from Xu and Van Tonder, 2001).

Geology	% Recharge (soil cover <5m)	%Recharge (soil cover >5m)
Sandstone, mudstone, siltstone	5	2
Hard Rock (granite, gneiss)	7	4
Dolomite	12	8
Calcrete	9	5
Alluvial sand	20	15
Coastal sand	30	20
Alluvium	12	8
Coastal sand	30	20

The national scale Vegter's groundwater recharge map for South Africa used in the qualified guess method of groundwater recharge for the study area is shown in Figure 4-2 (Vegter, 1995).

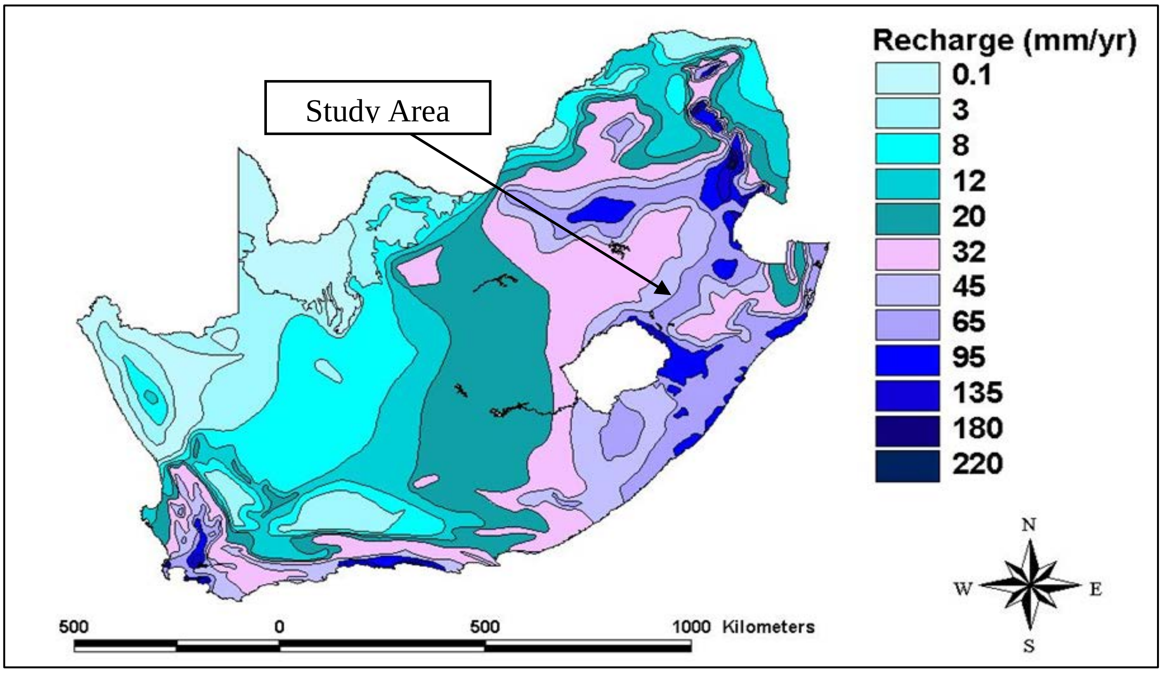


Figure 4-2: Vegter's groundwater recharge map for South Africa (Vegter, 1995).

The Agricultural Catchments Research Unit (ACRU) map (Figure 4-3) shows the mean annual recharge of soil water into the vadose zone (Schulze and Pike, 2004).

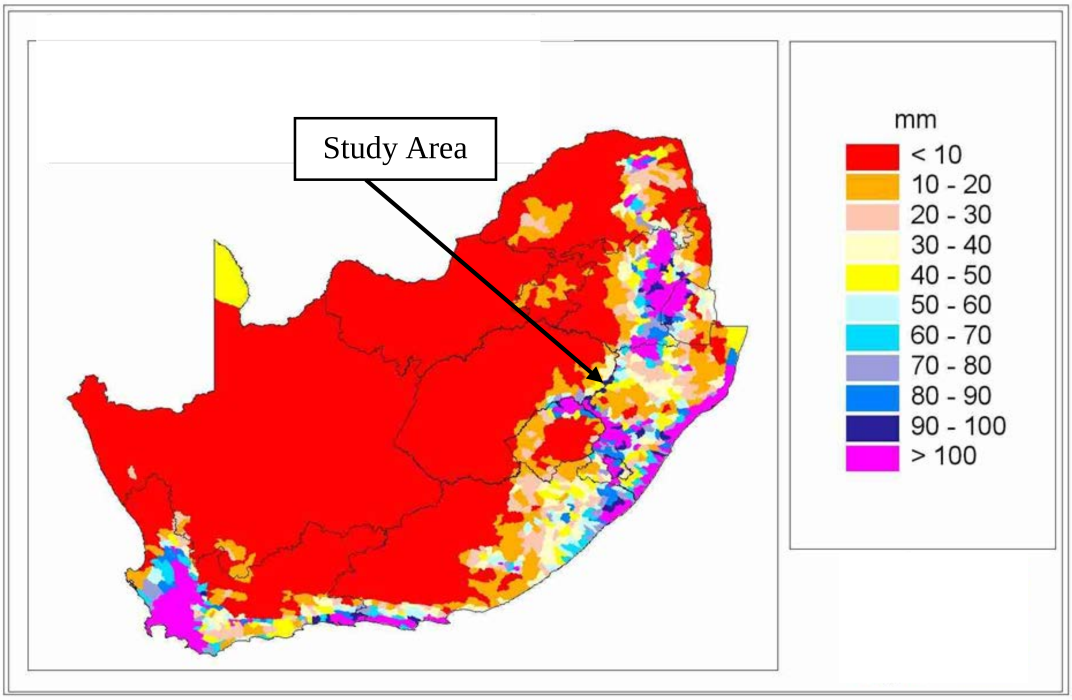


Figure 4-3: Map showing national mean annual recharge to the vadose zone estimated using ACRU (Schulze and Pike, 2004).

The groundwater harvest potential map in Figure 4-4 gives harvest potential throughout South Africa in m^3/km^2/annum.

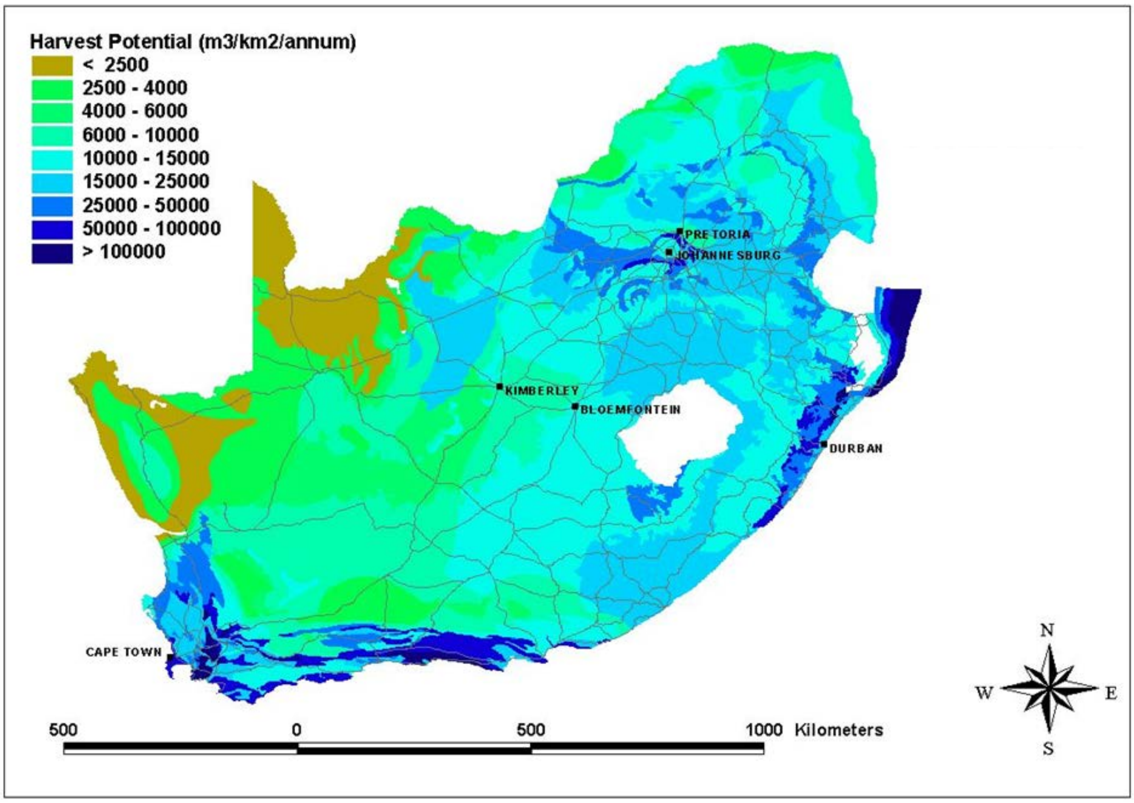


Figure 4-4: Groundwater Harvest Potential Map (Vegter, 1995).

Groundwater levels were taken from the standpipe piezometers and borehole monitored by ESKOM (Teffo, 2015).

4.2 Modelling Approach

The model input parameters were analysed, ranked and adjusted for hydrologic modelling purposes using respective time-steps (daily, monthly, or annual) as shown in the subsequent sections. Figure 4-5 shows the following sequence followed in the application of ArcSWAT in modelling the IPSS catchments:

- Delineation of watershed into sub-watersheds;
- Classification and overlaying the land use and soil data layers;
- Hydrologic Response Units (HRUs) distribution and definition;
- Editing ArcSWAT database by adding soils, land use/cover, and weather data;
- Defining the weather data: locations and records;
- Applying the default input files writer;
- Editing the default input files like reservoirs and nutrients;
- Setting up (requires specification of simulation period, PET calculation method) and run ArcSWAT;
- Applying a manual calibration method;
- Analysing, plotting, graphing ArcSWAT output and interpreting the results.

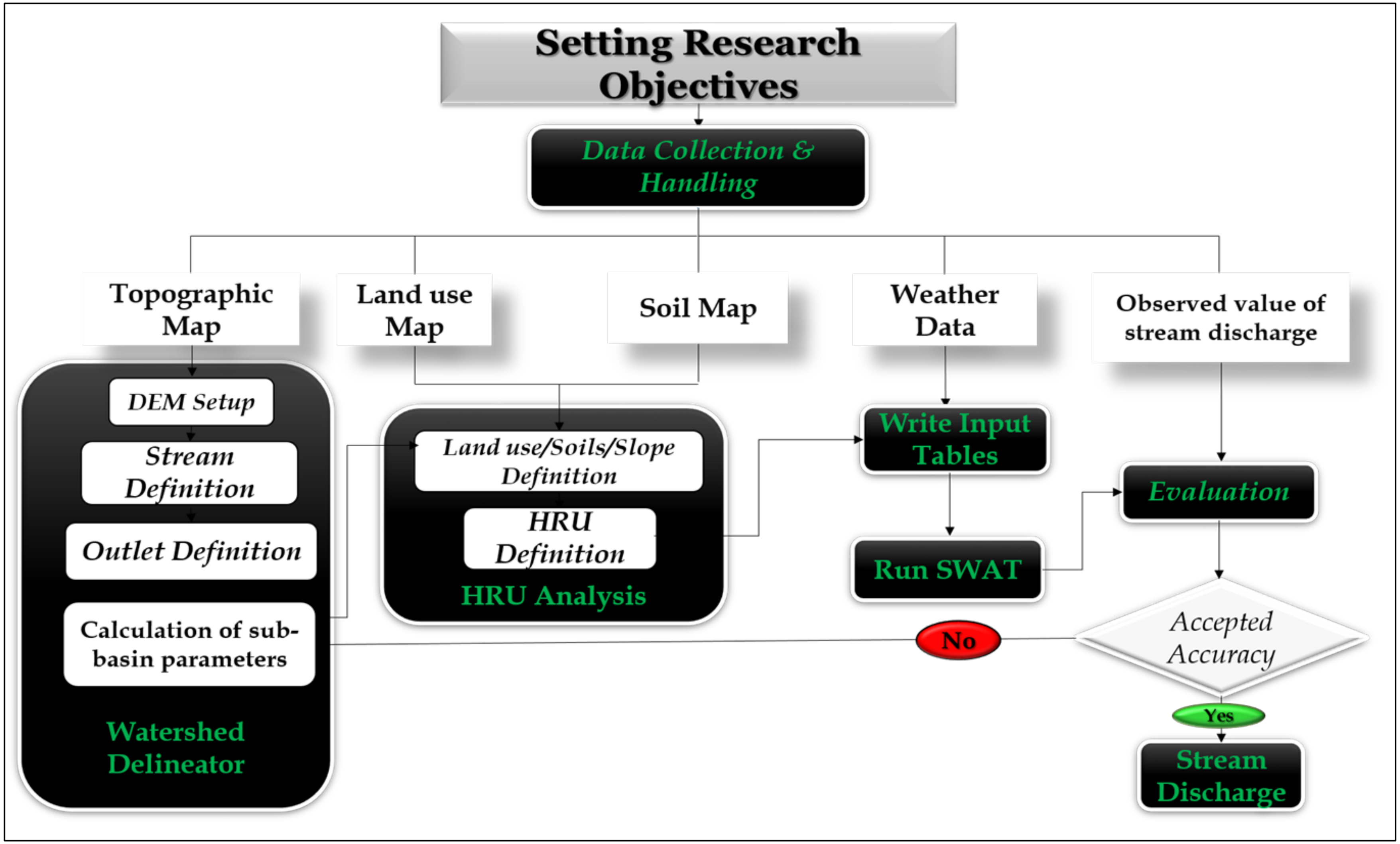


Figure 4-5: Schematic representation of the approach followed in the application of ArcSWAT to model the IPSS catchments.

4.2.1 Watershed Delineation

ArcSWAT uses the DEM to define the streams, direction of flow, and other hydrological features like reservoirs and ponds whilst in the watershed delineation process which is the first step in defining the watershed features needed in the modelling process. The defined hydrological features can further be described and given attributes when writing the user databases in ArcSWAT. The delineation of the two catchments for modelling purposes was limited to just downstream of both dams due to gauging constraints.

4.2.2 Classification of Land use/cover and Soil data Layers

The land use/cover maps of years 2000 and 2009 at a resolution of 30 m × 30 m were used. Meanwhile, user lookup tables were created to connect the ArcSWAT code with the land-use maps. Once the watershed is delineated and sub-divided to basins, the next step in ArcSWAT is the sub-division of subbasins into HRUs. The process requires definition of soil attributes, land use/cover, and slope analysis.

The soil map used for the Braamhoek and Bedford catchments was provided by the Agricultural Research Council (ARC)-Institute for Soil, Climate and Water of South Africa and projected to the same projected coordinate system as the DEM. The soil properties were mainly sourced from the soil reports and analysis as reported by Partridge and Maud (2004). The soils information were added into ArcSWAT following similar methodology used for adding the land use/cover data.

4.2.3 HRU Definition and Distribution

In the SWAT modelling approach, a study basin is divided into multiple subbasins which are connected by surface flow. The subbasins are prioritised by area. Thereafter, each subbasin is further divided into groups of homogenous land use/cover, soil types, slope and management practice which, because they are supposed to give similar hydrological responses, are called hydrologic response units (HRUs). In each HRU, hydrological components in water budget for surface, soil and groundwater are calculated independently, and then the calculation results are collected to the basin outlet. The HRUs are not represented spatially in SWAT but rather are percentages of the subbasins based on the unique combinations of characteristics (Gassman *et al.*, 2007). Figure 4-6 shows an example of the HRU definition using subbasin 4 and 5 of the Braamhoek catchment.

Input information for each sub-basin is grouped into the following categories: climate, hydrologic response units (HRUs), ponds/wetlands, groundwater, and main channel. HRU analysis in SWAT includes divisions of HRUs by slope classes in addition to land use and soils. The multiple slope option (an option which considers different slope classes for HRU definition) was selected where 5 slope classes in increments of 20% were used. The HRUs were defined to include every class.

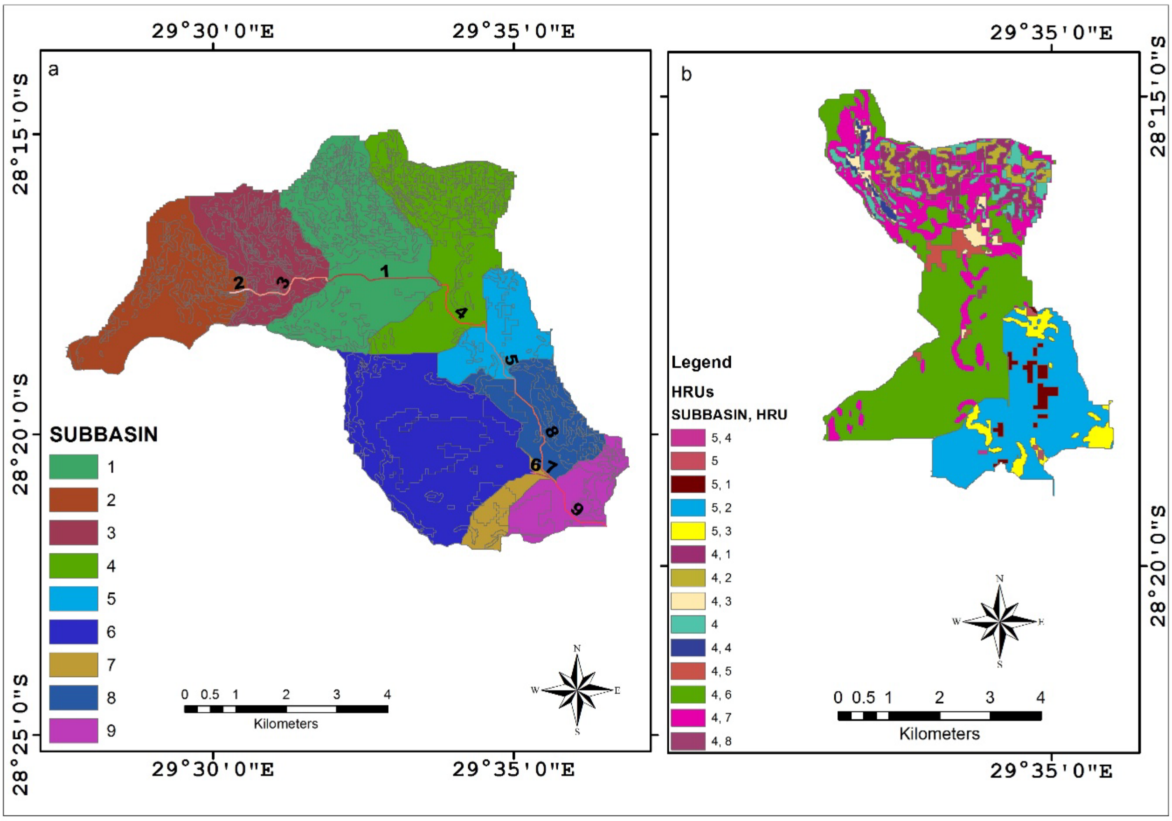


Figure 4-6: Subbasin and stream reach definitions (a), and HRUs (b) at Braamhoek catchment of the IPSS.

4.2.4 Weather Data Definition

Meteorological data used includes daily precipitation, maximum and minimum temperature, solar radiation, relative humidity, and wind speed. Customised climatic input data include 1) simulation of up to ten elevation bands to account for orographic precipitation and/or for snow melt calculations, 2) adjustments to climate inputs to simulate climate changes, and 3) forecasting of future weather patterns. Number two and three above formed a basis of weather data input and simulation process in this study.

The importance of hydro-meteorological data lies in that the climate data gives the moisture and energy inputs that control the water balance. The weather stations present in the study area started operating in 2008 and provide daily records of maximum and minimum air temperature (ºC), wind speed (km/hr) and wind direction, and rainfall (mm). Relative humidity and solar radiation were estimated using equations 4-1 and equation 4-2, respectively following Allen *et al*. (1998).

$$RH = 100 \times \left[e^{\left(\frac{17.625 \times TD}{243.04 + TD}\right)} / e^{\left(\frac{17.625 \times T}{243.04 + T}\right)} \right] \tag{4-1}$$

Where:

- TD is minimum temperature, and T is maximum temperature both in °C.

$$R_s = kR_s \times R_a \times \sqrt{\left((T_{max} - T_{min})\right)} \tag{4-2}$$

Where:

- R_a is extra-terrestrial radiation [MJ m^{-2} d^{-1}],
- T_{max} is maximum air temperature [°C],
- T_{min} is minimum air temperature [°C], and
- kR_s is the adjustment coefficient (0.16 or 0.19) [°C-0.5].

During the course of the modelling processes, interpolation and extrapolation of the meteorological data were deemed necessary. The WeatherMan program which is a part of DSSAT was used to generate more data on the basis of the weather data from both the Braamhoek and the Bedford weather stations.

Table 4-3: Table of user Weather Generator elements.

Element	Description
Station ID	Station Name and Coordinates
Rain_Yrs	Number of years used to determine values for precipitation parameters
TMPMX	Average maximum air temperature in a month in °C (Jan to Dec)
TMPMN1	Average minimum air temperature in a month in °C (Jan to Dec)
TMPSTDMX	Standard deviation of maximum air temperature in a month in °C (Jan to Dec)
TMPSTDMN	Standard deviation of minimum air temperature in a month in °C (Jan to Dec)
PCPMM1	Average precipitation in a month (mm/day)
PCPSTD	Standard Deviation for daily precipitation in a month (mm/day)
PCPSKW	Skew Coefficient for daily precipitation in a month (mm/day)
PR_W1_1	Probability of wet day following dry day in a month
PR_W2_1	Probability of wet day following wet day in a month
PCPD	Average number of days of precipitation in a month
RAINHHMX1	Maximum 0.5 h rainfall in a month for entire period of record (mm)
DEWPT	Average dew point temperature in a month (°C)
SOLARAV	Average daily solar radiation in a month ($MJ/m^2/day$)
WINDAV	Average wind speed in a month (m/s)

4.2.5 Model Calibration and Validation

In the calibration and validation of the model, comparisons were made between the predictions and observations, and the model was improved by using feedback mechanisms from the continuous assessments. In the Braamhoek catchment, the dam started impounded water in November 2011. A 135° V-notch weir with an automatic recorder that is capable of measuring flow including low-flows downstream of the dam has been constructed (Stephenson, 2005). The discharge rate at the weir is recorded with a standard electric logger that records every 15 minutes. This weir started operating in November 2010. The Bedford reservoir started reserving water pumped from the Braamhoek Dam in March 2016.This invoked the Ingula Water Usage Licence (IWUL) terms such as the logging in the weir downstream the dam. As a result, the data from the Braamhoek reservoir has been used to calibrate and validate the reservoir output of the model.

Several weather and land use/cover combinations were established to run the manual model calibration processes.

Sensitivity analysis was undertaken using a built-in SWAT sensitivity analysis tool that uses the Latin Hypercube One-Factor-at-a-Time (LH-OAT) (Fadil *et al.*, 2011). ArcSWAT 2012 has both manual algorithms and automated methods of calibration that have been developed for SWAT simulations. An iterative approach for manual calibration was used in this study involving the following steps: performing the simulation; comparing measured and simulated values; assessing if reasonable results have been obtained; if not, adjust input parameters based on expert judgement and other guidance from relevant .literature within reasonable parameter value ranges; and repeat the process until it is determined that the best results have been obtained.

The streamflow calibration process was then completed by varying several SWAT hydrologic calibration parameters within their acceptable ranges, to match the model simulated average monthly streamflow with corresponding measured values. These parameters include the curve number (CN2), soil available water capacity (SOL_AWC), evaporation compensation coefficient (ESCO), groundwater delay (GW_DELAY), groundwater recession coefficient (GW_ALPHA), and surface runoff lag coefficient (SURLAG). Following Baron *et al.* (1999) and Stephenson (2005), the following input aquifer parameters were set:

- Initial depth of water in the shallowest aquifer (SHALLST) was set to 1000 mm; and
- Initial water depth in the deepest aquifer (DEEPST) was set to 10000 mm.

Following the objective of the research that is assessing stream outflow against the change in climate and land use/cover.

The assessment of the model’s response to land use/cover changes was performed using land use/cover maps of 2000 and 2009. The two maps were paired with weather data from 1990-1935 and the outputs were compared. The catchments’ response to climate change was modelled by increasing and decreasing DSSAT-generated precipitation by 10%.

CHAPTER 5 RESULTS AND DISCUSSION

5.1 Results of the HRU Definition

The Braamhoek catchment was delineated into five (5) different subbasins (Figure 5-1) based on the streams (reaches) using the DEM shown in Figure 5-1 within ArcSWAT. The streams are in the course of the Braamhoekspruit, the main tributary of the catchment. The total area of the delineated catchment is 58.87 km^2. The Braamhoek reservoir in the simulation is at the end of stream 5.

Subbasins were further discretised with respect to the slope, land use/cover, and the soil types. The breakdown of each subbasin into its HRUs as depicted in Figure 5-1 is presented in Appendix A.

The Bedford catchment was subdivided into 3 subbasins using the DEM and its attributes are shown in Appendix B. The distribution of the subbasins over the catchment are shown in Figure 5-2. The total area of the delineated catchment is 21.15 km^2. The Bedford reservoir lies in subbasin 3 where Bedfordspruit starts as a linking stream of the Wilge River. Appendix B shows the breakdown of the HRUs in the Bedford catchment.

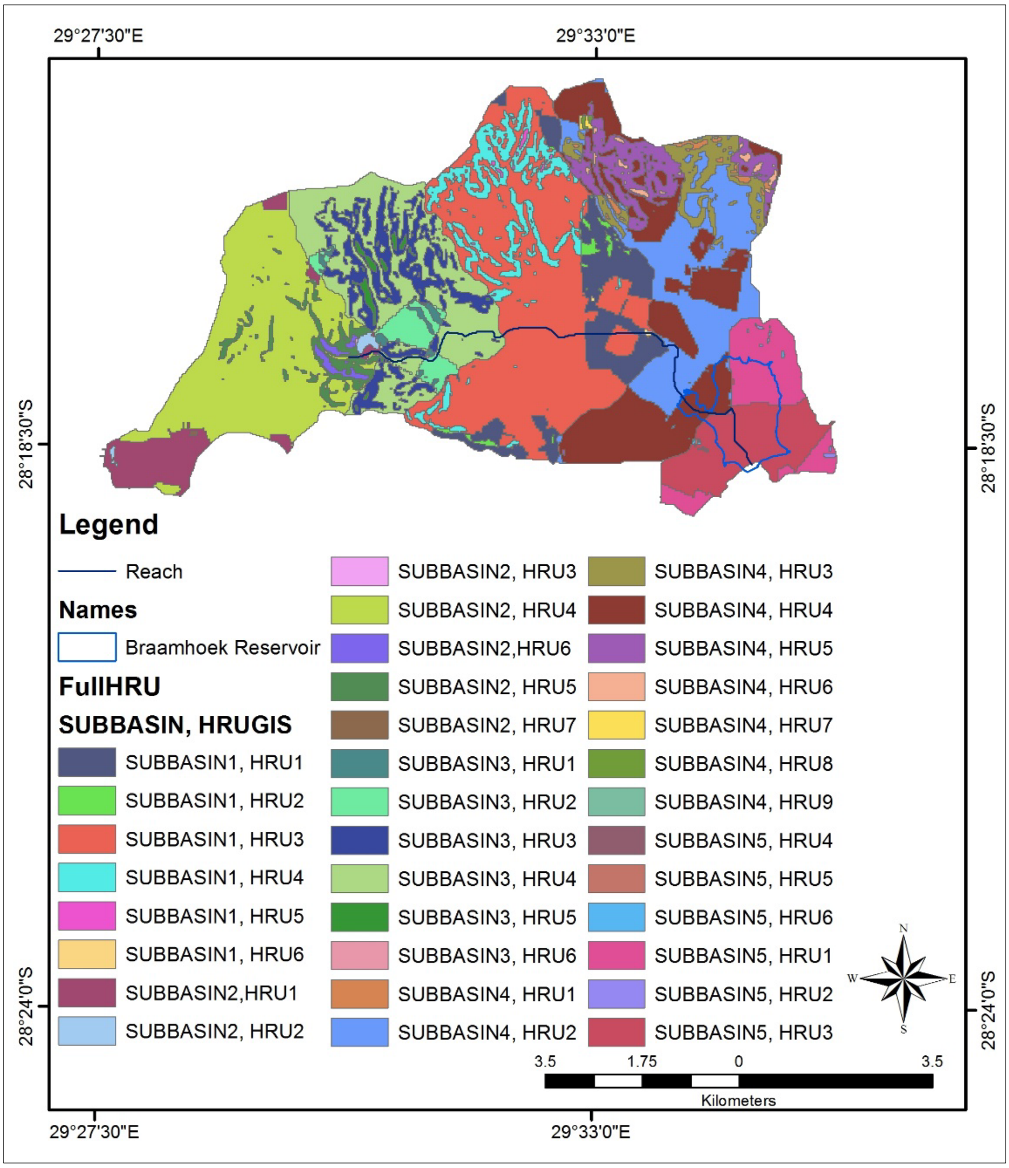


Figure 5-1: Braamhoek catchment delineation into subbasins and HRUs.

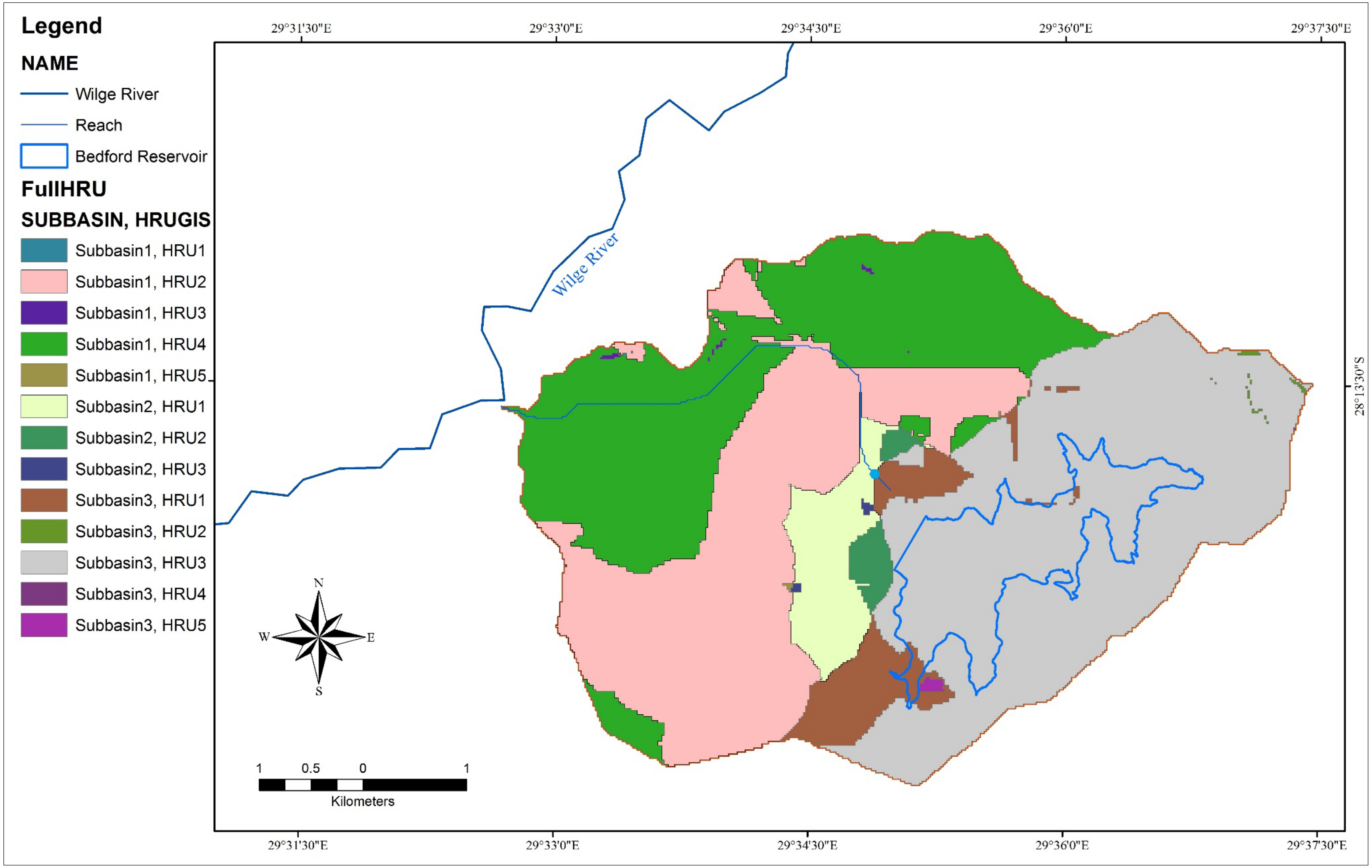


Figure 5-2: Delineation of the Bedford catchment into subbasins and HRUs.

5.2 Model Input Data Pre-processing, Calibration and Validation

5.2.1 Weather data pre-processing

The model was initially calibrated using the rainfall data from the weather stations, which upon validation was found to be not sufficient. The weather data were then patched and the length extended using DSSAT. The DSSAT-generated data were compared with the measured precipitation and mean temperature from the Braamhoek weather station and found to fit adequately. Figure 5-3 and Figure 5-4 show the goodness of fit between the precipitation data, where the R^2 for precipitation data was found to be 0.85 and for temperature 0.79.

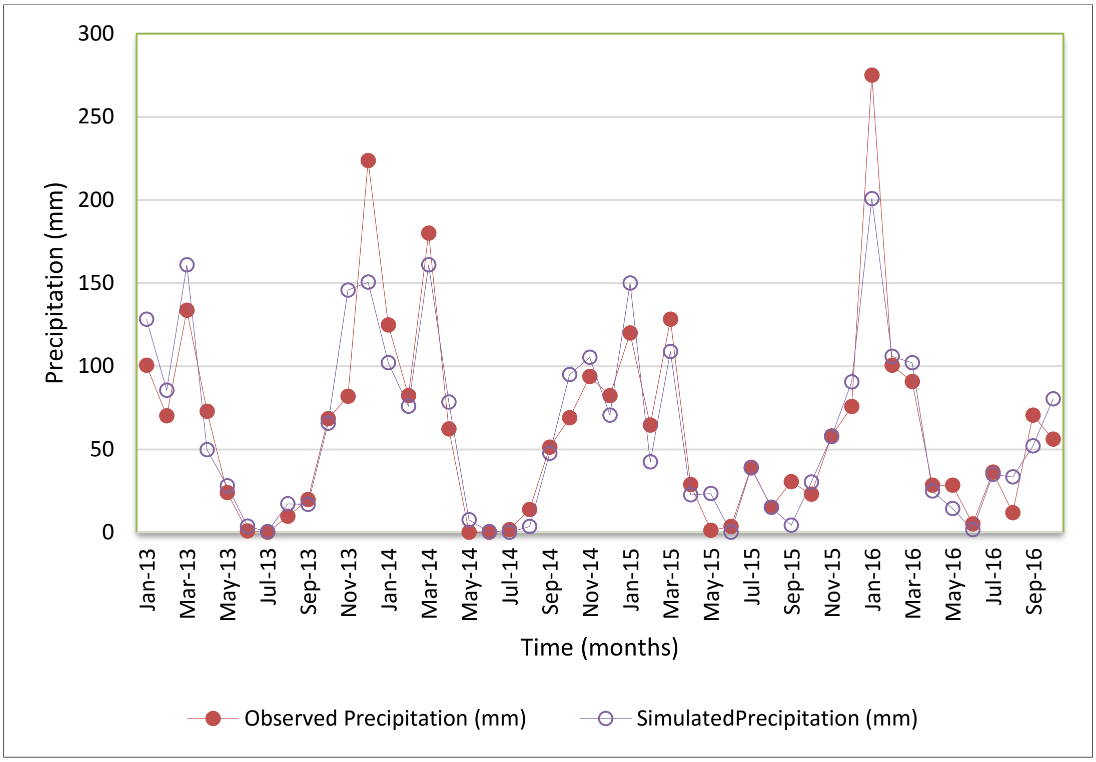


Figure 5-3: Comparison of DSSAT generated precipitation data to measured data for the period from 2013 to 2016.

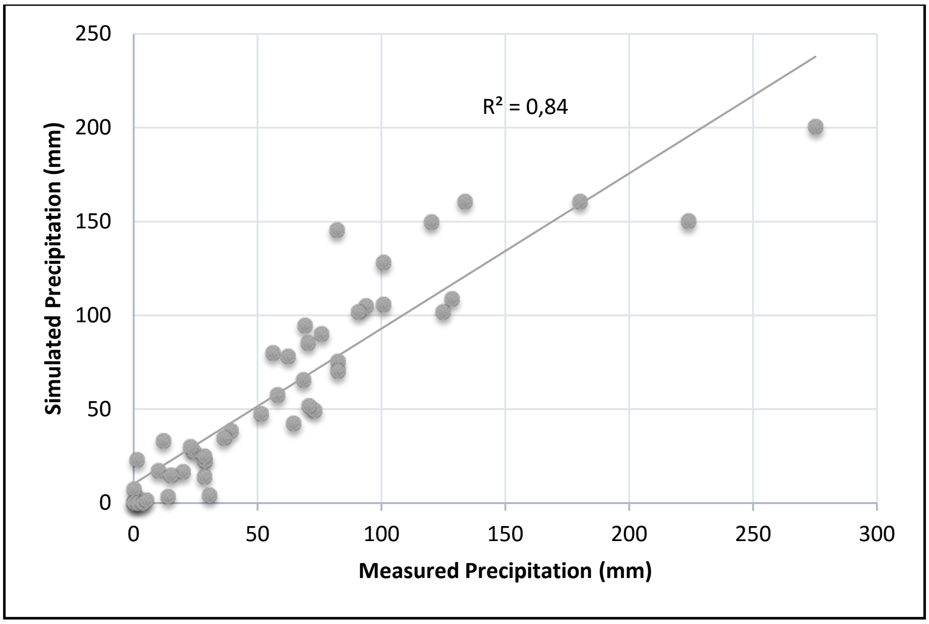


Figure 5-4: Goodness of fit between measured precipitation data and DSSAT-generated precipitation data.

Figure 5-5 and Figure 5-6 show the goodness of fit between the mean temperature data; the R^2 was found to be 0.79.

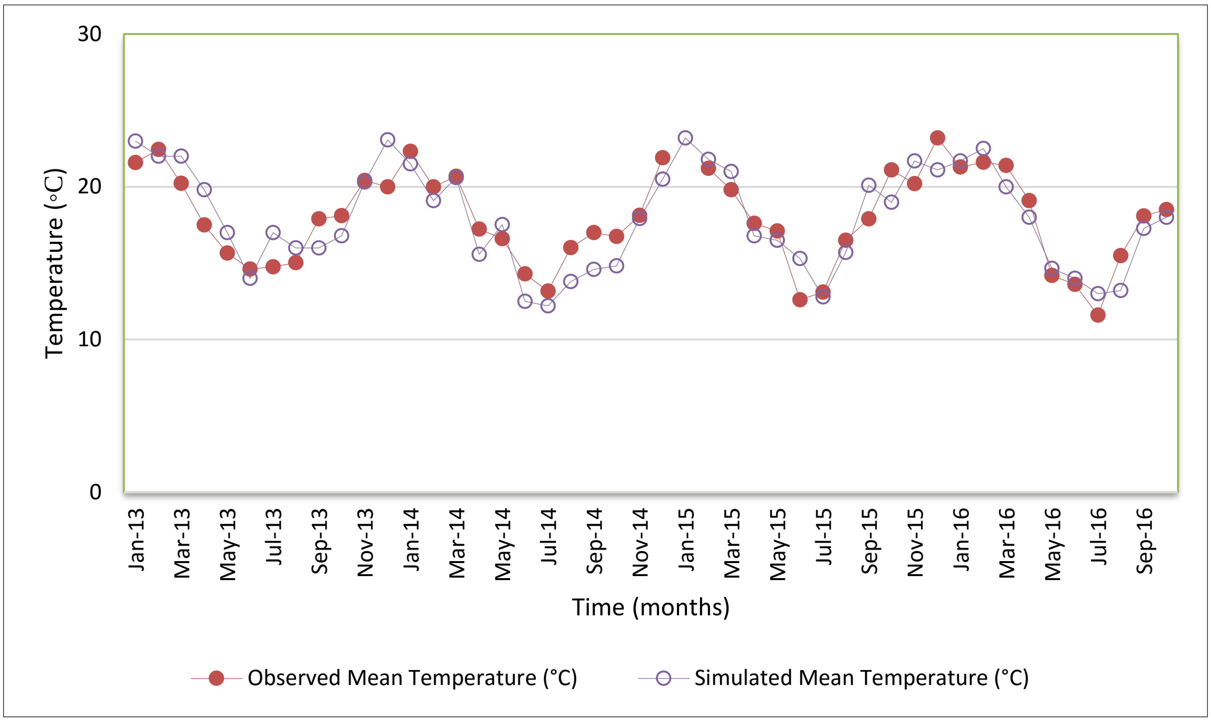


Figure 5-5: Plot of measured mean temperature data against DSSAT-generated data.

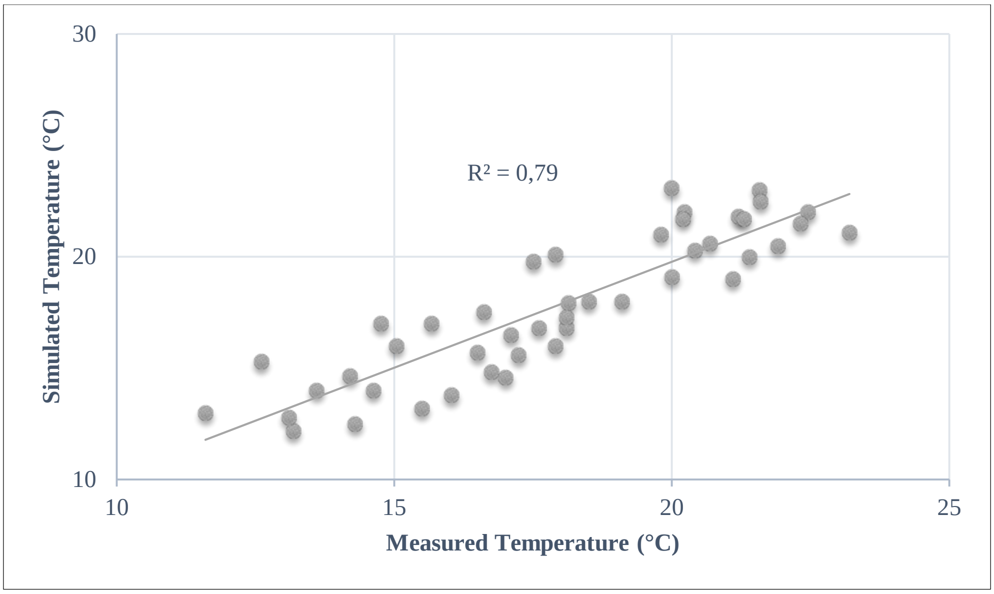


Figure 5-6: Goodness of fit between measured mean temperature data and DSSAT-generated data.

5.2.2 Groundwater input parameters

The groundwater input parameters were estimated using the water level data obtained from ESKOM, hydrogeological maps (DWA, 2000), and the Microsoft Excel-based "RECHARGE" spreadsheet software that was developed by Xu and Van Tonder (2001) based on the Qualified Guesses using the cumulative rainfall departure (CRD) method.

Boreholes and piezometers (Table 5-1) were drilled upstream and downstream of the Bedford reservoir to monitor groundwater levels. Based on water strike depths, groundwater depth is expected to be less than 8 m below the surface (Terrel *et al.*, 2012). Figure 5-7 shows the groundwater levels in the piezometers and boreholes surrounding the Bedford reservoir. The data plot indicates that groundwater levels fluctuate in response to changes in precipitation rates (that is. groundwater level decrease during low rainfall seasons and increase with increase in precipitation during the wet season). This groundwater level response is typical for groundwaters that gets direct recharge from rainfall. Figure 5-8 shows the water levels obtained from foundation piezometers downstream the Braamhoek reservoir plotted with rainfall from the Braamhoek weather station against time.

Table 5-1: Boreholes and standpipe piezometers installed around Bedford Catchment.

Name	Longitude	Latitude	Depth to Groundwater (m bgl)
BHP1	3124802	-57430.4	16.32
BHP2	3124776	-57495.1	7.38
SD3	3126525	-58290.5	3.24
SD4	3126481	-58149.1	8.48
SD5	3126699	-58354.2	7.83
SD6	3126694	-58445.5	13.93

Additional monitoring wells (MW) were drilled in the Braamhoek catchment as part of the IWUL condition (Table 5-2) (Teffo, 2015 pers. comm.). These wells were drilled to monitor groundwater contamination and are monitored by the Eskom Environmental Team (Teffo, 2016 pers. comm.). For the purpose of this study, these monitoring wells were used for groundwater level insights in the Braamhoek Catchment. Table 5-2 shows the water level data taken during the field visit undertaken in December 2015. This data in conjunction with data taken during the drilling of these monitoring wells in June 2014 were used to estimate groundwater levels in the Braamhoek catchment for model input.

MW1 and MW2 were both drilled and installed to 20 m bgl; east and west of the Braamhoek Dam, respectively. Groundwater was not encountered; however, slight seepage was evident during the drilling between 7 and 9 m bgl within the mudstone.

MW3, MW4, MW5, MW6 and MW7 were drilled and installed up- and down-hydraulic gradient of each potential groundwater contamination source. In MW3 water strikes were encountered at 6 and 11 m bgl in MW3; at 12 and 13 m bgl in MW4; at 8 m bgl in MW5; at 7 and 10 m bgl in MW6; and 7 and 9 m bgl in MW8. Borehole MW5 was not completed to the depth of 20 mbgl due to continual collapse of the borehole walls; this well was terminated at a depth of 10.5 mbgl.

MW8, constructed to a depth of 7 m bgl (metres below ground level) as a result of continual borehole wall collapse while drilling. Groundwater seepage was encountered from roughly the contact between the clayey soil and the fresh mudstone at 3 mbgl to the borehole's termination depth.

Table 5-2: Groundwater monitoring wells in the Braamhoek catchment.

Well	Borehole Location			Depth of borehole (m bgl)	Water Strike (m bgl)	Depth to groundwater level (m bgl)		Temp (°C)
	X	Y	Altitude (m amsl)			(2014[1])	(2015[2])	
MW1	28.307	-29.571	1298.3	20	7 and 9	7.11	10.87	19
MW2	28.302	-29.585	1283.2	20	7 and 9	8.48	10	18
MW3	28.294	-29.605	1206.7	20	6 and 11	2.16	3.5	19
MW4	28.287	-29.588	1286.2	20	12 and13	15.22	14.15	19
MW5	28.286	-29.594	1290.2	10.5	8	1.44	3	**
MW6	28.2866	-29.585	1287.5	30	7;10	29.65	**	**
MW7	28.282	-29.585	1304.3	20	7;9	8.21	3.88	18
MW8	28.283	-29.564	1300.0	7	3;5	2.44	**	**

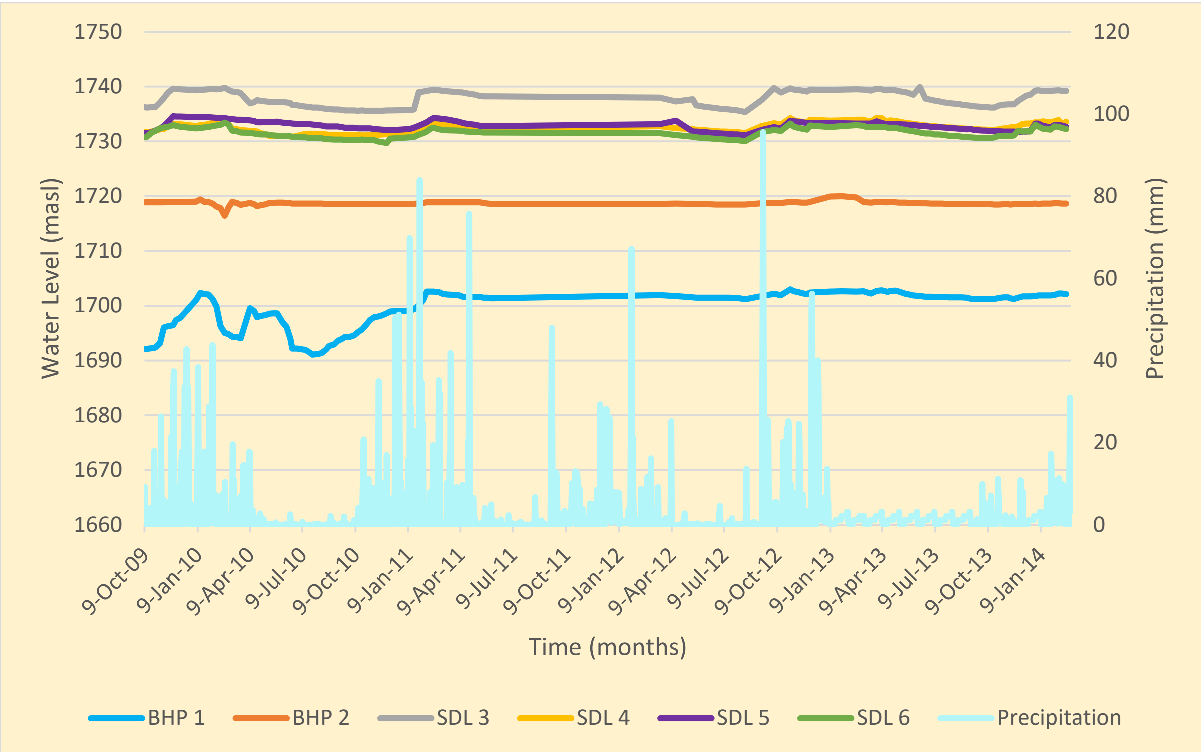


Figure 5-7: Groundwater levels in boreholes around the Bedford Dam plotted along with precipitation recorded at the Bedford weather station.

[1] Levels taken on the 17-18 June 2014
[2] Levels taken on the 14-15 December 2015
** Levels not taken due to access problems

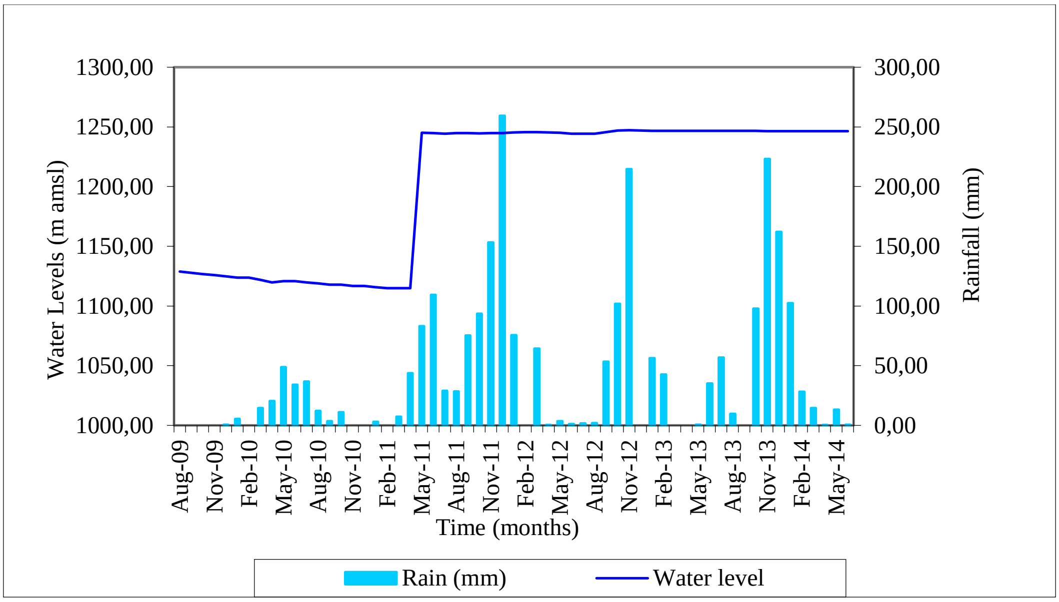


Figure 5-8: Piezometric levels plotted along with rainfall downstream the Braamhoek Dam. Note that the dam filled up in summer 2010 after which the piezometers maintained a steady state level.

The results of groundwater recharge estimated for the IPSS catchments using various methods including measured data, and interpolation from known values following the guidelines reported in Bredenkamp *et al*. (1995) are presented in Table 5-3. The average recharge obtained from these methods is 28.1 mm/a, which is slightly above the range from 15 mm/a to 25 mm/a estimated in Baron (1999). During the model calibration, this groundwater recharge was adjusted between 20 and 28 mm/a.

Table 5-3: Groundwater recharge rate estimated using different Qualified Guesses methods.

Method of Derivation	Recharge (mm/a)
Soil Information	19.7
Geology	36.0
Vegter	35.0
ACRU	30.0
Harvest Potential	20.0
Average Qualified Guesses	**28**

5.2.3 Model Setup, Calibration and Validation of Results

The discharge data downstream of the Braamhoek reservoir used for calibration is from November 2010 (at the start of the reservoir impounding) to December 2014. This measured data is presented in Appendix C. The model was calibrated using the reservoir outflow between November 2010 and December 2012, and was validated using the remaining years, that is from January 2013 to September 2014. The reservoir calibration and validation inputs and outputs were in monthly time-steps.

The model was first calibrated using Setup 1 (pairing weather data from 2008 to 2014 with land use/cover data of 2000) and Setup 2 (using weather data from 2008 to 2014 and land use/cover data of 2009). These are shown in Table 5-4. For Setups 1 and 2, the first two years of weather data were used for model warm up and for Scenarios 3 and 4 the first five years.

Table 5-4: Setups developed for assessing streamflow by pairing different weather data periods and different land use/cover.

Setup	Weather Data	Land use/cover
Setup 1	2008-2014	2000
Setup 2	2008-2014	2009
Setup 3	1990-2035	2000
Setup 4	1990-2035	2009

However, as shown in Table 5-5, Figure 5-9, and Figure 5-10 which are the outputs for reservoir; the calibration target was not achieved as indicated by error indices falling outside the respective acceptable ranges (that is using both land use/cover setups (Setups 1 and 2), the model performance was poor and had ranges from 0.39-0.51, 0.15-0.33, 0.33-0.54, 0.15-0.91 for R^2, NSE, PBIAS and RSR, respectively (Table 5-5).

This was attributed to short weather time series data (that is only between September 2008 and November 2014). The short periods of weather data limited the number of warm up years when running the model. This necessitated the use of a weather generator to generate more data.

Table 5-5: Calibration summary statistics of the model performance under model setup 1 and 2.

Index	Reservoir Discharge	Summary Acceptable Range
Setup 1		
R^2	0.50	**>0.5**
NSE	0.32	**0.5< NSE ≤1**
RSR	0.82	**0< RSR <0.7**
PBIAS	0.50	**≤ ±0.7**
Setup 2		
R^2	0.46	**>0.5**
NSE	0.30	**0.5< NSE ≤1**
RSR	0.19	**0< RSR <0.7**
PBIAS	0.37	**≤ ±0.7**

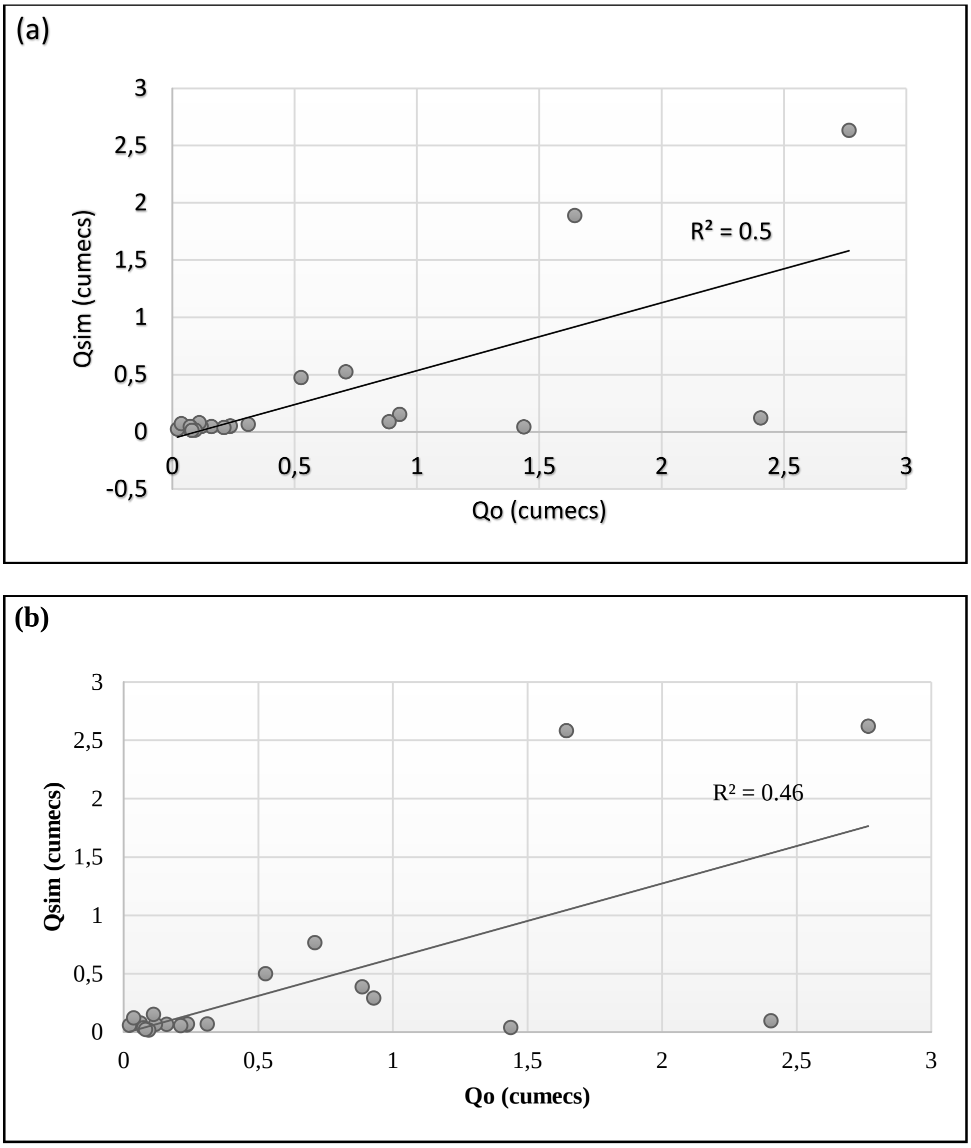
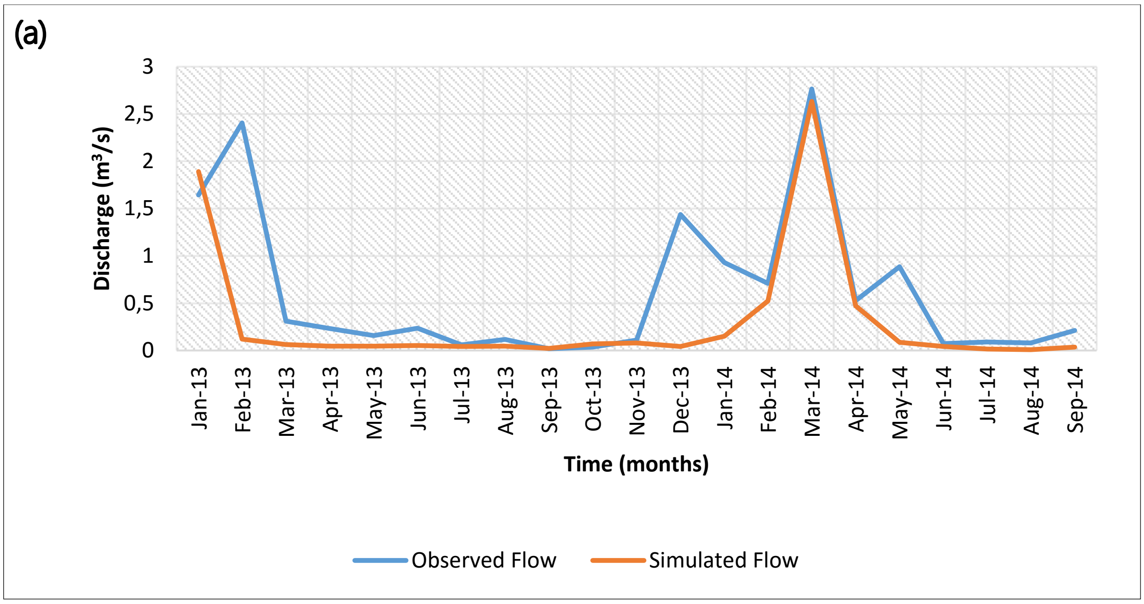


Figure 5-9: Plots of simulated discharge against observed Braamhoek reservoir discharge for Setup 1 (a) and Setup 2 (b).



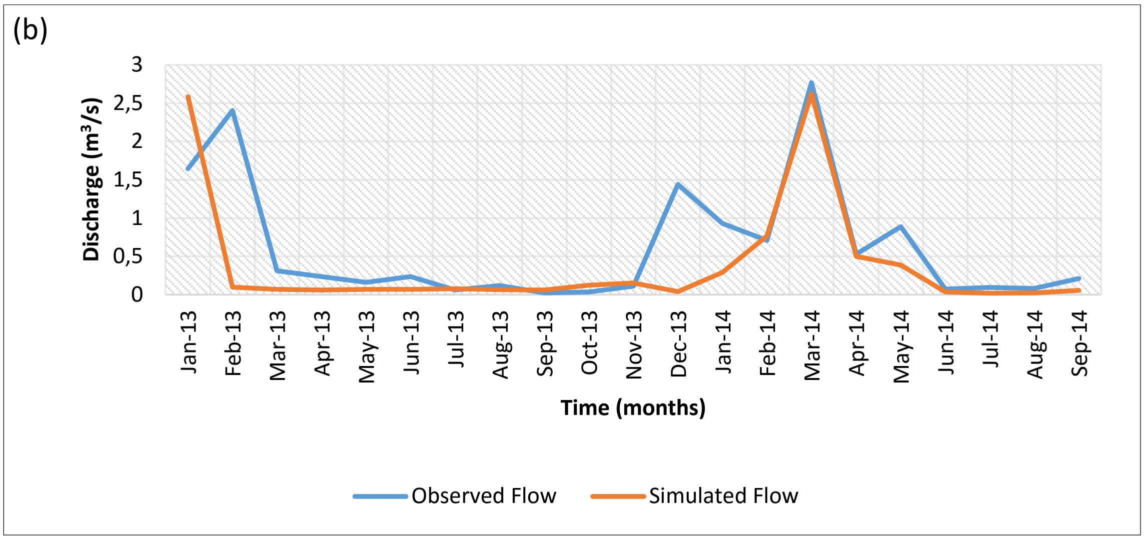


Figure 5-10: Plots of observed and simulated reservoir discharge for (a) Setup 1 and (b) Setup 2 for the validation period.

The model was rerun using Setup 3 (that is using weather data generated for the period from 1990 to 2035 and land use/cover data of 2000) and Setup 4 (that is using land use/cover data generated for the period from 1990 to 2035 and land use data of 2009). The model results of discharge downstream the reservoir in the simulation is presented in Appendices D and E, for Setup 3 and Setup 4 correspondingly. The resulting model simulation showed good to very good performance as shown from outputs for reservoir, Table 5-6, Figure 5-11, and Figure 5-12. Therefore, for the weather data from 1990 to 2035 in both land use/cover setups, the model performance ranges are from 0.86-0.92, 0.85-0.88, 0.07-0.08, and 0.025-0.24 for R^2, NSE, RSR and PBIAS, respectively, indicating that the model is calibrated satisfactorily and hence can be used for predictions.

Table 5-6: Calibration summary statistics of the model performance under Setup 3 and Setup 4.

Index	**Reservoir Discharge**		**Summary Acceptable Range**
	Setup 3		
R^2	0.92		**>0.5**
NSE	0.88		**0.5< NSE ≤1**
RSR	0.07		**0< RSR <0.7**
PBIAS	0.24		**≤ ±0.7**
	Setup 4		
R^2	0.86		**>0.5**
NSE	0.85		**0.5< NSE ≤1**
RSR	0.08		**0< RSR <0.7**
PBIAS	0.025		**≤ ±0.7**

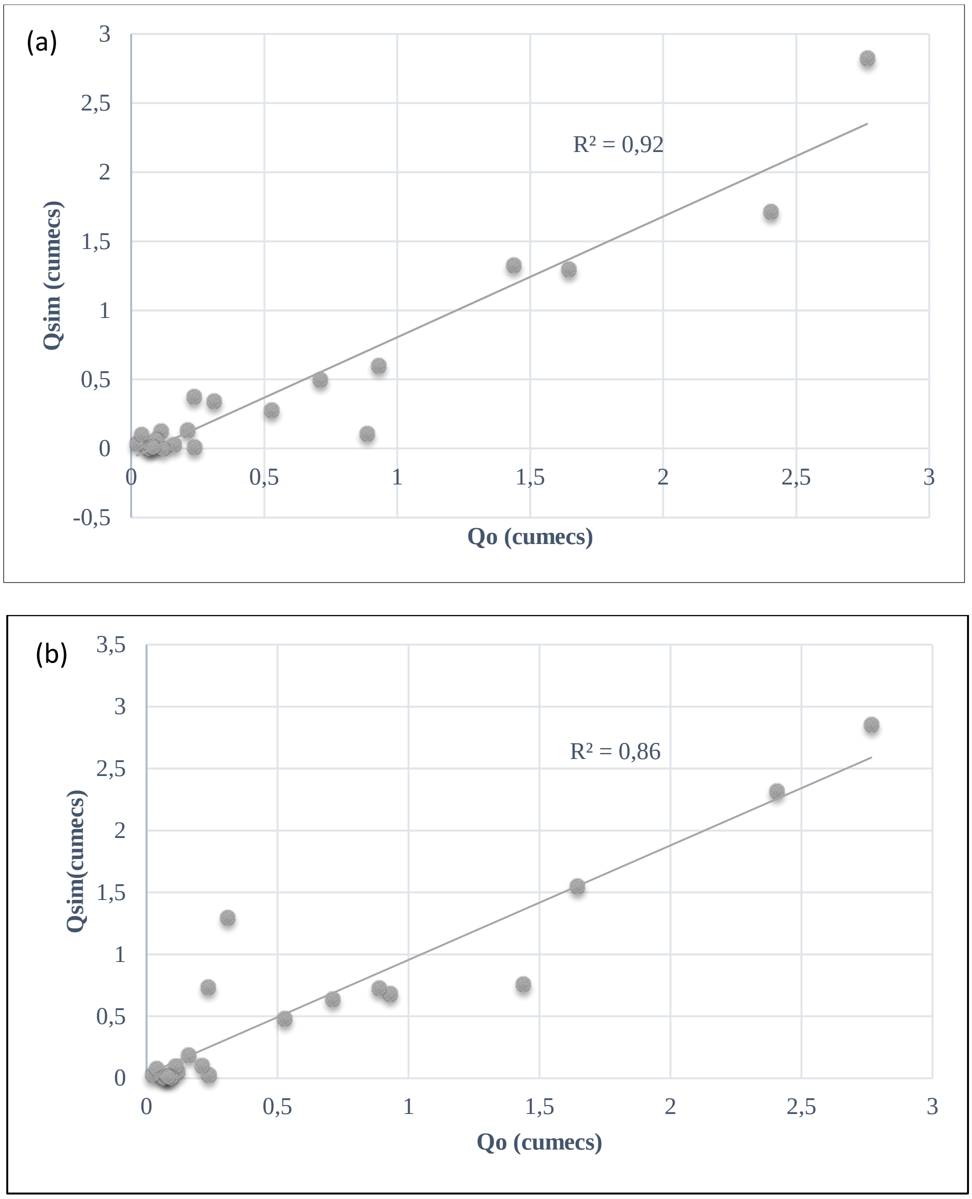


Figure 5-11: Plots of simulated discharge against observed discharge downstream of the Braamhoek reservoir for Setup 3 (a) and Setup 4 (b).

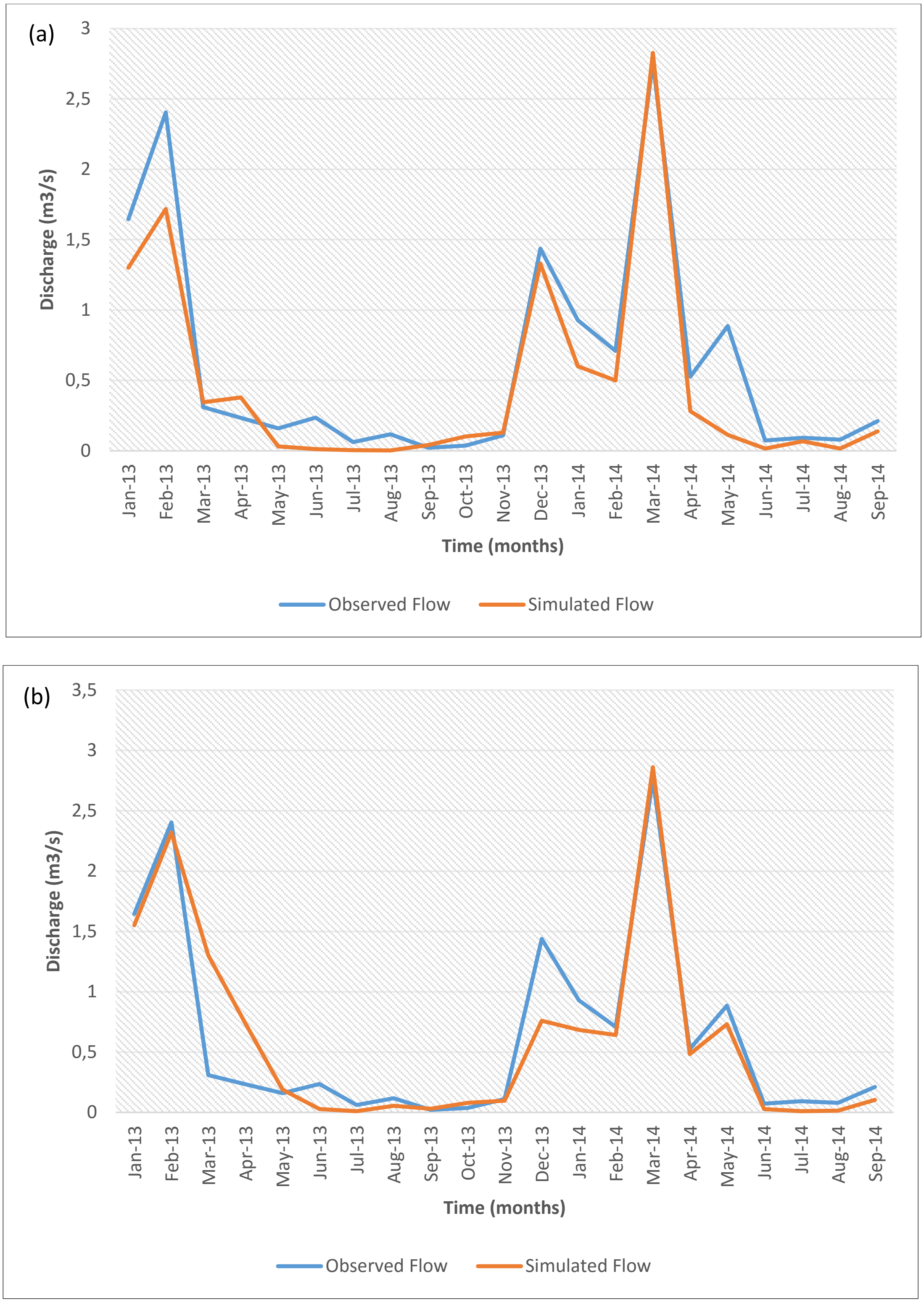


Figure 5-12: Plot of observed and simulated reservoir discharge for (a) Setup 3 and (b) Setup 4 for the validation period.

The calibrated model was applied for simulation of the Bedford catchment bearing in mind the differences between the two catchments. Appendices H and I show the resulting output for this exercise for land use/cover 2000 and 2009, respectively. The output data was compared with the available data to get and insight of the reliability of the exercise. Figure 5-13 below shows the goodness of fit of the discharge and the R^2 was found to be 0.7.

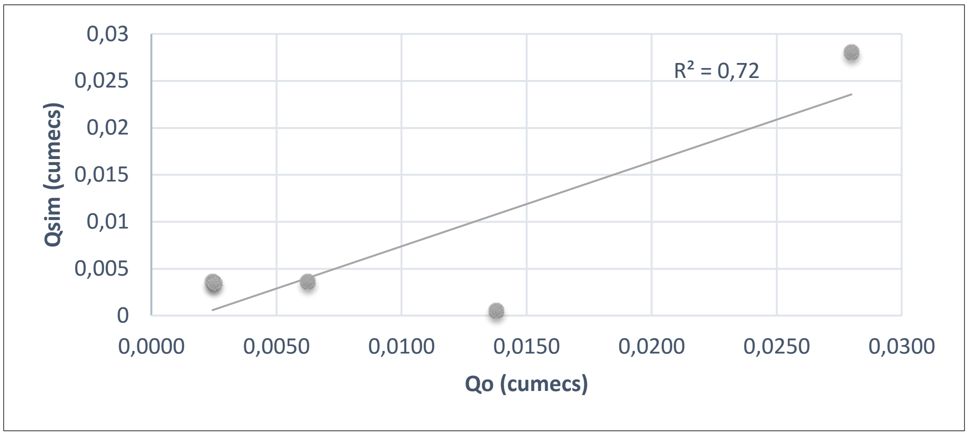


Figure 5-13: Correlation of model output and observed data in the Bedford catchment.

5.3 Scenario Analysis

5.3.1 Land use/cover Scenario Results

The assessment of the model's sensitivity to land use/cover changes was performed using land use/cover maps of 2000 and 2009. These maps were used in their original state, without making any alterations. Table 5-7 shows the summary of land use/cover data used for the respective years with the percentages of each given with respect to the total area of the study area. The main differences between the two maps is the decrease (by about 10%) in natural grasslands and the emergence of built environment in 2009. The land covered with plantations increased by about 7%; degraded land increased by about 3%; and the waterbodies also increased from less than 1% in 2000 to about 1% in 2009.

Table 5-7: Land use/cover summary of the study area based on land use/cover maps of 2000 and 2009.

Land use/cover	2000 (% of catchment area)	2009 (% of catchment area)
Plantations	0.032	6.949
Degraded Grasslands	0.006	2.718
Natural Grasslands	99.945	88.191
Built up	-	0.973
Waterbodies	0.013	1.169

The results of the land use/cover scenario analysis are presented in Table5-8 and Figure 5-14 for the discharge downstream the Braamhoek reservoir. Table 5-8 shows the mean monthly discharge changes for the simulation period (1995-2035, where LUC represents land use/cover). The maximum difference was in July with a 30% difference between discharge under land use/cover 2000 and 2009; the minimum change was shown in September at 2%. Overall, mean monthly discharge was higher under land use/cover 2009 in comparison with land use/cover 2000 results.

Figure 5-14 shows the simulated flow volume downstream the Braamhoek weir for both land use/cover scenarios. The maximum volume on both scenarios is in January with 7.43 Mm^3 and 8.73 Mm^3 for land use/cover 2000 and 2009, respectively.

Table 5-8: Results of modelled discharge volume downstream of the Braamhoek reservoir under a changed land use/cover scenario

	LUC2000 mean monthly discharge (cumecs)	LUC2009 mean monthly discharge (cumecs)	Change (cumecs)	% Change
Jan	2.774156	3.259585	0.485	15
Feb	1.643451	1.99012	0.347	17
Mar	2.001027	2.365649	0.365	15
Apr	0.459844	0.593651	0.134	23
May	0.163111	0.229883	0.067	29
Jun	0.074874	0.089551	0.015	16
Jul	0.007869	0.011214	0.003	30
Aug	0.040437	0.044539	0.004	9
Sep	0.080883	0.08214	0.001	2
Oct	0.111642	0.14377	0.032	22
Nov	0.428664	0.456116	0.027	6
Dec	2.235207	2.757971	0.523	19

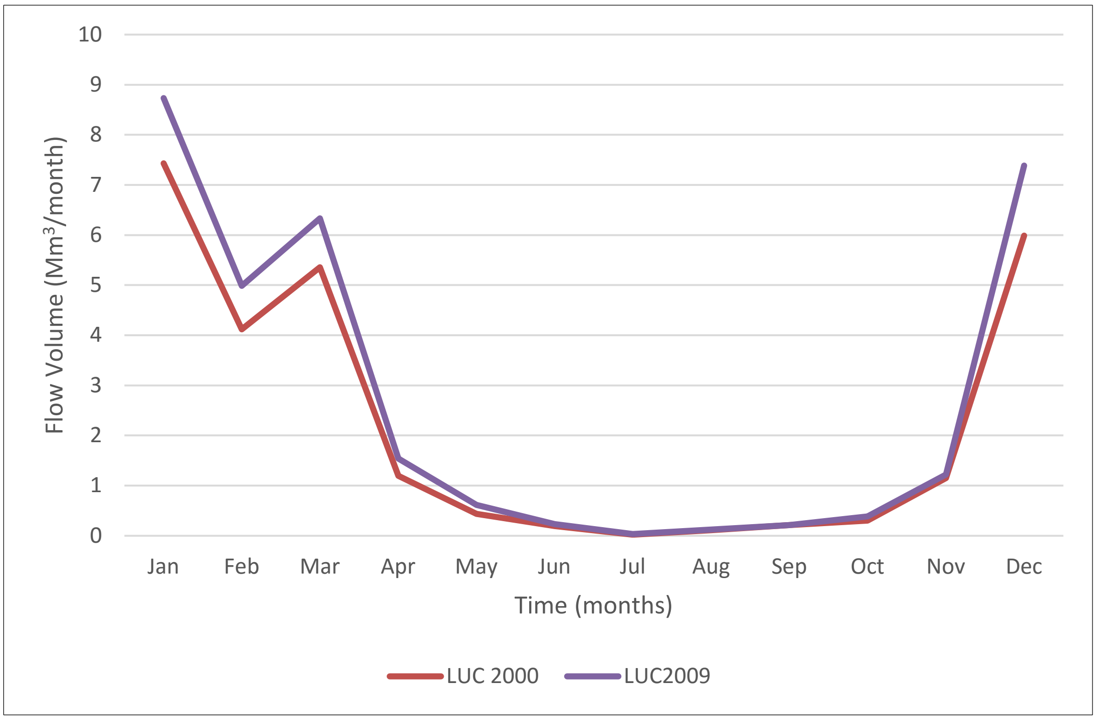


Figure 5-14: Simulated flow volume downstream of the Braamhoek reservoir for land use/cover 2000 and 2009.

The results of the land use/cover scenario analysis are presented in Table 5-9 and Figure 5-15 for the discharge at Bedford catchment. These result show that the maximum difference in mean discharge downstream of the Bedford reservoir for the land use/cover scenarios is 44% as seen in the months of May and June in Table 5-9. Figure 5-15 shows the simulated flow volume downstream the Bedford weir for both land use/cover scenarios. The maximum volume on both scenarios is in the month January with 1.23 Mm^3 and 1.35 Mm^3 for land use/cover 2000 and 2009, respectively. The minimum streamflow is in the month of July with 0.02 and 0.03 Mm^3 for land use/cover 2000 and 2009, respectively.

Table 5-9: Results of land use/cover changes downstream Bedford Dam.

	LUC2000 mean monthly discharge (cumecs)	LUC2009 mean monthly discharge (cumecs)	Change (cumecs)	% Change
Jan	0.459844	0.502752	0.043	9
Feb	0.255811	0.381533	0.126	33
Mar	0.340738	0.47659	0.136	29
Apr	0.068214	0.105145	0.037	35
May	0.053776	0.095588	0.042	44
Jun	0.024905	0.044564	0.020	44
Jul	0.007869	0.011417	0.004	31
Aug	0.019183	0.024111	0.005	20
Sep	0.019064	0.030952	0.012	38
Oct	0.026222	0.045187	0.019	42
Nov	0.101355	0.138234	0.037	27
Dec	0.428343	0.466107	0.003	8

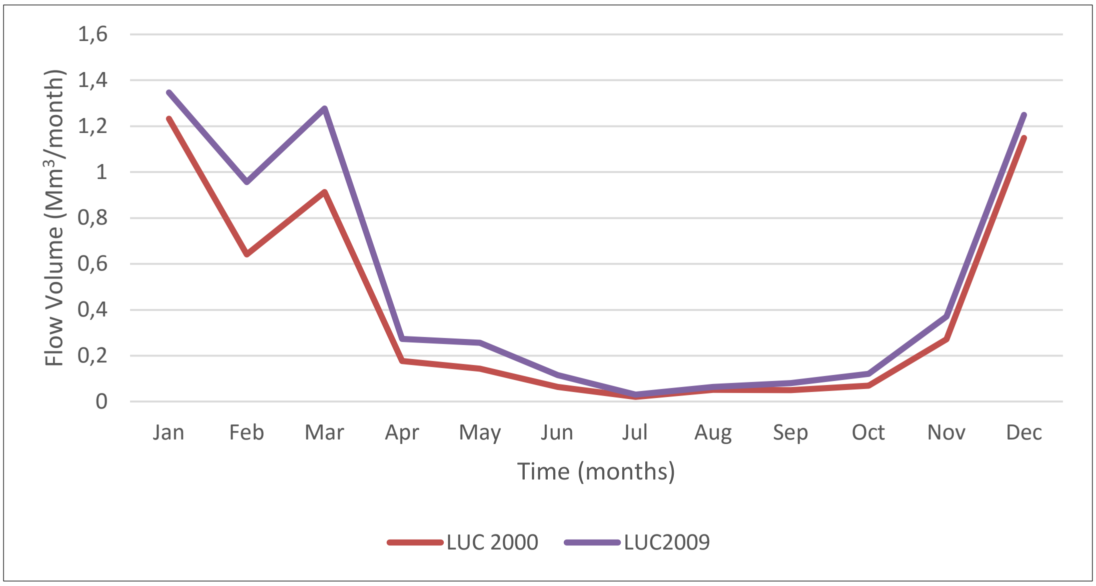


Figure 5-15 : Simulated flow volume downstream of the Bedford reservoir for land use/cover 2000 and 2009.

5.3.2 Climate Change Scenario Results

A hypothetical climate change scenario was modelled by increasing and decreasing the DSSAT-generated precipitation data by 10% to represent wet and dry years, respectively. The model was run using the changed precipitation data along with the 2009 land use/cover (Setup 4). These combinations of climate and land use/cover changes were simulated according to the setups shown in Table 5-10. Setup 4 was used and then sub-divided into Scenario SU4a and Scenario SU4b as shown in Table 5-10. The results of these scenarios are shown in Appendix F for SU4a in the Braamhoek catchment; Appendix G for SU4b for Braamhoek catchment; Appendix J for SU4a in the Bedford catchment; and Appendix K for SU4b for the Bedford catchment.

Table 5-10 : The two scenarios used for modelling the response of the Braamhoekspruit and Bedfordspruit catchments to climate changes.

Scenarios	Rainfall	Land use/cover
SU4a	10% increase	2009
SU4b	10% decrease	2009

The scenario simulated results of outflow downstream of the Braamhoek Dam are presented in Figure 5-16 and Table 5-11. Table 5-11 shows the changes incurred for both scenarios where positive percentages represent increase in flow and negative values indicate a decrease in flow. These results of these modelled scenarios were compared to the model results based on 2009 conditions (Setup 4). The maximum changes in monthly mean discharge downstream of the Braamhoek Dam for Scenario SU4a, Scenario SU4b were found to be 36% and 49%, respectively. The volume of flow as flow, as shown by Figure 5-16, show that the maximum volume is in January for both scenarios; where scenario SU4a yielded 9.99 Mm^3 and SU4b yielded 7.075 Mm^3. The minimum flow as encountered in the month of July is 0.015 Mm^3 and 0.035 Mm^3 for SU4b and SU4a, respectively.

Table 5-11 : Results of the scenarios used for modelling the response of the Braamhoekspruit to climate changes.

	SU4 (cumecs)	SU4a (cumecs)	%Change	SU4b (cumecs)	%Change
Jan	3.260	3.730	14	2.642	-19
Feb	1.990	2.282	15	1.396	-30
Mar	2.366	2.703	14	1.445	-39
Apr	0.594	0.673	13	0.303	-49
May	0.230	0.262	14	0.128	-44
Jun	0.090	0.110	23	0.069	-23
Jul	0.011	0.013	18	0.006	-49
Aug	0.045	0.052	18	0.036	-19
Sep	0.082	0.094	14	0.070	-15
Oct	0.144	0.176	22	0.134	-7
Nov	0.456	0.621	36	0.424	-7
Dec	2.758	3.296	20	2.408	-13

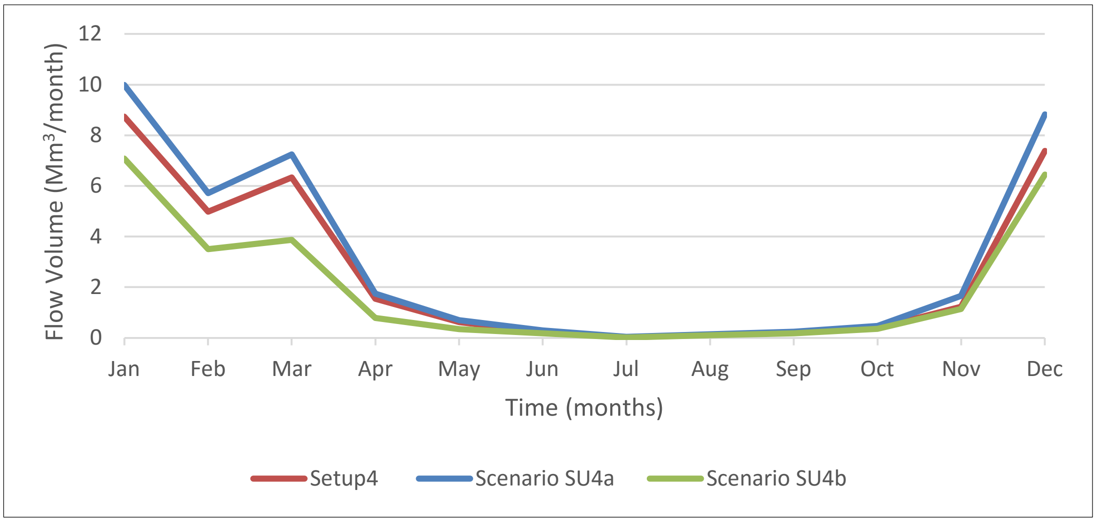


Figure 5-16: Results of the response of Braamhoekspruit to precipitation changes.

The responses of the Bedfordspruit catchment to rainfall changes were modelled using scenario SU4a and SU4b. The simulation results are presented in Table 5-12 and Figure 5-17. Table 5-12 shows the changes experienced for both scenarios where positive percentages represent increase in flow and negative values indicate a decrease in flow. The results of these modelled scenarios were compared to the model results based on 2009 conditions (Setup 4). The maximum changes in monthly mean discharge downstream of the Bedfordspruit catchment for Scenario SU4a, Scenario SU4b were found to be 31% and 41%, respectively. The volume of flow as flow, in Figure 5-17 below, show that the maximum volume is in January for both scenarios; where scenario SU4a yielded 1.53 Mm^3 and SU4b yielded 1.30 Mm^3. The minimum flow as encountered in the month of July is 0.0261 Mm^3 and 0.035 Mm^3 for SU4b and SU4a, respectively.

Table 5-12 : Results of the scenarios used for modelling the response of the Bedfordspruit to precipitation changes.

	Setup (cumecs)	SU4a (cumecs)	%Change	SU4b (cumecs)	%Change
Jan	0.502752	0.570121	13	0.48677	-3
Feb	0.381533	0.436925	15	0.248677	-35
Mar	0.47659	0.539366	13	0.310681	-35
Apr	0.105145	0.121522	16	0.079958	-24
May	0.095588	0.110414	16	0.056743	-41
Jun	0.044564	0.05072	14	0.033048	-26
Jul	0.011417	0.012981	14	0.009751	-15
Aug	0.024111	0.028354	18	0.02311	-4
Sep	0.040952	0.044611	9	0.029016	-29
Oct	0.048671	0.063683	31	0.035583	-27
Nov	0.138234	0.181692	31	0.114128	-17
Dec	0.466107	0.566641	22	0.29561	-37

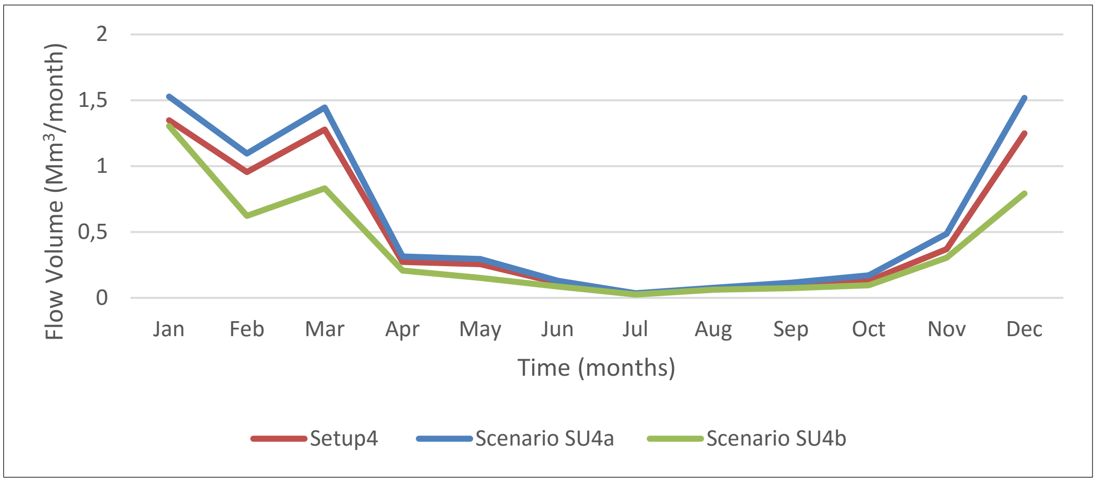


Figure 5-17: Results of modelled outflow downstream of Bedford Dam for various scenarios.

The responses of the two modelled catchments are slightly different which is evident in the results of the scenario analysis.

CHAPTER 6 CONCLUSIONS AND RECOMMENDATIONS

Envisioning and evaluating future scenarios has emerged as a critical component of both science and social decision-making. Studying and predicting the amount and quality of water available at the watershed level under different scenarios of land use/cover and weather conditions is the best approach towards achieving an equitable and sustainable allocation and use of the water resource. In this regard, computer-based hydrologic simulation models, remote sensing technologies, GIS, GPS, and DSS tools are amongst the tools available to hydrologists and watershed managers.

Hydrologic systems are heterogeneous, with substantial spatial variability in model inputs such as soil and land use/cover. The development of input files for such model for large watersheds is a time-consuming task. GIS plays a major role in developing model inputs from digital geospatial databases through model–GIS interfaces. The SWAT model and its GIS interfaces aid the water resources professional in basin-scale studies of water availability and water quality, and help reduce the time and cost necessary to conduct such studies several-fold.

This study aimed at determining the suitability of ArcSWAT for modelling mountainous data-scarce catchments in South Africa and its applicability to water resources assessments in the light of drought and the ongoing development of the country. The two catchments where ESKOM Limited is constructing the hydropower station, Ingula Pumped Storage Scheme (IPSS), were used for the modelling exercise. Two weather stations located in the respective catchments, which have been in operation since 2008, were used in the modelling exercise. The Braamhoek catchment has a short history of gauged flow at the Braamhoekspruit downstream the Braamhoek Dam. The Bedford catchment, on the contrary, only started gauging in March 2016.

The Braamhoek catchment was delineated within ArcSWAT into five (5) different subbasins based on the streams (reaches) using the DEM which were further subdivided into 34 HRUs in total. The total area of the delineated catchment is 58.87 km^2. The Bedford catchment was also delineated. This catchment was subdivided into three (3) subbasins using the DEM and the total area of the catchment is 27.15 km^2. The delineated subbasins were further subdivided into eight (8) HRUs with respect to soil, land use/cover, and slope.

The performance and applicability of the ArcSWAT model was evaluated through model calibration, validation, and scenario analysis on these two catchments. The performance of

SWAT was evaluated statistically and graphically. The model simulation outputs were compared against measured outflow data at a weir located just downstream of the Braamhoek Dam. The calibration exercise indicated the need to extend the weather data. WeatherMan, an extension of DSSAT was used for extrapolating the weather data. The application of WeatherMan improved the quality of the model output substantially. The simulated flow trends matched the observed flow trends within acceptable calibration criteria ranges where R^2, NSE, PBIAS and RSR ranged from 0.86 to 0.92, 0.88 to 0.85, 0.24 to 0.025, and 0.07 to 0.28, respectively.

The calibrated model was used to get an insight of the sensitivity of the IPSS catchments to land use/land cover and climate changes (as represented by changes in precipitation). The simulation results show that a 10% increase and decrease in precipitation resulted in a maximum mean monthly flow increase of 36% and decrease of 49% downstream of Braamhoek dam. The same changes in precipitation resulted in a modelled 31% increase and 41% decrease in the discharge of the Bedfordspruit, downstream of Bedford dam. The mean monthly flow volume for both catchments was found to be higher for 2009 land use/cover than for 2000 which means both catchments are sensitive to precipitation and land use/cover changes.

ArcSWAT was successfully applied to simulate flow for the IPSS catchments on a monthly time-scale, which confirms SWAT's capability to capture monthly flow trends regardless of catchment characteristics and location. In spite of the data shortage for Bedford catchment, using the known parameters and calibration parameters of the Braamhoek catchment, the model was able to simulate the reaction of the Bedfordspruit downstream the dam satisfactorily. Adequately calibrated, ArcSWAT model can be employed for studying land use change scenarios and probable climate change impacts on basin hydrology depending on availability of data.

Considering the good results of SWAT in this study and comprehensiveness of the model in land surface processes representation, the model is very promising for land and water management studies and expected to give valuable information to land and water resources managers. It is recommended that for erosion application of the model, care should be taken to develop a detailed soil map of the study area. To capture water quality trends, it is recommended to get a substantial amount of observed data matching land use/cover of the study area for calibration and validation of the model.

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Appendices

Appendix A - HRU Definition of the Braamhoek Catchment

HRUs	**Description (Landuse/Soil/Slope**	**Area (ha)**
Subbasin 1		
1.0	Agricultural Land-Generic --> AGRL/Magwa/0-30	309.3
2.0	Agricultural Land-Generic --> AGRL/Magwa/30-60	23.6
3.0	Unimproved Natural Grassland --> UNGR/Magwa/0-30	1155.8
4.0	Unimproved Natural Grassland --> UNGR/Magwa/30-60	244.3
5.0	Unimproved Natural Grassland --> UNGR/Magwa/60-9999	7.3
6.0	Urban Village (dense bush) --> UVDB/Magwa/0-30	2.0
		1742.3
Subbasin 2		
7	Agricultural Land-Generic --> AGRL/Magwa/0-30	175.2
8	Agricultural Land-Generic --> AGRL/Magwa/30-60	11.5
9	Agricultural Land-Generic --> AGRL/Magwa/60-9999	0.4
10	Unimproved Natural Grassland --> UNGR/Magwa/0-30	860.5
11	Unimproved Natural Grassland --> UNGR/Magwa/30-60	96.3
12	Unimproved Natural Grassland --> UNGR/Magwa/60-9999	20.8
13	Urban Village (dense bush) --> UVDB/Magwa/0-30	0.9
		1165.6
Subbasin 3		
14	Agricultural Land-Generic --> AGRL/Magwa/30-60	23.4
15	Agricultural Land-Generic --> AGRL/Magwa/0-30	92.8
16	Unimproved Natural Grassland --> UNGR/Magwa/30-60	283.9
17	Unimproved Natural Grassland --> UNGR/Magwa/0-30	532.5
18	Unimproved Natural Grassland --> UNGR/Magwa/60-999	23.3
19	Urban Village (dense bush) --> UVDB/Magwa/30-60	0.2
		956.1

HRUs	Description (Landuse/Soil/Slope	Area (ha)
	Subbasin 4	
20	Agricultural Land-Generic --> AGRL/Magwa/60-9999	18.28
21	Agricultural Land-Generic --> AGRL/Magwa/0-30	481.04
22	Agricultural Land-Generic --> AGRL/Magwa/30-60	137.2
23	Unimproved Natural Grassland --> UNGR/Magwa/0-30	614.52
24	Unimproved Natural Grassland --> UNGR/Magwa/30-60	195.08
25	Unimproved Natural Grassland --> UNGR/Magwa/60-999	18.28
26	Water --> WATR/Magwa/0-30	3.36
27	Water --> WATR/Magwa/30-60	2.44
28	Urban Village (dense bush) --> UVDB/Magwa/0-30	0.16
		1470.4
	Subbasin 5	
29	Agricultural Land-Generic --> AGRL/Magwa/0-30	239.32
30	Agricultural Land-Generic --> AGRL/Magwa/30-60	3.8
31	Unimproved Natural Grassland --> UNGR/Magwa/0-30	306.04
32	Unimproved Natural Grassland --> UNGR/Magwa/30-60	1.24
33	Urban Village (dense bush) --> UVDB/Magwa/30-60	0.4
34	Urban Village (dense bush) --> UVDB/Magwa/0-30	1.4
		552.2

Appendix B – HRU Definition of the Bedford Catchment

HRUs	Description (Landuse/Soil/Slope	Area (ha)
	Subbasin 1	
1	Unimproved Natural Grassland --> UNGR/Avalon/50-9999	1.96
2	Unimproved Natural Grassland --> UNGR/Avalon/0-50	1418.32
		1420.28
	Subbasin 2	
3	Unimproved Natural Grassland --> UNGR/Avalon/0-50	165
		165
	Subbasin 3	
4	Wetlands-Mixed --> WETL/Avalon/50-9999	0.6
5	Wetlands-Mixed --> WETL/Avalon/0-50	10.24
6	Wetlands-Mixed --> WETL/Dundee/0-50	0.04
7	Unimproved Natural Grassland --> UNGR/Avalon/50-9999	1.64
8	Unimproved Natural Grassland --> UNGR/Avalon/0-50	1117.4
		1129.92

Appendix C – Measured outflow downstream the Braamhoek Dam

Date (months)	Outflow (cumecs)
Nov-10	0.047
Dec-10	0.148
Jan-11	0.272
Feb-11	0.263
Mar-11	0.220
Apr-11	0.038
May-11	0.167
Jun-11	0.178
Jul-11	0.285
Aug-11	0.391
Sep-11	0.209
Oct-11	0.102
Nov-11	0.159
Dec-11	0.433
Jan-12	2.062
Feb-12	0.232
Mar-12	0.300
Apr-12	0.171
May-12	0.143
Jun-12	0.077
Jul-12	0.137
Aug-12	0.088
Sep-12	0.122
Oct-12	1.893
Nov-12	1.128

Date (months)	Outflow (cumecs)
Dec-12	4.731
Jan-13	1.645
Feb-13	2.405
Mar-13	0.310
Apr-13	0.235
May-13	0.160
Jun-13	0.237
Jul-13	0.062
Aug-13	0.118
Sep-13	0.021
Oct-13	0.037
Nov-13	0.111
Dec-13	1.437
Jan-14	0.929
Feb-14	0.710
Mar-14	2.766
Apr-14	0.526
May-14	0.886
Jun-14	0.073
Jul-14	0.092
Aug-14	0.080
Sep-14	0.211
Oct-14	0.084
Nov-14	0.041

Appendix D – Simulated outflow downstream the Braamhoek Dam for Setup 3 (Land use/cover 2000 and Weather data 1990-2035) in cumecs

	1995	1996	1997	1998	1999	2000	2001	2002	2003	2004	2005	2006	2007	2008	2009	2010	2011	2012	2013	2014	2015
Jan	2.18600	2.20900	2.59700	0.47900	4.01100	2.88600	2.83600	4.21000	1.56200	4.24000	1.54400	1.95200	3.78100	6.17000	2.12500	3.78500	6.01000	3.17300	2.19400	0.58260	3.85000
Feb	0.77180	0.41800	0.75130	0.29870	3.85400	0.89240	1.92100	2.22600	0.46870	3.28500	1.51300	1.54100	1.49600	1.53800	2.53700	0.69200	1.72600	1.65400	1.90300	1.28100	0.99810
Mar	2.18000	0.48570	0.76330	1.86400	2.56300	1.55000	2.57300	0.83850	0.60460	1.45500	1.86400	1.54600	0.70770	1.91800	0.71420	0.88360	1.04400	2.00700	0.82570	3.93200	2.45200
Apr	0.24270	0.04715	0.14070	0.16610	0.38370	0.64010	0.38480	0.18580	0.01476	0.64280	0.41980	0.20370	0.11580	0.35280	0.15420	0.44600	0.18060	0.41350	0.38280	0.28140	0.74840
May	0.03477	0.01713	0.01004	0.02657	0.19200	0.09543	0.14470	0.02257	0.01747	0.11540	0.05501	0.03822	0.00980	0.07121	0.03585	0.03090	0.05229	0.12900	0.03104	0.11300	0.16600
Jun	0.00596	0.00236	0.00157	0.00286	0.29640	0.01834	0.01912	0.00657	0.00076	1.54500	0.02128	0.00438	0.01227	0.01107	0.16310	0.00943	0.01122	0.02117	0.01310	0.01681	0.03092
Jul	0.00239	0.00088	0.00080	0.00156	0.00706	0.00528	0.00666	0.00391	0.00007	0.01270	0.00408	0.00172	0.00284	0.00499	0.00196	0.00382	0.00555	0.00853	0.00469	0.00675	0.01138
Aug	0.02813	0.05262	0.00007	0.01323	0.01352	0.00286	0.07538	0.01104	0.00042	0.06899	0.00175	0.09142	0.00151	0.00292	0.13150	0.00214	0.05038	0.00567	0.00215	0.01548	0.06290
Sep	0.02110	0.16350	0.11920	0.15650	0.09065	0.25450	0.15270	0.21590	0.06624	0.43590	0.07653	0.00010	0.06097	0.08334	0.14550	0.00166	0.01163	0.04156	0.04097	0.14870	0.14830
Oct	0.11300	0.09573	0.08408	0.05223	0.22490	0.02681	0.09514	0.16930	0.23270	0.38530	0.07945	0.26350	0.14340	0.09140	0.35220	0.22860	0.18080	0.09542	0.10280	0.21780	0.09411
Nov	0.19620	0.67990	0.26420	0.36790	0.90580	0.72910	0.52030	0.28350	1.65000	0.65500	0.18670	2.14900	1.05500	0.97560	1.56900	0.77900	0.03849	0.57770	0.12870	0.79380	1.26100
Dec	2.87600	1.37500	4.30100	4.27200	3.63000	2.96700	3.41300	2.22700	7.01100	4.07900	1.68200	2.31600	1.72700	2.38700	5.10100	4.17800	1.80100	2.06800	1.45400	4.86700	1.76400

	2016	2017	2018	2019	2020	2021	2022	2023	2024	2025	2026	2027	2028	2029	2030	2031	2032	2033	2034	2035	
Jan	2.47200	4.72200	3.24300	3.66100	2.22600	2.95900	4.46100	3.87900	2.07700	1.68000	2.32400	3.51300	3.54900	2.07400	2.43500	2.47700	3.56500	2.56100	5.27500	4.96800	
Feb	0.99390	1.36000	1.08300	1.03100	1.33700	1.50100	1.73000	5.64300	2.45000	1.25100	2.44300	0.99430	1.64200	2.01300	0.95740	0.77140	1.91400	1.28000	2.04700	1.85500	
Mar	1.19600	3.04900	0.95120	1.45500	2.16400	1.14100	2.69300	0.96460	3.27200	3.25400	1.80300	0.26290	2.76000	1.93900	1.23100	0.36580	3.03000	2.87400	1.31000	2.79800	
Apr	0.14460	0.44590	0.12550	0.23330	0.84100	0.29340	0.44420	0.35750	0.44510	0.33630	0.35830	0.07319	0.36260	0.33340	0.44490	0.02422	0.27990	0.44660	0.58830	0.55880	
May	0.03477	0.16740	0.05034	0.05607	0.20650	0.03783	0.20250	0.09877	0.17210	0.08190	0.12540	0.02531	0.13410	0.07896	0.06717	0.02618	0.06142	0.11430	0.14040	0.14350	
Jun	0.00880	0.17320	0.00688	0.01209	0.03430	0.20440	0.03371	0.01858	0.02725	0.01993	0.01914	0.00420	0.18320	0.43040	0.01172	0.00296	0.01755	0.05635	0.21410	0.02526	
Jul	0.00412	0.01039	0.00349	0.00617	0.00966	0.00586	0.01236	0.00901	0.01079	0.00640	0.00740	0.00176	0.00887	0.00880	0.00538	0.00134	0.00768	0.00919	0.01129	0.00967	
Aug	0.06324	0.00504	0.02804	0.23010	0.03649	0.01152	0.34650	0.00488	0.50710	0.05608	0.00324	0.05127	0.04294	0.02790	0.01925	0.00038	0.00433	0.03868	0.03359	0.04712	
Sep	0.05366	0.10970	0.18890	0.04020	0.09910	0.12070	0.04532	0.17670	0.03176	0.02252	0.06798	0.18510	0.25080	0.02171	0.16590	0.09892	0.03671	0.24070	0.04968	0.13580	
Oct	0.13410	0.07538	0.35320	0.12180	0.15650	0.28050	0.15700	0.33280	0.03028	0.21330	0.09634	0.11250	1.47600	0.10040	0.38300	0.24320	0.21960	0.49750	0.16970	0.08603	
Nov	0.57750	0.57950	0.41300	0.08123	0.94920	0.28990	0.71240	0.27480	0.58680	0.77290	0.18760	0.93500	0.59340	0.23720	1.01400	1.25000	1.34700	1.12700	1.57300	0.66880	
Dec	2.57800	2.67400	3.54000	0.98870	3.40400	2.72300	3.30000	3.76000	2.87300	1.45500	2.44200	2.70900	3.04700	2.36900	1.11000	3.50100	3.51900	5.22200	1.31700	2.25300	

Appendix E – Simulated outflow downstream the Braamhoek Dam for Setup 4 (Land use/cover 2009 and Weather data 1990-2035) in cumecs

	1995	1996	1997	1998	1999	2000	2001	2002	2003	2004	2005	2006	2007	2008	2009	2010	2011	2012	2013	2014	2015
Jan	2.33200	2.39700	2.81500	0.65430	4.06700	2.97300	2.91300	4.35300	1.76700	4.37000	2.00400	2.07500	4.01100	6.16000	2.38200	4.30200	6.21700	3.12100	2.25400	0.68370	4.00300
Feb	1.13500	0.59130	0.93580	0.36320	4.22200	1.72100	2.36200	2.57600	0.77230	3.47100	1.89400	1.69500	2.01800	2.07000	2.90400	0.90730	2.22900	2.23900	2.52900	1.47300	1.36700
Mar	2.83000	0.96600	1.68300	2.53900	3.25700	2.11000	3.13700	1.16400	1.42300	2.52100	2.80600	2.48100	1.28100	2.68400	1.40200	1.48000	1.57200	2.43400	1.08800	4.15000	3.31700
Apr	0.46980	0.17370	0.37640	0.35180	0.68660	1.01900	0.58190	0.36120	0.25610	1.02800	0.73300	0.51030	0.36340	0.57210	0.37370	0.73940	0.35370	0.59470	0.73690	0.44840	1.07400
May	0.21390	0.02091	0.12640	0.16310	0.35880	0.31690	0.30800	0.09562	0.10850	0.34200	0.28800	0.21090	0.09381	0.26360	0.12330	0.19740	0.12630	0.27840	0.18920	0.23020	0.37600
Jun	0.02193	0.00409	0.00910	0.01188	0.22570	0.05828	0.04148	0.00904	0.00664	1.16700	0.04018	0.01759	0.01475	0.02680	0.12640	0.02417	0.01695	0.04317	0.02892	0.02792	0.09788
Jul	0.00607	0.00284	0.00432	0.00429	0.01180	0.01427	0.01053	0.00621	0.00280	0.01442	0.01016	0.00545	0.00595	0.00922	0.00532	0.00746	0.00956	0.01351	0.01028	0.01006	0.02139
Aug	0.02280	0.03912	0.00239	0.01224	0.01347	0.00688	0.05744	0.01164	0.00157	0.05528	0.00593	0.06849	0.00357	0.00579	0.09168	0.00491	0.03986	0.00831	0.00553	0.01537	0.05441
Sep	0.01657	0.12260	0.08797	0.11550	0.07020	0.18100	0.11610	0.16710	0.05105	0.24650	0.05920	0.00145	0.04720	0.06289	0.10080	0.00399	0.01051	0.03413	0.03149	0.10490	0.10610
Oct	0.08561	0.07199	0.06781	0.03977	0.17590	0.02325	0.07664	0.13440	0.17200	0.23080	0.06387	0.19470	0.10680	0.07501	0.21570	0.16920	0.13910	0.07289	0.08025	0.16080	0.07315
Nov	0.16380	0.50020	0.19410	0.24740	0.72650	0.37570	0.28090	0.21110	0.86230	0.80250	0.15270	1.52500	0.48970	0.44280	1.39800	0.38530	0.04171	0.30730	0.09883	0.35450	0.66580
Dec	2.13000	1.26900	3.65400	3.64800	3.76000	2.70700	2.85300	1.94700	6.88800	4.17600	1.15400	2.35900	1.69600	2.38400	5.28100	4.11900	1.22200	1.67200	0.77610	4.45800	1.89700

	2016	2017	2018	2019	2020	2021	2022	2023	2024	2025	2026	2027	2028	2029	2030	2031	2032	2033	2034	2035
Jan	2.71600	4.81900	3.40000	4.12700	2.16100	3.33200	4.75400	3.97300	2.24400	1.81600	2.37700	3.56200	3.87300	2.17700	2.56200	2.63200	3.74100	2.86100	5.35500	5.30700
Feb	1.49900	1.85200	1.45400	1.34300	1.48400	1.86200	2.19700	5.95400	2.79000	1.54900	2.74300	1.28300	2.14100	2.63100	1.20500	1.21300	2.32500	1.66100	2.55500	2.37900
Mar	1.78000	3.60900	1.75900	1.79900	2.66000	1.65100	3.23100	1.50000	3.83300	3.87300	2.60400	0.37610	3.46500	2.90200	2.06400	0.80950	3.99100	3.77200	1.57000	3.41800
Apr	0.37600	0.63750	0.33000	0.38300	1.19300	0.44850	0.62150	0.54440	0.60110	0.70620	0.65480	0.15010	0.56570	0.63350	0.80790	0.19580	0.48690	0.76410	1.50700	0.92860
May	0.16240	0.31610	0.13720	0.16160	0.36420	0.15410	0.34390	0.24710	0.32140	0.28820	0.31000	0.02952	0.29760	0.31720	0.24760	0.04574	0.22490	0.31200	0.37070	0.34250
Jun	0.02171	0.15920	0.01700	0.02007	0.10360	0.13950	0.07720	0.03319	0.05212	0.04910	0.04723	0.00612	0.14570	0.32630	0.03764	0.00885	0.03743	0.08563	0.20700	0.07712
Jul	0.00953	0.01596	0.00821	0.00996	0.01807	0.01073	0.01934	0.01415	0.01650	0.01348	0.01368	0.00351	0.01511	0.01731	0.01259	0.00491	0.01369	0.01736	0.02075	0.01902
Aug	0.04880	0.00826	0.02313	0.17930	0.03151	0.01175	0.27670	0.00791	0.41990	0.04666	0.00699	0.03772	0.03606	0.02630	0.01886	0.00216	0.00795	0.03620	0.03190	0.04137
Sep	0.04223	0.08928	0.13460	0.03551	0.07568	0.09261	0.03763	0.13280	0.02684	0.02153	0.05422	0.13450	0.18260	0.01912	0.11640	0.07664	0.03023	0.17990	0.04308	0.10510
Oct	0.10780	0.06746	0.20930	0.09397	0.12000	0.19650	0.12440	0.23430	0.03009	0.16390	0.08134	0.08383	0.86990	0.08066	0.22060	0.17450	0.16460	0.23530	0.13310	0.07337
Nov	0.33770	0.31380	0.22250	0.06631	0.58450	0.21890	0.32110	0.14690	0.34220	0.37990	0.14360	0.66530	0.65560	0.18230	0.45730	0.60790	0.68810	0.90930	0.92420	0.30720
Dec	2.19000	2.54000	3.54700	0.48070	3.59500	2.86800	3.13200	3.63400	2.61900	1.48000	1.85900	2.90300	3.22300	1.95100	1.22300	3.43500	3.58600	5.29100	1.64100	1.82900

Appendix F – Simulated outflow downstream the Braamhoek Dam Scenario SU4a (Land use/cover 2009 and Increased Weather data 1990-2035) in cumecs

	1995	1996	1997	1998	1999	2000	2001	2002	2003	2004	2005	2006	2007	2008	2009	2010	2011	2012	2013	2014	2015
Jan	2.70500	2.78900	3.23200	0.76070	4.65900	3.25400	3.33100	4.96500	2.07700	4.91500	2.31800	2.45400	4.57400	7.00500	2.77500	4.84100	7.01500	3.56700	2.62400	0.85590	4.58800
Feb	1.36000	0.70020	1.09600	0.45430	4.75700	2.09400	2.68600	2.92000	0.93150	3.90200	2.15400	1.98400	2.29000	2.36100	3.31100	1.02900	2.52600	2.60100	2.91800	1.78900	1.57200
Mar	3.28600	1.16100	1.98600	2.97500	3.64300	2.41100	3.54200	1.31300	1.67400	2.85600	3.21800	2.89800	1.48600	3.05100	1.61400	1.71500	1.78700	2.79900	1.24800	4.73400	3.77500
Apr	0.53110	0.22090	0.45490	0.39610	0.74790	1.16400	0.63430	0.40090	0.29510	1.16200	0.83590	0.58820	0.41150	0.63780	0.41220	0.83550	0.38860	0.67260	0.88170	0.50810	1.22700
May	0.25420	0.02878	0.16680	0.18970	0.39090	0.35650	0.33480	0.12030	0.13570	0.37560	0.33500	0.25330	0.12100	0.29880	0.15180	0.23920	0.14550	0.31210	0.23130	0.26080	0.41620
Jun	0.02686	0.00527	0.01316	0.01629	0.29070	0.08840	0.05958	0.01136	0.00980	1.38100	0.05178	0.02353	0.01915	0.03460	0.15530	0.03017	0.01941	0.06500	0.03745	0.03414	0.11950
Jul	0.00738	0.00373	0.00549	0.00521	0.01345	0.01715	0.01262	0.00725	0.00377	0.01705	0.01241	0.00680	0.00711	0.01138	0.00637	0.00884	0.01091	0.01605	0.01241	0.01178	0.02533
Aug	0.02666	0.04420	0.00324	0.01446	0.01567	0.00820	0.06416	0.01416	0.00278	0.06172	0.00711	0.07792	0.00439	0.00673	0.10720	0.00630	0.04493	0.01037	0.00735	0.01804	0.06129
Sep	0.01937	0.13760	0.09894	0.13000	0.07871	0.20800	0.13080	0.18610	0.05812	0.30110	0.06707	0.00220	0.05328	0.07083	0.11520	0.00520	0.01242	0.03948	0.03636	0.12130	0.11960
Oct	0.09713	0.08275	0.07744	0.04566	0.20230	0.02696	0.08879	0.15710	0.19550	0.39430	0.07301	0.22250	0.12120	0.08488	0.27010	0.18910	0.15550	0.08193	0.09105	0.18640	0.08293
Nov	0.18910	0.63340	0.22860	0.28250	1.07900	0.47710	0.33220	0.25110	1.25800	1.02000	0.17720	2.00000	0.68520	0.69090	1.85100	0.50500	0.04793	0.36360	0.11220	0.45350	0.96720
Dec	2.72800	1.68900	4.39000	4.43100	4.32600	3.27600	3.52500	2.50800	7.84200	4.72600	1.54400	2.74900	2.10500	2.78300	5.97900	4.83000	1.67100	2.15200	1.12400	5.29900	2.20300

	2016	2017	2018	2019	2020	2021	2022	2023	2024	2025	2026	2027	2028	2029	2030	2031	2032	2033	2034	2035
Jan	3.15400	5.49400	3.87600	4.74100	2.63100	3.77400	5.40100	4.54400	2.59900	2.09400	2.75900	4.09300	4.44200	2.46500	2.95100	3.01300	4.29400	3.29400	6.04300	5.96700
Feb	1.74100	2.11300	1.67100	1.57000	1.76300	2.11300	2.46200	6.67000	3.16700	1.80100	3.15000	1.49700	2.45800	2.97900	1.40100	1.42500	2.67700	1.89100	2.85600	2.71100
Mar	2.03000	4.08000	2.03000	2.05000	3.06000	1.89100	3.64500	1.71200	4.33000	4.36700	3.01000	0.42850	3.91000	3.30500	2.43000	0.96210	4.48400	4.28400	1.78000	3.86200
Apr	0.41780	0.70490	0.36690	0.42760	1.39100	0.54100	0.67010	0.60180	0.65380	0.79120	0.74000	0.18090	0.61700	0.70490	0.94770	0.24130	0.53330	0.87280	1.70800	1.05800
May	0.18880	0.34530	0.16200	0.19110	0.40870	0.19660	0.37080	0.28450	0.34930	0.31900	0.34520	0.03599	0.32770	0.34920	0.29510	0.05615	0.25850	0.34120	0.40950	0.38390
Jun	0.02647	0.19900	0.02028	0.02433	0.12850	0.17110	0.09246	0.03905	0.06728	0.06503	0.06104	0.00739	0.17690	0.39720	0.04744	0.01088	0.04141	0.10650	0.25760	0.09689
Jul	0.01107	0.01813	0.00950	0.01158	0.02215	0.01276	0.02210	0.01600	0.01851	0.01576	0.01602	0.00433	0.01684	0.02053	0.01602	0.00618	0.01541	0.02020	0.02384	0.02271
Aug	0.05479	0.00938	0.02650	0.21860	0.03661	0.01427	0.33370	0.00917	0.50570	0.05306	0.00828	0.04252	0.04055	0.02982	0.02202	0.00356	0.00959	0.04133	0.03592	0.04663
Sep	0.04908	0.10040	0.15920	0.04171	0.08543	0.10410	0.04256	0.14880	0.03092	0.02470	0.06194	0.15020	0.20570	0.02245	0.13310	0.08652	0.03458	0.20020	0.04901	0.11850
Oct	0.12180	0.07694	0.25630	0.10530	0.13610	0.23990	0.14300	0.27790	0.03517	0.18610	0.09258	0.09561	1.26900	0.09055	0.25250	0.19950	0.18740	0.29160	0.14920	0.08324
Nov	0.41950	0.38640	0.30470	0.07927	0.89360	0.42110	0.39860	0.21180	0.42080	0.50290	0.16530	0.94280	0.81220	0.20980	0.75030	0.96120	1.05100	1.25400	1.31100	0.36770
Dec	2.77100	3.16700	4.19500	0.65860	4.12400	3.32400	3.75700	4.34600	3.22700	1.92000	2.41100	3.41300	3.67800	2.48100	1.48300	3.95900	4.09700	5.99500	1.92100	2.32600

Appendix G – Simulated outflow downstream the Braamhoek Dam Scenario SU4b (Land use/cover 2009 and Decreased Weather data 1990-2035) in cumecs

	1995	1996	1997	1998	1999	2000	2001	2002	2003	2004	2005	2006	2007	2008	2009	2010	2011	2012	2013	2014	2015
Jan	1.84800	1.82800	2.21300	0.39610	3.50900	2.54800	2.44000	3.63300	1.25700	3.83500	1.35300	1.56600	3.26300	5.29800	1.75000	3.28000	5.26800	2.63900	1.84600	0.42790	3.33400
Feb	0.62870	0.43590	0.65580	0.27920	3.39100	0.78430	1.65600	1.94300	0.40310	2.82000	1.32000	1.32500	1.33700	1.33200	2.18700	0.64900	1.49900	1.37900	1.58100	0.99240	0.90830
Mar	1.79200	0.38480	0.51730	1.44500	2.31500	1.30800	2.24600	0.71430	0.39750	1.24800	1.48700	1.20600	0.58460	1.57800	0.59750	0.66350	0.86250	1.69600	0.75930	3.36100	2.02100
Apr	0.21640	0.03633	0.07480	0.15050	0.43310	0.56320	0.40250	0.18600	0.00347	0.57540	0.35120	0.13590	0.09956	0.34570	0.14290	0.37000	0.16040	0.39540	0.30770	0.31790	0.64650
May	0.03240	0.01148	0.00283	0.02761	0.21900	0.06111	0.14850	0.02218	0.01094	0.08937	0.05038	0.02442	0.00895	0.05130	0.02808	0.02357	0.03872	0.11570	0.03112	0.12430	0.14670
Jun	0.00453	0.00239	0.00135	0.00257	0.20200	0.01188	0.01536	0.00662	0.00078	1.26000	0.01294	0.00337	0.00910	0.00957	0.10280	0.00671	0.01007	0.01841	0.01092	0.01499	0.02565
Jul	0.00236	0.00091	0.00064	0.00155	0.00729	0.00516	0.00678	0.00398	0.00006	0.01039	0.00415	0.00150	0.00292	0.00507	0.00202	0.00369	0.00534	0.00803	0.00454	0.00654	0.01081
Aug	0.01771	0.03244	0.00004	0.00799	0.00975	0.00278	0.04930	0.00681	0.00000	0.04532	0.00176	0.05705	0.00158	0.00301	0.08066	0.00194	0.03225	0.00429	0.00164	0.01058	0.04118
Sep	0.01297	0.10240	0.07416	0.09766	0.05789	0.15840	0.09643	0.13620	0.04078	0.29420	0.04821	0.00008	0.03796	0.05297	0.08715	0.00081	0.00716	0.02602	0.02524	0.09097	0.08972
Oct	0.06844	0.05917	0.05055	0.03151	0.14150	0.01678	0.05923	0.10420	0.14040	0.23670	0.04866	0.16400	0.08706	0.05604	0.21540	0.14310	0.11350	0.05937	0.06311	0.13350	0.06032
Nov	0.12360	0.39070	0.16010	0.21770	0.62490	0.46570	0.29100	0.16560	1.23600	0.49820	0.11570	0.66300	0.69570	0.64590	0.70000	0.49840	0.02238	0.33930	0.07941	0.44630	0.74750
Dec	2.24200	1.00300	3.50100	3.47200	3.00400	2.45200	2.82600	1.74200	5.88400	3.44500	1.25500	1.90100	1.38400	1.99900	4.33600	3.52600	1.36700	1.64900	1.05400	4.14900	1.43100

	2016	2017	2018	2019	2020	2021	2022	2023	2024	2025	2026	2027	2028	2029	2030	2031	2032	2033	2034	2035
Jan	2.07400	4.00700	2.76000	3.11800	1.81600	2.54000	3.84500	3.33400	1.76900	1.42300	1.96200	2.97900	2.97700	1.84300	2.05400	2.11500	3.09700	2.21100	4.56200	4.29000
Feb	0.84620	1.19200	0.93870	0.89730	1.12500	1.30800	1.53100	4.94400	2.10900	1.08000	2.09900	0.87040	1.41100	1.69300	0.84030	0.62590	1.66700	1.10800	1.81700	1.62300
Mar	0.97420	2.58200	0.74190	1.23800	1.78100	0.93030	2.26600	0.83290	2.75700	2.76500	1.45800	0.25370	2.34200	1.56300	0.91660	0.25370	2.60600	2.35800	1.07300	2.37400
Apr	0.11900	0.42940	0.10910	0.24350	0.72870	0.25250	0.43920	0.36500	0.43380	0.30440	0.32950	0.05642	0.37700	0.29480	0.31140	0.01239	0.26750	0.40750	0.54730	0.48980
May	0.02775	0.16930	0.13585	0.04604	0.18740	0.13279	0.20550	0.18645	0.16580	0.58560	0.19324	0.01739	0.12180	0.75730	0.39730	0.17350	0.15150	0.10050	0.11290	0.12890
Jun	0.00767	0.11680	0.00664	0.01146	0.02899	0.13640	0.03202	0.01901	0.02597	0.01492	0.01575	0.00408	0.12200	0.30970	0.00893	0.00214	0.01546	0.04141	0.14580	0.02031
Jul	0.00362	0.01007	0.00336	0.00591	0.00875	0.00549	0.01206	0.00920	0.01058	0.00603	0.00685	0.00174	0.00863	0.00850	0.00423	0.00091	0.00742	0.00884	0.01069	0.00903
Aug	0.04052	0.00496	0.01778	0.15140	0.02402	0.00765	0.23860	0.00507	0.36930	0.03572	0.00304	0.03223	0.02844	0.01849	0.01196	0.00020	0.00355	0.02513	0.02288	0.03099
Sep	0.03224	0.06928	0.11570	0.02364	0.06244	0.07529	0.02924	0.11170	0.02031	0.01416	0.04206	0.11620	0.15170	0.01351	0.10240	0.06168	0.02376	0.14910	0.03161	0.08367
Oct	0.08175	0.04656	0.22440	0.07582	0.09761	0.17080	0.09816	0.20740	0.01782	0.13280	0.05820	0.06950	1.14000	0.06251	0.21190	0.14550	0.13560	0.30050	0.10580	0.05412
Nov	0.33090	0.32400	0.20520	0.04885	0.43140	0.14120	0.45550	0.15190	0.33050	0.48710	0.11430	0.43890	0.45650	0.14590	0.45058	0.87270	0.96670	0.91630	0.58000	0.40580
Dec	2.14200	2.24300	2.97700	0.65130	2.86600	2.21600	2.76200	3.09000	2.38000	1.16700	1.88400	2.29000	2.53900	1.85300	0.85780	2.92900	2.94700	4.43800	1.00700	1.85100

Appendix H – Simulated outflow downstream the Bedford Dam for Setup 3 (Land use/cover 2000 and Weather data 1990-2035) in cumecs

	1995	1996	1997	1998	1999	2000	2001	2002	2003	2004	2005	2006	2007	2008	2009	2010	2011	2012	2013	2014	2015
Jan	0.34840	0.36750	0.42520	0.06507	0.62580	0.45730	0.42090	0.70770	0.28480	0.62790	0.27970	0.32720	0.63840	1.03700	0.35060	0.65900	1.06200	0.47340	0.32870	0.07282	0.60030
Feb	0.11250	0.01814	0.07831	0.01340	0.60070	0.19590	0.28430	0.39600	0.09405	0.49160	0.23250	0.24830	0.25580	0.27200	0.41860	0.05044	0.30690	0.32840	0.37910	0.18830	0.16810
Mar	0.41750	0.15100	0.23800	0.35150	0.50680	0.27330	0.45030	0.10950	0.19060	0.35900	0.42580	0.36820	0.16840	0.37540	0.19290	0.18660	0.21330	0.30710	0.09983	0.68010	0.49410
Apr	0.32810	0.10840	0.26190	0.24470	0.49630	0.79790	0.43460	0.26850	0.16110	0.82170	0.59050	0.35720	0.25590	0.46270	0.27530	0.60000	0.26840	0.43880	0.55430	0.29270	0.84680
May	0.00021	0.00066	0.00018	0.00016	0.01925	0.00073	0.00052	0.00052	0.00141	0.00049	0.00052	0.00102	0.00039	0.00047	0.00256	0.00042	0.00097	0.00030	0.00026	0.00015	0.00095
Jun	0.00024	0.00030	0.00021	0.00018	0.11850	0.00076	0.00057	0.00055	0.00035	0.40810	0.00069	0.00037	0.00058	0.00042	0.06537	0.00049	0.00045	0.00033	0.00036	0.00019	0.00045
Jul	0.00355	0.00096	0.00187	0.00241	0.00816	0.00861	0.00723	0.00397	0.00067	0.01014	0.00652	0.00284	0.00360	0.00643	0.00321	0.00489	0.00689	0.00990	0.00690	0.00676	0.01557
Aug	0.00253	0.00478	0.00061	0.01277	0.01221	0.00436	0.06808	0.01062	0.00009	0.06444	0.00366	0.08274	0.00178	0.00373	0.01083	0.00292	0.04627	0.00530	0.00302	0.01547	0.06185
Sep	0.00064	0.00497	0.00262	0.00436	0.01302	0.05908	0.02144	0.01237	0.00171	0.10000	0.00497	0.00024	0.00173	0.00524	0.02147	0.00033	0.00048	0.00110	0.00104	0.00531	0.03423
Oct	0.00231	0.00517	0.00187	0.00106	0.02075	0.00091	0.00524	0.02189	0.01832	0.05833	0.00218	0.01923	0.00682	0.00216	0.05919	0.02137	0.00699	0.00498	0.00235	0.02281	0.01430
Nov	0.00704	0.15170	0.03305	0.03424	0.10780	0.15200	0.05439	0.03563	0.17890	0.09191	0.02086	0.28980	0.14950	0.11240	0.21650	0.12130	0.00072	0.09845	0.00258	0.09798	0.17420
Dec	0.39280	0.17630	0.63670	0.65830	0.61970	0.46690	0.53160	0.38430	1.21300	0.66260	0.22370	0.36560	0.26880	0.36400	0.90020	0.68740	0.27860	0.23440	0.18150	0.78090	0.29480

	2016	2017	2018	2019	2020	2021	2022	2023	2024	2025	2026	2027	2028	2029	2030	2031	2032	2033	2034	2035
Jan	0.43490	0.82390	0.52350	0.69340	0.30460	0.48260	0.74070	0.59640	0.29730	0.26620	0.37080	0.62740	0.60580	0.29030	0.37650	0.39800	0.58630	0.42250	0.84920	0.91100
Feb	0.20210	0.22390	0.13000	0.13960	0.19760	0.17940	0.24220	0.96310	0.40160	0.16210	0.38530	0.14270	0.27180	0.35130	0.12050	0.15320	0.30670	0.18170	0.27540	0.32470
Mar	0.20270	0.55270	0.30090	0.19900	0.35360	0.21170	0.47210	0.18410	0.58680	0.63510	0.38370	0.01582	0.51300	0.43980	0.31420	0.07012	0.66350	0.61170	0.16620	0.53430
Apr	0.27740	0.52290	0.23880	0.28980	0.94320	0.36530	0.52710	0.43260	0.50560	0.57860	0.49580	0.10910	0.41730	0.51670	0.61810	0.12290	0.35610	0.59290	1.30000	0.77760
May	0.00037	0.00045	0.00146	0.00033	0.00077	0.00041	0.00067	0.00260	0.00070	0.00096	0.00442	0.00061	0.00134	0.00047	0.00090	0.00078	0.00044	0.00039	0.00127	0.00402
Jun	0.00037	0.06636	0.00043	0.00034	0.00023	0.06326	0.00058	0.00065	0.00043	0.00051	0.00038	0.00027	0.05247	0.13280	0.00055	0.00028	0.00044	0.00698	0.09362	0.00068
Jul	0.00674	0.01209	0.00571	0.00721	0.01227	0.00778	0.01508	0.01046	0.01278	0.01008	0.01014	0.00167	0.01160	0.01312	0.00876	0.00260	0.01030	0.01308	0.01606	0.01405
Aug	0.05792	0.00594	0.02559	0.01823	0.03368	0.01050	0.00272	0.00543	0.00039	0.05317	0.00468	0.04565	0.04039	0.02748	0.01885	0.00076	0.00519	0.00394	0.00333	0.00462
Sep	0.00134	0.00391	0.02963	0.00104	0.00597	0.01273	0.00722	0.01132	0.00089	0.00087	0.00134	0.00521	0.04208	0.00085	0.02956	0.00245	0.00120	0.02943	0.00479	0.00646
Oct	0.00434	0.00184	0.07196	0.00938	0.00658	0.02834	0.02176	0.07984	0.00087	0.01301	0.00190	0.01110	0.18100	0.00298	0.04355	0.02612	0.03351	0.06418	0.01612	0.01089
Nov	0.11000	0.06177	0.04037	0.00250	0.13570	0.03254	0.09924	0.04955	0.08515	0.12280	0.02236	0.19020	0.06111	0.03392	0.11320	0.15790	0.20450	0.13050	0.25920	0.11210
Dec	0.40700	0.46810	0.58230	0.11070	0.57090	0.38700	0.49510	0.64000	0.42620	0.22430	0.36180	0.42360	0.49740	0.37510	0.14960	0.55760	0.57570	0.87550	0.24180	0.30610

Appendix I – Simulated outflow downstream the Bedford Dam for Setup 4 (Land use/cover 2009 and Weather data 1990-2035) in cumecs

	1995	1996	1997	1998	1999	2000	2001	2002	2003	2004	2005	2006	2007	2008	2009	2010	2011	2012	2013	2014	2015
Jan	0.42810	0.45780	0.50380	0.10870	0.72340	0.53150	0.52280	0.81560	0.34590	0.70650	0.32750	0.41530	0.73030	1.17600	0.44970	0.29220	0.19710	0.00570	0.17680	0.02441	0.16070
Feb	0.17840	0.03528	0.11330	0.03569	0.70940	0.25600	0.39580	0.45250	0.13410	0.59080	0.29460	0.31570	0.31570	0.33160	0.45510	1.01100	0.81070	0.40060	0.34600	0.30290	0.91300
Mar	0.54020	0.19510	0.32630	0.48630	0.56960	0.35910	0.55620	0.15630	0.26790	0.44280	0.53610	0.47760	0.22360	0.46900	0.51430	0.74710	1.16300	0.58570	0.42880	0.12730	0.71620
Apr	0.02258	0.01641	0.03041	0.01421	0.03363	0.13940	0.01625	0.02556	0.00600	0.12410	0.06074	0.03576	0.01653	0.05202	0.25180	0.08311	0.37070	0.41540	0.47320	0.27500	0.20460
May	0.00795	0.00873	0.00603	0.00578	0.04793	0.01644	0.01375	0.01412	0.01346	0.01477	0.01243	0.01263	0.00962	0.01096	0.02112	0.26510	0.26910	0.41150	0.14560	0.79210	0.60090
Jun	0.00733	0.00528	0.00398	0.00331	0.16090	0.01466	0.01215	0.00926	0.00581	0.45430	0.01000	0.00667	0.00968	0.00948	0.01550	0.07655	0.01361	0.03060	0.09487	0.00542	0.15170
Jul	0.00643	0.00352	0.00390	0.00335	0.01282	0.01314	0.01081	0.01008	0.00516	0.01302	0.01034	0.00574	0.00721	0.00936	0.10850	0.01122	0.01454	0.00910	0.00825	0.00640	0.01481
Aug	0.00496	0.00472	0.00174	0.00102	0.01042	0.01036	0.04599	0.00662	0.00146	0.02915	0.00681	0.03995	0.00410	0.00653	0.00764	0.01024	0.00788	0.00802	0.00729	0.00495	0.01054
Sep	0.00223	0.02222	0.01057	0.02625	0.03895	0.12420	0.05753	0.05501	0.00824	0.15520	0.01983	0.00204	0.01035	0.03663	0.05698	0.00857	0.00597	0.00689	0.00632	0.00341	0.00983
Oct	0.01218	0.01799	0.00408	0.00442	0.05651	0.00955	0.02237	0.05875	0.05196	0.09500	0.01270	0.05336	0.02960	0.01497	0.04928	0.00659	0.01774	0.00579	0.00390	0.00172	0.02672
Nov	0.03924	0.22460	0.08294	0.07903	0.18190	0.23210	0.12220	0.07891	0.28860	0.14290	0.05836	0.40690	0.23790	0.22670	0.10400	0.00545	0.00258	0.00687	0.00512	0.03409	0.07501
Dec	0.5543	0.2728	0.7947	0.7954	0.742	0.5798	0.6737	0.5003	1.359	0.7957	0.336	0.4593	0.3582	0.4497	0.2922	0.06688	0.03893	0.02937	0.01074	0.05104	0.03838

	2016	2017	2018	2019	2020	2021	2022	2023	2024	2025	2026	2027	2028	2029	2030	2031	2032	2033	2034	2035
Jan	0.26050	0.17430	0.61920	0.77110	0.43530	0.59570	0.87460	0.74020	0.39230	0.34330	0.43340	0.70850	0.69740	0.35050	0.46210	0.47500	0.67160	0.50510	0.99290	1.01000
Feb	0.36190	0.53100	0.19830	0.19470	0.27870	0.26540	0.31780	1.10100	0.49930	0.23370	0.49530	0.20350	0.35500	0.44430	0.16540	0.20360	0.39530	0.24890	0.35430	0.39730
Mar	0.52660	0.92690	0.35730	0.28570	0.47130	0.28480	0.59530	0.24450	0.71020	0.73310	0.48870	0.03489	0.61110	0.54980	0.40370	0.13550	0.72890	0.72130	0.22390	0.61820
Apr	0.26650	0.28370	0.01830	0.00896	0.16730	0.04510	0.02851	0.03121	0.04148	0.04953	0.06042	0.01768	0.02440	0.04133	0.10610	0.00455	0.02690	0.10100	0.23360	0.08698
May	0.28770	0.66510	0.01531	0.01021	0.01338	0.01172	0.01746	0.02233	0.01498	0.01618	0.02305	0.00771	0.01505	0.01220	0.01042	0.01285	0.01072	0.01080	0.01996	0.02196
Jun	0.00951	0.04201	0.00765	0.00719	0.00713	0.12020	0.01256	0.01373	0.01088	0.01004	0.00843	0.00318	0.09457	0.18840	0.00776	0.00500	0.00985	0.02576	0.12920	0.01302
Jul	0.00898	0.01080	0.00767	0.00593	0.00772	0.01079	0.01208	0.01147	0.00993	0.00893	0.00810	0.00288	0.00821	0.00989	0.00664	0.00392	0.00918	0.01040	0.01382	0.01309
Aug	0.00666	0.09769	0.00866	0.09821	0.01671	0.00934	0.17060	0.00915	0.21800	0.01649	0.00561	0.00862	0.01629	0.01221	0.00550	0.00115	0.00590	0.01092	0.02277	0.01769
Sep	0.00526	0.00798	0.07012	0.00474	0.02874	0.05242	0.02503	0.05152	0.00840	0.00463	0.00945	0.02549	0.08568	0.00589	0.06383	0.00791	0.01187	0.08309	0.02266	0.02711
Oct	0.02295	0.00528	0.11620	0.03216	0.03595	0.08491	0.06042	0.14610	0.00715	0.05113	0.01052	0.02834	0.25160	0.01713	0.07890	0.06860	0.08427	0.11130	0.05086	0.03372
Nov	0.00585	0.01662	0.08642	0.01407	0.23090	0.08016	0.16260	0.08851	0.17640	0.20330	0.07306	0.26740	0.11250	0.07569	0.16920	0.23550	0.29400	0.22160	0.34510	0.17330
Dec	0.02175	0.008613	0.7089	0.2149	0.686	0.5446	0.6342	0.7741	0.5404	0.3269	0.5004	0.5309	0.6058	0.4771	0.236	0.6465	0.6852	1.02	0.3218	0.4279

Appendix J – Simulated outflow downstream the Bedford Dam Scenario SU4a (Land use/cover 2009 and Increased Weather data 1990-2035) in cumecs

	1995	1996	1997	1998	1999	2000	2001	2002	2003	2004	2005	2006	2007	2008	2009	2010	2011	2012	2013	2014	2015
Jan	0.40650	0.42810	0.49330	0.06958	0.70530	0.53890	0.49900	0.77010	0.32290	0.71220	0.33250	0.39250	0.68030	1.16100	0.42570	0.66120	1.13200	0.56910	0.40880	0.11670	0.68150
Feb	0.15730	0.02735	0.10060	0.03165	0.69350	0.18680	0.35660	0.44280	0.11730	0.64590	0.24690	0.27280	0.26750	0.32090	0.42570	0.98490	0.79530	0.42300	0.35520	0.33190	0.91920
Mar	0.45140	0.15390	0.22000	0.41690	0.52780	0.29840	0.51410	0.15340	0.21120	0.30140	0.44530	0.39950	0.18240	0.41320	0.46330	0.66120	1.13200	0.56910	0.40880	0.11670	0.68150
Apr	0.01100	0.00515	0.01933	0.00924	0.02309	0.10930	0.01146	0.01216	0.00667	0.10190	0.04409	0.02275	0.00912	0.03775	0.20580	0.07522	0.34810	0.36230	0.36850	0.24400	0.19330
May	0.00350	0.00326	0.00286	0.00296	0.03603	0.01124	0.01139	0.01095	0.01026	0.01180	0.00756	0.00929	0.00852	0.00831	0.01024	0.22400	0.23680	0.35610	0.12490	0.75880	0.52720
Jun	0.00373	0.00237	0.00291	0.00317	0.15490	0.00977	0.01046	0.01055	0.00614	0.45110	0.00835	0.00644	0.00820	0.00835	0.00930	0.06323	0.00956	0.01738	0.06518	0.00482	0.12550
Jul	0.00364	0.00162	0.00357	0.00363	0.00947	0.01004	0.01062	0.00991	0.00654	0.01052	0.00722	0.00520	0.00673	0.00793	0.09909	0.00873	0.01112	0.00741	0.00579	0.00528	0.01218
Aug	0.00914	0.00737	0.00297	0.00355	0.01023	0.00848	0.05779	0.01018	0.00504	0.04081	0.00582	0.04930	0.00691	0.00779	0.06959	0.00765	0.02729	0.00614	0.00496	0.00589	0.03431
Sep	0.00602	0.03053	0.02365	0.05290	0.04623	0.14030	0.07666	0.07915	0.02572	0.18070	0.02656	0.00419	0.01969	0.04770	0.06257	0.00625	0.00650	0.01226	0.01426	0.06189	0.08692
Oct	0.02384	0.02213	0.01039	0.01144	0.06500	0.01037	0.03288	0.07645	0.08205	0.10650	0.01712	0.07505	0.04973	0.02374	0.11920	0.08929	0.06032	0.04321	0.02744	0.07854	0.04688
Nov	0.05563	0.23070	0.09947	0.11020	0.19080	0.24010	0.14090	0.11030	0.30940	0.14810	0.06611	0.41530	0.27890	0.25450	0.30360	0.21490	0.00878	0.20980	0.03882	0.19680	0.27850
Dec	0.55950	0.24460	0.80870	0.79300	0.68960	0.56990	0.66840	0.46620	1.35300	0.78690	0.33130	0.44550	0.34470	0.43620	0.98490	0.79530	0.42300	0.35520	0.33190	0.91920	0.33820

	2016	2017	2018	2019	2020	2021	2022	2023	2024	2025	2026	2027	2028	2029	2030	2031	2032	2033	2034	2035
Jan	0.48400	0.90800	0.57740	0.68610	0.41970	0.52090	0.83960	0.71480	0.37510	0.31410	0.42460	0.68950	0.64900	0.34060	0.44260	0.43930	0.66040	0.47300	0.97230	0.93680
Feb	0.33820	0.51630	0.16950	0.17540	0.26710	0.23420	0.26520	1.06100	0.46730	0.22630	0.44990	0.18270	0.31300	0.39200	0.14840	0.20360	0.39530	0.24890	0.35430	0.39730
Mar	0.48400	0.90800	0.32400	0.24300	0.40280	0.25040	0.52760	0.20890	0.64750	0.67270	0.40910	0.02085	0.53700	0.44440	0.34720	0.13550	0.72890	0.72130	0.22390	0.61820
Apr	0.23190	0.20570	0.01032	0.00788	0.14030	0.02905	0.01954	0.02139	0.02829	0.03287	0.03659	0.00830	0.01611	0.02112	0.07257	0.00455	0.02690	0.10100	0.23360	0.08698
May	0.22710	0.60930	0.01203	0.00673	0.01110	0.00887	0.01137	0.01794	0.01035	0.00861	0.01506	0.00545	0.00967	0.00836	0.00992	0.01285	0.01072	0.01080	0.01996	0.02196
Jun	0.00818	0.03264	0.00649	0.00513	0.00580	0.11990	0.00917	0.01173	0.00709	0.00711	0.00647	0.00291	0.10180	0.19380	0.00678	0.00500	0.00985	0.02576	0.12920	0.01302
Jul	0.00662	0.00740	0.00777	0.00553	0.00487	0.00765	0.00904	0.01056	0.00769	0.00612	0.00623	0.00293	0.00496	0.00648	0.00688	0.00392	0.00918	0.01040	0.01382	0.01309
Aug	0.03743	0.00572	0.01445	0.12040	0.01652	0.00902	0.18370	0.01043	0.22600	0.02189	0.00515	0.01586	0.02079	0.01374	0.00985	0.00558	0.00689	0.01513	0.02292	0.01983
Sep	0.01244	0.03629	0.08698	0.00854	0.03109	0.05832	0.02885	0.06922	0.01020	0.00722	0.01389	0.04067	0.10270	0.00843	0.08933	0.02813	0.01917	0.10360	0.02471	0.03863
Oct	0.03899	0.01619	0.13190	0.04670	0.03915	0.09282	0.06893	0.15480	0.01084	0.06535	0.01264	0.03676	0.26870	0.02518	0.10140	0.10670	0.10610	0.12100	0.05812	0.03717
Nov	0.19850	0.15150	0.09973	0.02050	0.22920	0.08035	0.16870	0.09572	0.19340	0.20980	0.08339	0.28150	0.10650	0.09039	0.17900	0.24720	0.31510	0.21810	0.39220	0.18700
Dec	0.51630	0.53270	0.69970	0.24110	0.63150	0.52080	0.61550	0.76000	0.51800	0.29970	0.49130	0.51060	0.56990	0.46320	0.21150	0.65750	0.65880	0.98510	0.29290	0.41100

Appendix K – Simulated outflow downstream the Bedford Dam Scenario SU4b (Land use/cover 2009 and Decreased Weather data 1990-2035) in cumecs

	1995	1996	1997	1998	1999	2000	2001	2002	2003	2004	2005	2006	2007	2008	2009	2010	2011	2012	2013	2014	2015
Jan	0.34660	0.35260	0.41800	0.05054	0.60750	0.46260	0.42710	0.66280	0.26890	0.61980	0.28510	0.32670	0.58110	1.00400	0.35640	0.56540	0.98660	0.47680	0.34730	0.08794	0.57950
Feb	0.12400	0.01991	0.08244	0.02225	0.59050	0.15100	0.29620	0.38390	0.09718	0.55550	0.20610	0.22870	0.22150	0.27140	0.39410	0.05808	0.29970	0.30040	0.30400	0.19430	0.16230
Mar	0.37260	0.12320	0.16560	0.33810	0.46110	0.24760	0.43860	0.12580	0.16820	0.25340	0.36740	0.32550	0.14810	0.34540	0.16820	0.18270	0.19770	0.29350	0.10270	0.65060	0.43800
Apr	0.00714	0.00276	0.01307	0.00637	0.01734	0.08817	0.01012	0.01072	0.00578	0.08328	0.03460	0.01693	0.00692	0.02865	0.16830	0.05811	0.29970	0.30050	0.30400	0.19430	0.16230
May	0.00218	0.00238	0.00174	0.00181	0.02896	0.00973	0.01040	0.00994	0.00797	0.01077	0.00674	0.00666	0.00738	0.00740	0.00736	0.00695	0.00916	0.00631	0.00512	0.00422	0.00995
Jun	0.00274	0.00129	0.00166	0.00197	0.13250	0.00836	0.00947	0.00953	0.00522	0.39920	0.00702	0.00570	0.00693	0.00746	0.08014	0.00767	0.00711	0.00478	0.00501	0.00414	0.00773
Jul	0.00269	0.00044	0.00245	0.00257	0.00874	0.00907	0.00969	0.00891	0.00564	0.00967	0.00645	0.00419	0.00573	0.00706	0.00522	0.00660	0.00738	0.00461	0.00463	0.00438	0.00761
Aug	0.00591	0.00376	0.00188	0.00245	0.00842	0.00754	0.04767	0.00886	0.00415	0.03296	0.00509	0.03868	0.00594	0.00695	0.05477	0.00676	0.02117	0.00519	0.00395	0.00474	0.02751
Sep	0.00371	0.01792	0.01513	0.03867	0.03650	0.01127	0.06070	0.05921	0.01924	0.01479	0.02044	0.00331	0.01429	0.03863	0.04906	0.00536	0.00551	0.00894	0.00997	0.04807	0.06991
Oct	0.01600	0.01341	0.00589	0.00790	0.04794	0.00865	0.02482	0.05837	0.06249	0.08563	0.01226	0.05337	0.03615	0.01747	0.09328	0.06771	0.04500	0.03311	0.01971	0.03937	0.03599
Nov	0.03801	0.17870	0.07400	0.08084	0.14720	0.01971	0.10970	0.08707	0.24440	0.11980	0.04916	0.33160	0.21960	0.20030	0.24870	0.17120	0.00710	0.16660	0.02761	0.15390	0.22460
Dec	0.45530	0.18930	0.67740	0.66270	0.58120	0.47410	0.56070	0.38530	1.16500	0.67010	0.26160	0.37370	0.28230	0.36770	0.84660	0.67680	0.34340	0.28390	0.26760	0.78360	0.28040

	2016	2017	2018	2019	2020	2021	2022	2023	2024	2025	2026	2027	2028	2029	2030	2031	2032	2033	2034	2035
Jan	0.40650	0.78230	0.49300	0.59020	0.34380	0.44390	0.72390	0.61370	0.31690	0.26320	0.36260	0.59260	0.55310	0.28980	0.37130	0.37160	0.56750	0.40310	0.84400	0.81130
Feb	0.18990	0.16770	0.13600	0.14340	0.21950	0.19000	0.22340	0.92710	0.40060	0.18730	0.37920	0.14910	0.25920	0.32760	0.12180	0.16090	0.30400	0.16980	0.27370	0.30210
Mar	0.18580	0.51770	0.27430	0.19980	0.33080	0.20670	0.44650	0.17400	0.55250	0.57850	0.33570	0.01417	0.45330	0.36550	0.28300	0.06145	0.58810	0.54470	0.24790	0.46350
Apr	0.19000	0.16770	0.00713	0.00679	0.11230	0.02235	0.01563	0.01784	0.02070	0.02550	0.02785	0.00525	0.01160	0.01527	0.05458	0.06860	0.08427	0.11130	0.05086	0.03372
May	0.00589	0.00642	0.00967	0.00584	0.00765	0.00764	0.00971	0.01491	0.00942	0.00662	0.01218	0.00431	0.00682	0.00752	0.00771	0.00649	0.00885	0.00689	0.01114	0.01199
Jun	0.00439	0.08248	0.00585	0.00431	0.00477	0.10120	0.00810	0.01083	0.00628	0.00605	0.00508	0.00178	0.08395	0.16600	0.00571	0.00364	0.00791	0.01853	0.10500	0.00749
Jul	0.00427	0.00570	0.00682	0.00471	0.00387	0.00666	0.00824	0.00969	0.00682	0.00518	0.00537	0.00178	0.00388	0.00548	0.00597	0.00475	0.00727	0.00647	0.00904	0.00736
Aug	0.02962	0.00488	0.01102	0.10060	0.01216	0.00742	0.15530	0.00958	0.19330	0.01592	0.00428	0.00980	0.01551	0.01030	0.00753	0.00465	0.00596	0.01120	0.01868	0.01546
Sep	0.00942	0.02694	0.06917	0.00630	0.02311	0.04494	0.02317	0.05260	0.00836	0.00521	0.01026	0.02578	0.07792	0.00661	0.07056	0.01914	0.01496	0.08010	0.01984	0.02748
Oct	0.02781	0.01194	0.10640	0.03587	0.02764	0.06921	0.05390	0.01255	0.00862	0.04744	0.00879	0.02557	0.02133	0.01790	0.07671	0.07990	0.08371	0.07534	0.04358	0.02890
Nov	0.16070	0.11520	0.07511	0.01514	0.18300	0.06241	0.13620	0.07896	0.15190	0.16800	0.06290	0.22790	0.08230	0.06792	0.14320	0.19100	0.25700	0.17420	0.32810	0.15090
Dec	0.42820	0.44770	0.58920	0.19110	0.53260	0.43010	0.51810	0.64450	0.43080	0.24020	0.39750	0.41720	0.48040	0.37720	0.16630	0.55570	0.55920	0.84600	0.24130	0.33870