INTEGRATED HYDROLOGICAL MODELLING FOR SUSTAINABLE WATER ALLOCATION PLANNING: MKOMAZI BASIN, SOUTH AFRICA CASE STUDY

Submitted in fulfilment of the requirements for the degree of

Doctor of Engineering

in the Department of Civil Engineering and Geomatics,
Faculty of Engineering and the Built Environment at

Durban University of Technology

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November 2018

ABSTRACT

Allocation of freshwater resources between societal needs and natural ecological systems is of great concern for water managers. This development has challenged decision-makers regarding how to reasonably allocate available water resources to meet the competing demands. Thus, turning these concerns into opportunities requires the need for both water technology innovation and water behavioural change, in order to manage fresh water in a sustainable manner.

This study aimed at investigating the applicability of an integrated hydrological model in a Geographical Information Systems (GIS) environment for sustainable water allocation planning and management, using the Mkomazi Basin in KwaZulu-Natal Province, South Africa, as a case study. Specifically, the study identified ecosystems that depend on Mkomazi River for preservation of their environmental and public benefit values; developed a water allocation mechanism to achieve equitable water distribution and large benefits from water uses across the basin's users; synthesised rules for sustainable development in sharing the limited water resources and maintaining environmental quality; and finally, established a framework for water trading in order to encourage water use efficiency and allow movement of water to new users.

Historical 15-year (1990-2015) observed streamflows and daily meteorological variables (precipitation sums (mm), relative humidity (%), wind speed (m s^{-1}), mean, minimum and maximum air temperature (^{o}C), solar radiation (MJ/m^2), sunshine duration (h) and evapotranspiration (mm)) were used for this study. The hydro-meteorological data collected from various sources were subjected to frequency trend analysis, correlation, regression and the double mass curve to test their accuracy, reliability, homogeneity, consistency and localisation gaps. The ombro-thermic diagram was used to classify the months into wet and dry periods.

The identification of prominent ecosystems that depend on the Mkomazi River was achieved through a comprehensive desktop survey and documentation acquired from the Department of Water and Sanitation (DWS). Multivariate statistical methods; cluster, factor and principal component analysis, were applied to analyse the surface water quality data sets extracted from the repository of South Africa's water resources website (WR2012), in other assess their impact on the aquatic net benefit values and environmental preservation.

A semi-distributed event process and an integrated Soil and Water Assessment Tool (SWAT) model in a GIS environment, with descriptive statistical of mean, median, mode, standard deviation, skewness, and kurtosis were employed to simulate the basin's hydrological process in evaluating the basin's water balance. The SWAT model was parameterised, calibrated and validated from corrected hydro-meteorological data from 2004 to 2013. Sequential Uncertainty Fitting Algorithm (SUFI2) was used for the model sensitivity analysis, calibration and validation of the model.

Artificial Neural Networks (ANNs), Probability Distribution Functions (PDF), and a Flow Duration Curve (FDC) were used to project future available water. Based on the estimated available water, an estimation of allocable water was made based on percentage dependability of the river yield to the different users. The weilbul ranking was used for choosing the dependable flow; this was subsequently used for the different water riparian's demand distribution. Large benefits derivation from water uses across the basin's users was based on priority-driven sustainability.

Extensive literature review work was used to synthesise rules for sharing limited water resources and maintaining environmental quality for sustainable development. These rules were all drawn from similar world experiences for efficient and gainful utilisation of water and other natural resources. The synthesised rules and principles were modified to suit

KwaZulu-Natal Province (KZN) water allocation reform regulations. The established water rules were subsequently adapted to the present (Mkomazi) case study area.

The proposed developed water trading framework leans on an inclusive simulation of 'Hydrology, Environment, Life (aquatics), Policy and Sensitivity' (HELPS) collective response of the basin in exploring the socio-economic and environmental consequences of water regulation. It uses a System Dynamic (SD) simulation technique to form a composite supply-side augmentation with demand-side improvement system to allow movement of water to new users and encourage water use efficiency.

The results of the agglomerative hierarchical cluster analysis grouped the 10 sub-basin sites into three clusters of highly polluted (HP), medium polluted (MP) and relatively less polluted (LP) group basins with latent factors of 81.9, 3.14 and 0.858 (%) in the total water quality variance data sets. The water quality index analysis shows a mild effect on irrigation farming and aquatic species.

The results of water balance simulation show that mean monthly values were 28.6 m^3/s over the years with Nash-Sutcliffe Efficiency (NSE) values of 0.83 and a coefficient of determination (R^2) of 0.77 at validation stage. The Curve Number (CN) is the most sensitive parameter for the estimation of both streamflow and water yield within the catchment. Other water balance simulation ratios include: Streamflow/precipitation (0.4 mm); Baseflow/Total flow (0.67 mm); Surface Runoff/Total flow (0.33 mm); Percolation/precipitation (0.20 mm); Deep recharge/precipitation (0.01 mm) with an Evapotranspiration/precipitation ratio of 0.58 mm respectively. The water allocation results in the different dependable flow rates of 60%, 70%, and 85% reliability revealed it to be 17465.56, 8068.04 and 6373.35 (m^3/s) at U1H009 discharge station, respectively.

The synthesised literature rules suggest water allocation reform acts should be catalysed through the institutionalisation of capacity developmental platforms where climate change transformation experts and other stakeholders have input in legislating water reform acts, which should be supported by a strong political will.

The invented SD framework confirms agricultural water use as the highest demand when compared with other users. Its sustainability index was evaluated as the ratio of aggregated possible water demand relative to the corresponding supply in the same period. The result shows an integrated scenario which combines rainfall variation with improved irrigation water use efficiency and gives the optimal sustainability performance index (0.25) of the system at 70% dependable flow.

The simulated water balance results also reveal the use of scientific visualisation techniques in QSWAT to model spatially distributed and time-varying hydrologic-meteorological data sets in evaluating the water balance, while its calibration and validation in SWAT Calibration Uncertainty Procedure (SWAT-CUP) algorithm connotes a strong model efficiency performance.

The developed SD framework provides comprehensive assessment methodology for the decision-maker in assessing water trading. The applied integrated model can be used in similar river basins sharing related attributes to the study area in resolving the current water – stressed challenges in South Africa as well as other regions of the globe.

Considering the extent of the drought and the paucity of the uneven allocation of water resources at the study area, the needfulness of integrated hydrological models such as SWAT and ANNs cannot be overemphasised in ensuring the sustainability of Mkomazi Basin, while unlocking the untapped potential of water resources for the development of the agricultural and industrial sectors, and still meeting the requirements of the ecosystem.

DECLARATION

I hereby declare that the work reported in this thesis '**Integrated Hydrological Modelling for Sustainable Water Allocation Planning: Mkomazi Basin, South Africa Case Study'** is my original research work. All sources cited herein are indicated and acknowledged by means of a comprehensive list of references. I hereby certify that the work contained in this thesis has not previously been submitted either in its entirety or in part for a degree at this or any other university. Obvious similarities are prior publications and manuscripts that were prepared, compiled or published during the course of the research work, and they are cited accordingly.

Oseni Taiwo AMOO

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DEDICATION

This doctoral thesis is dedicated to all my Teachers, who believed in the nobility of their work and the sanctity of their covenant in service to humanity.

ACKNOWLEDGMENT

‘‘He released the two seas, meeting (side by side). Between them is a barrier (so) neither of them transgresses. So, which of the favours of your Lord would you deny?’’ Quran 55 vs 19-22.

Glory and Adoration belong to Almighty Allah, who made the completion of this thesis a reality. My indefatigable supervisor Dr. B. Dzwairo and my co- supervisor Prof D. Allopi (the unwritten mentor) for their painstaking role in proof-reading and ensuring technical accuracy of this work. Also, my indebtedness goes to Prof J.A. Adeyemo, for being my guardian during my study in South Africa.

This thesis has benefited from numerous workshop and conference participants at JGED, DUTPGCONF, ASABE, WASET, WISA, SAICE, WADER, RSC-Pan Africa Chemistry Network Congress and NIH, Roorkee.

I am grateful to the Centre for Science and Technology of Non-Aligned and Other Developing Countries (NAM S&T Centre) - India for the Fellowship award. I wish to thank the guardians Dr. S. Jain, Dr. P.K. Singh, and Dr. V.C. Goyal at the National Institute of Hydrology, Roorkee for their insightful comments and tutelage during the fellowship Training; it is well appreciated.

The financial assistance of the National Research Foundation (NRF) - South Africa towards this research outcome is hereby acknowledged. ‘‘Opinions expressed and conclusions arrived at are those of the author and are not necessarily to be attributed to the NRF’’. I am most grateful to the Postgraduate Research Support of Durban University of Technology, South Africa and National Water Resources Capacity Building Network, North Central Region, University of Ilorin, Nigeria for encouraging me to acquire international academic exposure.

I appreciate the support from South Africa's Water Research, Development, and Innovation (RDI) Roadmap: 2015-2025, Water Research Commission, the Department of Water and Sanitation (DWS), South African Sugar Cane Research Institute, South African Weather Service and Agricultural Research Council, South Africa, for their assistance in obtaining data and other information necessary for the completion of this research work.

My sincere thanks to the entire staff of the Civil Engineering and Geomatics Department, Durban University of Technology (DUT) for their supportive environment. Also, my sincere gratitude goes to the Faculty of Engineering and the Built Environment, the Dean, and members of the faculty for their support during the programme. May Allah (SWT) continue to strengthen you all and move the faculty forward.

I am grateful for the encouragement and guidance received from my friends: Bakre Olayemi, Taofeeq Abayomi, Bukunmi Fatoyinbo and Engr. Adeogun Abdulganiy, the Nigerian Muslim community in Durban, and Prof A.W. Salami with whom my journey to doctorate degree began. You are all much appreciated.

I greatly appreciate the patience of my darling wife, Hajia Hanifat Jimoh and my children throughout the period when I was away for international study. Your unflinching support and prayers are highly appreciated.

I am also indebted to several people who have provided assistance in one way or another during this study. It is impossible for me to list everyone. Some people have assisted me through manual and moral means and might even be surprised not to see their names mentioned here. To you all, I say *Jazakumullahu Khaeran*.

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LIST OF ABBREVIATIONS

AI	Artificial Intelligence
AIA	Agricultural Irrigation Area
ALPHA_BF	Baseflow Alpha factor
ANNs	Artificial Neural Networks
ARC	Agriculture Research Council
BaU	Business as Usual
CA	Cluster Analysis
CLD	Casual Loop Diagram
Cu.m	Cubic metre
CN	Curve Number
CMS	Catchment Management Strategy
CMA	Catchment Management Agency
CMC	Catchment Management Committees
DEM	Digital Elevation Model
DSS	Decision Support System
DUT	Durban University of Technology
DWA	Department of Water Affairs
DWAF	Department of Water Affairs and Forestry

DWS	Department of Water and Sanitation
EF	Environmental Flow
ELU	Exiting Lawful Use
FDC	Flow Duration Curve
FA	Factor Analysis
GLCC	Global Land Cover Characterization
GDP	Gross Domestic Product
GWP	Global Water Partnership
GW-DELAY	Groundwater Delay
GIS	Geographic Information System
HELP	Hydrology, Environment, Life and Policy
HRU	Hydrologic Response Units
HDI	Historically Disadvantaged Individual
IFR	Instream Flow Requirement
IHM	Integrated Hydrological Model
IWRM	Integrated Water Resources Management
KZN	KwaZulu-Natal Province
LULC	Land Use and Land Cover
MAR	Mean Annual Runoff

MAP	Mean Annual Precipitation
MRE	Mean Relative Error
MRB	Mkomazi River Basin
NSE	Nash-Sutcliff Efficiency
NWA	National Water Act, No 36 of 1998
NWRS	National Water Resources Strategy
PMB	Pietermaritzburg
RBM	River Basin Model
RBO	River Basin Organisation
RDP	Reconstruction Development Program
RQO	Resource Quality Objective
SAWS	South Africa Weather Services
SCS-CN	Soil Conversation Service-Curve Number
SD	System Dynamics
SFD	Stock Flow Diagram
SUFI2	Sequential Uncertainty Fitting-2
SVM	Support Vector Machine
SWAT	Soil and Water Assessment Tool
SWAT-CUP	SWAT Calibration Uncertainty Procedure
SWM	Sustainable Watershed Management
TDWD	Total Domestic Water Demand
TWQR	Target Water Quality Ranges
WEAP	Water Evaluation Assessment Programme

WAR	Water Allocation Reform (Acts)
WMA	Water Management Area
WSI	Water Sustainability Index
WUA	Water User Association

LIST OF PUBLICATIONS

A total of 18 research articles were prepared during this work. In all, seven journal articles and eleven conference papers were written. Four of the journal papers have been published, while the remaining three are under review in reputable academic journals at the time of compiling this thesis.

(1) Journals (Published, and under review)

(a) Peer Reviewed Journal Articles

1. **Amoo, O.** and Dzwairo, B. 2016. Trend analysis and Artificial Neural Networks forecasting for rainfall prediction. *Environmental Economics*, 7 (4): 254 - 266.

2. Salami, A.W. **Amoo, O.T**. Adeyemo, J.A., Mohammed, A.A. and Adeogun, A.G. 2016. Morphometrical Analysis and Peak Runoff Estimation for the Sub-Lower Niger River Basin, Nigeria. *Slovak Journal of Civil Engineering*, 24 (1):6-16.

3. **Amoo, O.T.** and Dzwairo, B. 2017. Hydrological Characterization of a Watershed for Stream Flow Prediction. *World Academy of Science, Engineering, and Technology, International Journal of Environmental, Chemical, Ecological, Geological and Geophysical Engineering*, 11 (5): 382-396.

4. **Amoo, O.T.** Fatoyinbo, B.S. Stretch, D. and Allopi, D. 2017. Catchment Yield Prediction in an Ungauged Basin Using PyTOPKAPI. *World Academy of Science, Engineering and Technology, International Journal of Environmental, Chemical, Ecological, Geological and Geophysical Engineering*, 11 (3): 271-278.

5. **Amoo, O.T.** and Dzwairo, B. 2017: Streamflow prediction in data-scarce catchment using Flow Duration Curve: Case study of Mkomazi Basin, (Under Review). *South Africa Institute of Civil Engineering Journal*.

6. **Amoo**, **O.T.** and Dzwairo, B. 2017: A study of water balances over the Mkomazi River Catchment, South African. (Under reviewed) *Journal of Agricultural Water Management.*

7. Bakre, O. **Amoo, O**. Garane, P. and Dorasamy, N.2018: Achieving the NDP 2030 agricultural agenda in uMzimkhulu: myth or possibility? (Under reviewed) *The Journal for Transdisciplinary Research.*

(b) Conference papers

8. **Amoo, O.T.** and Adeyemo, J.A. 2015: Water allocation in a watershed using Multi-Agent Methodology (Ref no JGED2015/007). Abstract proceedings of the Journal of Green Economy & Development's (JGED) 2nd Annual International Conference, Makaranga Lodge, Kloof, Durban, South Africa, 8-10 July 2015.

9. **Amoo, O.T.** and Adeyemo, J.A., 2016: Impact assessment of water allocation plan on the composition and diversity of aquatic species over Mkomazi River Basin, South Africa, (ISEM2016_0284) The International Society for Ecological Modelling Global Conference 8-12th May 2016, Baltimore (USA). http://www.elsevier.com/global-conferences.

10. **Amoo, O.** and Dzwairo, B. 2016: Trend analysis and Artificial Neural Networks forecasting for rainfall prediction. Abstract proceedings of the Journal of Green Economy & Development's (JGED) 2nd Annual International Conference, Salt Rock Hotel, Durban, South Africa, 15-18 July 2016.

11. **Amoo, O.T.** and Dzwairo, B. 2016: Sustainable water use under changing climate variability and land use for global food security: a case study of Mkomazi Basin, South Africa. Abstract proceedings of the American Society of Agricultural and Biological Engineers (ASABE). Theme: Engineering and Technology innovation for global food security, 24-27 October 2016, Stellenbosch, South Africa.

12. **Amoo, O.T.** and Dzwairo, B. 2016: Epistemology paradigm shift from technologically based solution to climate change and human capacity building for sustainable development, South Africa. Abstract proceedings of the 1st DUT postgraduate international interdisciplinary conference, 3-5 October 2016.

13. **Amoo**, **O.T.** Dzwairo, B. and Allopi,, D. 2017: Socio-Economic Perspective to Water Allocation in a Watershed using the Multi-Agent Methodology, Abstract proceedings of the 2nd DUT Interdisciplinary Research, Innovation, and Postgraduate Conference. Theme: Enhancing Multidisciplinary Research in Innovation and Entrepreneurship for Emerging Researchers 13–15th June 2017, Durban, South Africa. Submitted to *Interdisciplinary Journal of Economics and Business Law (IJEBL)*

14. **Amoo, O.T.** and Dzwairo, B. 2017: Water Allocation Management in the Mkomazi River Watershed using System Dynamic Model (Accepted for conference) 14th IWA Specialist Conference on Watershed and River Basin Management, Skukuza Kruger National Park, 9-11 Oct 2017, South Africa.

15. **Amoo, O.T.** and Dzwairo, B. 2017: Multivariate Statistical Evaluation of Surface Water Quality: Water and Health Issue. (Accepted for conference) 8th International Young Water Professionals Conference, 10-13 December 2017, Cape Town, South Africa. Towards IWA Science and Technology Journal.

16. **Amoo, O.T.** Dzwairo, B. and Allopi, D. 2017: Seasonal Pattern Analysis and Forecasting Hydrological Flow Regime: (Accepted for conference) WISA 2018 Bi-annual conference, Theme: 'Breaking barriers, Connecting ideas', CCICC, Cape Town, 24-27 June 2018. South Africa.

17. **Amoo. O.T.** and Dzwairo, B. 2017: Schaakle Shuffle Ensemble Method for Rainfall Post Processes Forecast, (Accepted for conference) 8th International Young Water Professionals Conference, 10-13 December 2017, Cape Town, South Africa.

18. **Amoo. O.T.** Allopi,, D. and Dzwairo, B. 2017: Towards Evolving Smart Cities Inudation Indices Map (Accepted for conference) 2nd International Peri-Urban Conference; 26-29 Nov. 2017 at Century City Conference Centre, Cape Town, South Africa.

(c) Edited Technical Reports:

Amoo, O.T. Dzwairo, B. and Singh, P.K. 2017: Hydrological Prediction for Drought and Desertification Control in Southern Africa: (Accepted) for the Centre for Science & Technology of the Non-Aligned and Other Developing Countries (NAM S&T Centre) in conjunction with Ferdowsi University of Mashhad (FUM). International Workshop on Drought Management and Desertification Control at Mashhad, Iran, 22–24 May 2017.

CHAPTER 1: OVERVIEW

1.0 Introduction

This chapter provides background information enabling the reader to understand and appreciate the interdisciplinary nature of this research within a larger theoretical framework of integrated water resources management. After placing the work in a broader context, the chapter outlines the aims, objectives and limitations of the study, and poses specific questions to be answered by the study. The applied methodology follows a brief outline of the dissertation and finally, it provides an outline of some manuscripts that were prepared, compiled or published during the research work.

1.1 Integrated watershed management

Water is a fundamental requirement for maintaining life and ensuring prosperous societal growth. However, the allocation of water among the contending different users and uses has been a challenge in most river basins of the world, especially in semi/arid regions (Shah, Makin and Sakthivadivel 2005). The occurrence, transformation and uses of water have been a complex and sensitive issue that affects many facets of life. Recent climate change and resultant drought conditions have caused remarkable fluctuation in water quantity and quality between wet and dry seasons (Dai 2013). Apart from causing watersheds to experience water scarcity which has economic consequences, climate change poses a serious threat to the temporal and spatial availability of the resources, besides other associated effects.

Many water researchers are of the opinion that sustainable development and management must be supported by the carrying capacity of the available water resources in promoting socio-economic growth, reducing poverty and offering added value to the depleted environment (Syme and Hatfield-Dodds 2007; Pearson *et al.* 2010; Patil and Stieglitz

2012; Pegram *et al.* 2013), especially in a river basin where erratic climate variability prompts [more] much evaporation occurrence compared to precipitation (Dai 2013).

Integrated hydrological modelling (IHM) presents a microcosm of a typical overarching vision for managing catchment on a local scale, with a socio-economic, event-based process of cause and effect. IHM encompasses the earlier Coupled Human And Natural Systems (CHANS) approach, which addresses many complexity aspects such as feedback, nonlinearity, heterogeneity, and emergence behaviour (Bonabeau 2002) use in managing watershed. It views the catchment system as a holistic dynamic interacting component of Hydrology, Environment, Life (aquatic) and Policy (HELP) (Donigian Jr *et al.* 1995; Matondo 2010; Wagener *et al.* 2010; Sivapalan, Savenije and Blöschl 2012; Bergstrom and Randall 2016).

Chartres and Varma (2011) advocated sustainable water allocation planning in arriving at and deciding on an equitable and acceptable water distribution among the various contending users and uses. This view has superseded an earlier environmental flow assessment concept that identifies a minimum flow regime. The evolving water allocation planning considered these requirements together with other socio-economic users' demands.

Interestingly, the growing body of sustainable development research works suggest that integrated hydrological modelling is the most viable approach in addressing today's and future water concerns (Louks 2000; UNW-DPC 2010). Integrated hydrological modelling has played a key role in the development and understanding of the cyclical movement of water through the environment (Jonker 2007). Integrated hydrological modelling provides a comprehensive approach which may closely investigate how water, the environment and human activities are mutually dependent and interactive (Watson and Burnett 1995). Few studies have attempted to integrate the hydrologic system dynamics with socio-economic challenges. Most of the existing studies are customised and basin-specific (Bergstrom and Randall 2016).

Among the plethora of available tools used to forecast and predict the quantity and quality of water for decision makers is hydrological model (Chow, Maidment and Mays 1988). Some of these models could also predict the impacts of natural and man-made anthropogenic activities on water resources. The quantification of spatial and temporal availability of the water resources for South Africa cannot be over-emphasised for a country that has been classified as a water-stressed country and the 30th driest in the world (Matondo 2010). Major actors and researchers have not been left out in formulating various policies and strategies towards ensuring continuous availability of water.

Developing countries are confronted with a daunting shortage of water and environmental degradation (Hawkins 2010; Hove, Ngwerume and Muchemwa 2013). Most water problems in the world's basins arise due to water demand exceeding the limited supply, thus the need to reform water allocation is urgent, regardless of the many unanswered questions regarding the feasibility, costs and likely environmental impact consequences (Charania, Geoinformatics and Charania 2005).

Before resources allocation and benefit for economic growth in the developing world were considered, water resources development activities were only associated with meeting the needs of the environment and the people (Sterman 2012; Roozbahani, Schreider and Abbasi 2013). The bulk of the water abstracted is allocated to irrigating agriculture (Rosegrant and Meinzen-Dick 1996; Sutherland *et al.* 2014).

In most developing countries, the level of investment in water resources development is borne by the state (Richter *et al.* 2003; Reyers *et al.* 2009). The state formulates and enforces legislation regarding the use of water, while paying close attention to water-related concerns, such as water-borne diseases and flood control. This has often given rise to the governmental sector playing a dominant role in the administration of water allocation (World Bank Water Demand Research Team 1993; Taylor 2000; Tajziehchi *et al.* 2013; Taylor *et al.* 2013; Umgeni Water 2015a).

Integrated watershed management is an emerging field reported to date (Di Baldassarre *et al.* 2013; Elshafei *et al.* 2014; Kandasamy *et al.* 2014; Liu *et al.* 2014; Sivapalan 2015). It uses simulation modelling techniques in addressing the management of water resources. It measures the river basin system behaviour over time (Sivapalan, Savenije and Blöschl 2012). The most important stage in integrated water resources studies is the conceptualisation phase because it provides the basic understanding of influence points for reasonable solutions (Amisigo, McCluskey and Swanson 2015).

The most popular water distribution approach is the priority quantity based and equity supplies based approach to domestic, irrigation and ecosystem demand (Weragala 2010; Wescoat 2013; Wang and Huang 2014). Both methods contribute to improve gross domestic product (GDP), provide food security, and ensure public and environmental health (Meinzen-Dick and Mendoza 1996; Bergstrom and Randall 2016). However, the priority quantity based is the most notably administrative technique employed in the developing world. This method allocates water in a preferential order. This has been attributed to several state objectives geared towards greater socio-economic development, independence and the sustenance of greater public good (Dinar, Rosegrant and Meinzen-Dick 1997; Thompson *et al.* 2001; Yates *et al.* 2005b; Sutherland *et al.* 2014).

The variety of objectives associated with public water allocation requires the assignment of priority directives. However, the prioritised public water allocation has been widely critiqued for its inability to ensure efficient water usage. The core reason behind this has been the lack of institutional incentives (Bergstrom and Randall 2016).

Collet *et al.* (2015) also stated other reasons for its criticism to include: unassertive decision guidelines during inter-sectoral allocations, political undertones, inordinate pricing structure, lack of synergy among sectoral units as well as the scope for rent-seeking amongst employees of the agency.

Considering the economic scarcity of water, the equity-aspect of water allocation is given less attention in comparison to the efficient-aspect. This represents a new transition towards formulating a framework for pricing water and inputs that affect water quality (Berbel and Gómez-Limón 2000; Hassanzadeh *et al.* 2014).

According to Hawkins (2010), the agenda behind an efficient water allocation is to derive maximal economic gains amongst the basin’s users. Achieving such efficient water allocation will imply apportioning water to the most beneficial users. Hawkins (2010) further advocates that facilitating an efficient allocation will require a voluntary exchange wherein water rights will be transferred from less efficient users to the more productive and high efficient water users. Unfortunately, negotiations and discussions around market-based water allocation on river basins among under-developed nations often do not exist are or very uncommon (Hellegers and Leflaive 2015). This has been attributed to political constraints, technological impoverishment and operational costs. Some of these are considered as the main reasons for the inappropriate defining of water rights. Hence, it is anticipated that the present priority-based allocation structure will be continuously utilised across several basins for years to come.

To this end, this study offers a dependable level of reliability method with the Soil and Water Assessment Tool (SWAT) as an integrated system modelling tool for decision support in managing a watershed (Vladimir.V and Nikolic 2012; Daggupati *et al.* 2016).

This study investigates the application of an integrated hydrological model in a Geographical Information Systems (GIS) environment for sustainable water allocation planning and management. It uses a simulation technique in achieving equitable water distribution while deriving large benefits from water uses across the basin's communities and users.

The employed methodology is a mixed design approach. It consists of theoretical aspects of the subject matter used in conjunction with practical field documentation records collected from selected stakeholders. In addition, data was gathered from relevant agencies as well as satellite sites. This data was used to evaluate the sustainability scenarios in managing the water allocation system under the current disposition (priority-based mechanism).

1.1.1 Water resources management in developing countries

Most developing countries had feasible water management blueprint policies with achievable national development programmes towards managing their river basins. However, transforming the theoretical content of these policies into practice had always been problematic in resolving the continuous conflict in meeting growing water demand at the expense of limited supply. This at best had been achieved in most developed countries' river basins, although it takes decades and sometimes centuries of gradual change to develop and implement (Merrey *et al.* 2005). Thus, developing countries can learn from developed countries' experience in managing their river basins. Both share many similarities in their socio-economic activities despite their great differences in demography and hydrologic conditions (Pearson *et al.* 2010; Pegram *et al.* 2013).

Jain and Singh (2003) suggest a system of trade-offs between various demands that maximises its benefits and still maintains the basin's overarching goals of development.

Developing countries only need to modify the transferred technology and innovation for local adaptation. This shared similarity index in water challenges allows a common set of questions like the following to be answered:

What is the institutional framework needed to develop and manage the basin's water resources? How should water be allocated to various users in times of shortage? How much of a watershed area could be managed in an integrated manner to guard against water scarcity? How will allocation, operations, and operating constraints change if new management strategies are introduced into the system? How will the hydrological responses affect climate change/ variability, population growth and land cover in the upstream-downstream catchment area?

This study examines how answering the above questions can help in articulating a best practice water management plan. The prefecture of Mkomazi River Basin located in KwaZulu-Natal Province of South Africa is based on recent weather events characterised by the non-homogenous distribution of rainfall (climate change impact), recent economic development and an on-going water augmentation transferring scheme to another basin (Jonker 2007). Thus, this development calls for a decision support tool for sustainable water use in the basin. A conservative integrated framework for sustainable water allocation planning was formulated for the basin using the simulated water balance to identify viable water supply and demand scenarios (Bergstrom and Randall 2016).

This study aims to assist with the work of the much larger catchment management agencies in South Africa as set out in the National Water Act of 1998, in terms of which the major objectives of the research have been tailored (DWA 1998). The novel feature of this study lies in its ability to mimic and absorb the multidisciplinary interrelationships common to the hydrologic, agronomic and economic components of a water system (Donigian Jr *et al.* 1995; Matondo 2010; Wagener *et al.* 2010; Sivapalan, Savenije and

Blöschl 2012; Bergstrom and Randall 2016). Water allocation is one component of a wider government mandate to address the inequities of the past. The allocation and reallocation of raw water to Historically Disadvantaged Individuals (HDIs) in communities for productive purposes has not progressed as quickly as it should have done.

The KwaZulu-Natal (KZN) Province subscribes to the broad objectives of water allocation as defined by DWS on the beneficial use of water and that water allocation should promote:

- Sectorial water balance
- Creation of jobs
- Social development and stability
- Equitable access to water
- Protection of aquatic ecosystems
- Efficient and non-wasteful use of water
- Economic growth and
- Investor confidence" (Department of Water Affairs 2013).

1.1.2 Development of integrated water resources management (IWRM)

Many researchers around the world have considered various aspect of water resources management (Venugopal, Giridharan and Jayaprakash 2009; Mahmoudi *et al.* 2010; Nasrabadi *et al.* 2010; Pamer *et al.* 2011; Feng *et al.* 2012; Ghaderi *et al.* 2012; Guinder, Popovich and Perillo 2012; Feizizadeh *et al.* 2013). The idea of integrated management of land and water resources or the use of the river basin as the most appropriate management unit is not new, but it is only in recent times that it has become an internationally accepted principle (Barron, van Andel and Pollard 2003; Biswas 2004b). The concept of integrated water resources management (IWRM) became acquainted with the International Water Resources Association some 30 years ago (Braga 2001).

Rasi Nezami *et al.* (2013) viewed IWRM as 'a systematic process in the context of social, economic and environmental objectives for the sustainable development, monitoring, and allocation of water resources'. The main objectives of IWRM are: to derive optimum benefit from a bearable source of water supply, which supports the catchment's growing population in satisfying their personal needs, allowing them to undertake their socio-economic activities without inflicting undue damage on the environment and subjecting them to minimal natural disasters impact [caused by] the environment (Prodanovic and Simonovic 2010).

Gleick (2014) views the concept of IWRM as 'Equitable access to sustainable use of water resources by all stakeholders at catchment, regional and international levels, while maintaining the characteristics and integrity of water resources at the catchment scale within agreed limits'. Similarly, the contribution by the Global Water Partnership (GWP) defines IWRM as 'a process that promotes the coordinated development and management of water, land and related resources, in order to maximise the resultant economic and social welfare in an equitable manner without compromising the sustainability of vital ecosystems' (Nowreen, Khan and Huq 2011).

As a way to approach the management of water resources in a given geographical context holistically, IWRM is viewed as a systematic process for the sustainable development, allocation and monitoring of water resources, which promotes more coordinated management of the river basin, land, water, upstream and downstream interests (UNW-DPC 2010). More recently, IWRM models combine the natural hydrologic cycle with the human-water interaction in technical, socio-economic, and political components (Labadie, Baldo and Larson 2000; Zagona *et al.* 2001; Zoltay *et al.* 2010). Integrated water resources management was introduced in order to optimise the use of water in a basin (Rahaman and Varis 2005; Muller 2015). A key element of IWRM is that catchments are usually the most appropriate physical units on which to plan the management of water. Thus, the use of integrated modelling tools evolves as watershed and river basin management tools.

1.1.3 Domestication of IWRM in South Africa

The process of IWRM starts with the identification of the basin goals, an assessment of water resources issues, and a demographic and climatic conditions assessment, which leads to an IWRM plan proposal in formulating water resources policy /strategy; stakeholder participation and re-evaluation of the IWRM plan stages. Although IWRM should not be taken as the ultimate solution to river basin challenges as highlighted in some reviews (Biswas 2004b; Jonker 2007; Dzwairo, Otieno and Ochieng 2010) in South Africa there are example basins where it has provided structure for water management. The Internal Strategic Perspective (ISP) for the Olifants River Water Management Area (Jonker 2007; Moseki, Tlou and Ruiters 2010) is one such document which focuses on IWRM.

The IWRM building blocks consist of the existing lawful use of water availability, water reserves and the future water requirement scenarios. The process uses the building blocks through a public participation process resulting in installed modelling systems, a water allocation schedule, management class, resource quality objectives (RQO) and the Catchment Management Strategy (CMS) (DWAF and Department of Water Affairs and Forestry 2004). It started with the development of the CMS, governed by the direction given by the National Water Resource Strategy (NWRS) as well as policies and guidelines developed by the Department of Water Affairs and Forestry (DWAF) (Nepfumbada and Muller 2012).

The National Water Resource Strategy 2 (NWRS-2) addresses concerns that the socio-economic growth of South Africa will potentially be restricted if water security, resource quality, and associated water management issues are not resolved in time.

It thus obliges the DWA (1998) to legislate that a Catchment Management Agency (CMA) was set up in each of the 19 Water Management Areas (WMA) in 2004. This was further reduced to 9 WMA in 2012; before a single CMA was formulated in 2017 (DWS, 2017). The CMA of the country were to see to the management of the water while the Department of Water and Sanitation (DWS) will develop policies and regulate guidelines on what should be addressed in the CMS (Fisher-Jeffes, Carden and Armitage 2014).

The CMA structure allows for the establishment of catchment management committees (CMC) which allow for representation and communication between water users and the CMA. The CMA structures directly oversee the management of water within a WMA (DWAF and Department of Water Affairs and Forestry 2004; Coleman, van Rooyen and Görgens 2007).

1.2 Statement of the problem

Although institutional and legal mechanisms for cooperation among the riparian users in the basin have been in place since 1998 when (CMA) was created to manage and develop the water resources on the basin in a sustainable way, comprehensive water allocation planning for the basin has not been developed to date. This has brought to the fore the need to develop a mechanism for water resource allocation planning in the basin.

The severe drought (Thompson *et al.* 2001; Van Koppen and Jha 2005; Hove, Ngwerume and Muchemwa 2013) and its attendant problems have contributed to the severe consequences on the status of the Mkomazi River and its tributaries, biodiversity, landscapes, key habitats, and floodplains. This has caused considerable pressures on the ecosystem and resultant conflicts over water resources allocation among its riparian users.

The study area is central to a sustainable water supply to the Mkomazi region and KwaZulu-Natal Province. There is strong competition for their water resources to be supplied to irrigation sites, commercial afforestation, tourism and recreational activities, as well as the paper production industry, which exists near the Mkomazi River mouth with little consideration for the immediate communities' survival. Recent rapid agricultural and economic development in the basin following the completion of the Mkomazi Dam and water transfer infrastructures has led to the increasing competition among the riparian communities for Mkomazi water.

There is now a growing concern that policies for sustainable water use, environmental quality and efficient allocation of the available water resources should be implemented, particularly in the study area (Uitto 2004; Crowley and van Vuuren 2013). This development calls for a structured strategy that includes efficient, equitable, and environmentally sustainable water allocation rules that support the socio-economic development in the basin.

1.3 Study aim and objectives

The aim of the study was to investigate the application of an integrated hydrological model in a Geographical Information Systems (GIS) environment for sustainable water allocation planning and management.

1.3.1 Specific objectives:

1. To examine the trade-off among users by identifying the basin ecosystem dependants and analyse the surface water quality index rating.

2. To propose water allocation mechanisms to achieve equitable water distribution and large benefits from water uses across the basin's communities and users.

3. To synthesise rules for sharing limited water resources towards operational analysis for environmental flows estimation

4. To establish a framework for water trading in order to encourage water use efficiency and allow movement of water to new users.

1.4 Rationale and justification for the study

South Africa is a water-stressed country and the 30th driest in the world (Jonker 2007; Crowley and van Vuuren 2013; Dai 2013; Hove, Ngwerume and Muchemwa 2013), and has not been left out when various policies and strategies towards ensuring continuous availability of water are being formulated.

The Mkomazi River was selected for evaluating and developing a sustainable framework for water allocation planning due to the following reasons:

- The climate of the characterized basin is seasonal with dry winters and summer rainfall season as Mean Annual Precipitation (MAP) varies between 700 and 1200mm $year^{-1}$ with high intra- and inter-seasonal streamflows fluctuation (Flügel *et al.* 2003).

- Currently, adequate water resources are available in the wet season to fulfill the basic needs, but there are regional water shortages during the dry season when there is a restriction on intakes to reduce the amount of water to be allocated to the downstream communities when the water reaches the minimum flow level (Taylor, Schulze and Jewitt 2003).

- Due to the increased demand for water in the Pietermaritzburg (PMB) and urban regions, it was concluded from a pre-feasibility study conducted by the Department of Water Affairs (DWA) that two potential impoundment sites

(Impendle and Smithfield) located in the upper-middle Mkomazi catchment be identified and proposed for the actualisation of the Mkomazi-Umgeni water transfer scheme (DWA 1999b, 2004).

- Despite the fact, there exist an abundance of water resources almost all the year round (DWA 2009). This has not been adequately harnessed for sustainable supply among its competing beneficiaries of the Mkomazi River, (irrigation, commercial afforestation, tourism and recreational activities), as well as the paper production industry which exists near the Mkomazi River mouth with little or no consideration for the ecosystem survival and the immediate surrounding communities (Umgeni Water 2015a).

1.5 Research methods

The employed mixed design research methodology is as presented in the flowchart (Figure 1) and outlined thus: fieldwork (archive documentation records, information gathering, analysis, and interpretation) and desktop (works of literature review and satellite image analysis for water balance, and water allocation scheduled). Microsoft Statistical software Excel and XLSTAT by Addinsoft was used for statistical data capture and analysis.

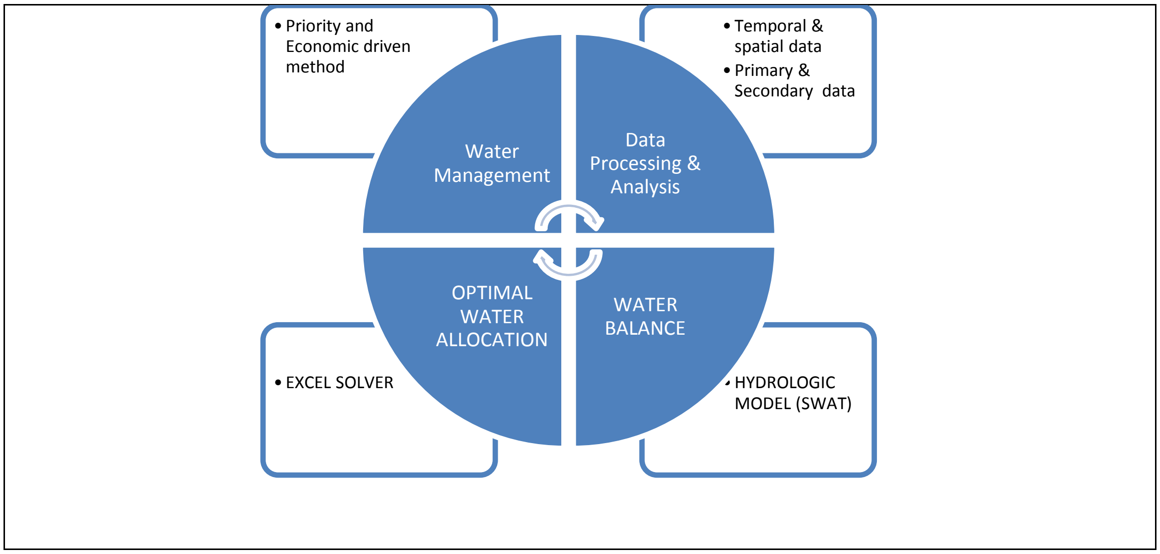

Figure 1: Sustainable IWRM framework for water allocation planning

To this end, detailed research methodology entails the division of the basin (hydrological and administratively) and its morphometric analysis using a GIS-based distributed watershed model, Soil Water Assessment Tool (SWAT) to estimate daily river water discharge in developing a water balance for the basin. The model combines topography, land use and soil maps, with observed daily meteorological time series to predict discharge hydrographs and spatial distribution of hydrological water balance for the catchment; this serves as the basis for initiating a system for allocating the existing resources (streamflow).

Assessment of existing and future water needs was done through collected population and users' daily water demand. Allocation of the resources was based on river dependability yield, computed from analytical hierarchical (priority and equity) factors. The SWAT-CUP optimisation algorithm was used in calibrating and validating the model. It also simulated and validated the available water, which was used for projecting future demand.

1.6 Scope of the study

The scope of the study was limited to the following areas:

1. The application of different multivariate statistical techniques to examine the trade-off among users by identify ecosystem, and rating the surface water quality index into pollution strength for their environmental and public values benefit preservation.
2. The evaluation of hydro-meteorological trend characterisation and its influence on the river basin.
3. The use of an artificial neural networks (ANNs) model for rainfall and streamflow forecasting.
4. The application of a semi-distributed hydrological model such as SWAT for water balance and catchment yield quantification.
5. The establishment of a system dynamics framework for sharing water between human and environmental needs.
6. Examining the trade-off among users in maximising the benefits (social, environmental, and economic) of water to the community.

1.7 Limitation of the study

This study considered surface water only. The quoted value in figures and tables was limited by the accuracy of secondary data and thematic satellite data collected from different agencies.

Also, the original intention of site diagnosis of problems and the organization of a minimum 2-day workshop with water managers (the officials of Department of Water and Sanitation (DWS), Durban and water user’s associations has been quite difficult due to their different official scheduled meetings and limited fund availability for the study.

Hence, archived documentations and reviewed records were gathered at different time with selected DWS conferences participant and water users during conferences participation.

The derivation of the acceptable trade-off for optimal basin water allocation to the community was also limited to current market price for evaluating the maximum net benefit in water uses. The uneven spatial distribution of both the rain gauge and stream gauge networks constrain hydrological simulation modelling, thereby limiting the spread and quality of data used. The bulk of information used in this thesis relied mostly on an extensive literature review and downscale globally satellite data which has many challenges.

1.8 The study area

The Mkomazi Basin is situated within the semi-arid area of KwaZulu-Natal Province in South Africa (Figure 2) and is the third largest in the province. The basin covers the entire numbered U Quaternary Catchments. It stretches 170 km from 3300m altitude in the northwest to sea level in the southeast (Taylor 2001; Taylor, Schulze and Jewitt 2003). The river catchment discharges into the Indian Ocean, draining an area of about 4 400km^2. It derives its source from the upper Drakensberg Mountains. ‘‘The Mkomazi Basin is characterised by steep gradients of altitude and rainfall; highly variable land uses as well as intra- and inter-annual streamflow variability’’. Despite the unevenness of the streamflow, the mainstream Mkomazi River, as well as most of its tributaries and its headwaters, is perennial under present climatic conditions (Oyebode, Adeyemo and Otieno 2014). A detailed description of the study area is presented in Chapter Three.

Figure 2: Mkomazi Basin in relation to South Africa

Source: ESRI ArcGIS 10.3.1 Software and online web base map

1.9 Outline of the thesis

This thesis comprises some of the manuscripts that were published, under reviewed and/or presented in conference proceedings. It is organised into six chapters. Chapter One presents the background knowledge of IWRM and the needs for integrated model assessment for sustainable water allocation. It highlights the project aim and objectives and a more detailed explanation on the need for the study follows in subsequent sections. Chapter Two provides the reader with theoretical IWRM background information and elucidates more on the emerging methodologies. It illustrates the trend in the model's application to river basin planning and management. The objectives, possibilities and limitations of some of the available models were subsequently examined. This information was synchronised in developing a framework and the selection of appropriate models suitable for the case study area.

Chapter Three details the study area description (Mkomazi River Basin). It examines the socio-economic and environmental consequences of water regulation on both the quality and quantity of water in the catchment.

Chapter Four elaborates on the employed research methodology in achieving the research objectives. It begins with the hydrological data process, modelling factors that affect water allocation, evaluates water balance, dependable water allocation and the subsequent trade-offs between environmental sustainability and water use. The hydrological model (SWAT) interface in GIS environment was used to evaluate the available water and provide details for a practical application to water allocation problems in Mkomazi River Basin.

Chapter Five presents the obtained results and discussion on the research objectives starting with objective 1 on the application of different multivariate statistical methods to examine the trade-off among users by identify ecosystem and rating the surface water quality index into pollution strength; followed by objective 2 on water allocation model's simulation, its sensitivity and calibration analysis. The research objectives 3 and 4 synthesise rules for sharing limited water resources and establishing a framework for water trading.

Chapter Six presents the conclusion and recommendations for future research.

CHAPTER 2: LITERATURE REVIEW

2.0 Introduction

This chapter presents a literature review relevant to the aim and objectives of the study. The chapter examines the epistemological stance and the evolving knowledge on the Integrated Water Resources Management (IWRM) concept. It discusses the underpinning philosophies in modelling a river basin, development of water allocation policies, and the evolving catchment management strategy. This is followed by a review of some selected integrated hydrological models that are particularly related to water allocation and shared resources benefit. The literature reviews consist of past related work on developing sustainable water allocation planning, methods of water allocation, a framework for water rights, and modelling of an equitable, priority-based water allocation. This is followed by sections that deal with existing South African water regulation Acts and licensing by the Department of Water and Sanitation (DWS). This section ends with the summarised rules regarding water allocation, shared resources benefit and the articulation of existing policy for sustainable water allocation planning.

Subsequent sections examine the concept of simulation, optimization, and mass-balance scenario-based methods employed in the research for sustainable water allocation management in a watershed. Based on the reviewed literatures, a methodological framework for conducting a sustainable water allocation management model in a watershed was developed. The invented framework was subsequently used to gain an understanding of the current state of research on a sustainable watershed management (SWM) model, which highlights areas of concern (knowledge gaps) upon which this study was premised and applied to an annotated Mkomazi Basin case study area, KwaZulu-Natal Province, South Africa.

2.1 Significance of water allocation planning

The increasing severe damage and sustained nature of the recent drought in some parts of the globe have resulted in the need to conduct studies relating to sustainable water allocation and management (Taylor, 2001). Water allocation planning is a set of rules for the sustainable use of water resources. The rules are required to establish a framework for sharing water between human and environmental needs. It involves a detailed framework that must enjoy coordination and cooperation among the riparian users if it involves two or more countries across the catchment border (Irene, Consuelo and David 2013).

Water allocation planning is required for improved water resources management. It provides management with tools for efficient and gainful utilization of water and other natural resources (Bergstrom and Randall 2016). This serves as a roadmap for water policy makers in preparation for disaster/calamities. It is usually based on sound scientific principles integrating nature and man (Biju 2011). Sadoff and Grey (2005) state that cooperation and mutual understanding are required among the riparian users in deriving net benefit value of water to the community. Adequate water allocation planning efforts are linked to alleviating poverty and human vulnerability. It is of the utmost use for institutional framework development, policy agreement and programme design for water sharing (Scheumann and Neubert 2006).

2.2 Integrated water resource management

It is apparent that water resources are vulnerable and the sustainable development of human society depends on managing it wisely (Araral and Wang 2013). Integrated watershed management (IWM) advances the studies of hydrological variations in time and space in conjunction with socio-economic impact on the catchment system (Hellegers and Leflaive 2015).

IWM aims to establish a feasible framework for efficient land and water use in meeting both human and ecosystem needs. The IWRM concept generates, reviews and adapts to changing concepts of water rights in balancing between societal water demand (Biswas 2004a; Bithas 2008). Integrated water resources management (IWRM) attempts to coordinate and balance human activities in a given watershed between the competing water demands in a way that optimises benefits and enhances equity (Kragt *et al.* 2011). Figure 3 illustrates the concept of integrated water resources management while Figure 4 depicts a framework for sustainable water use.

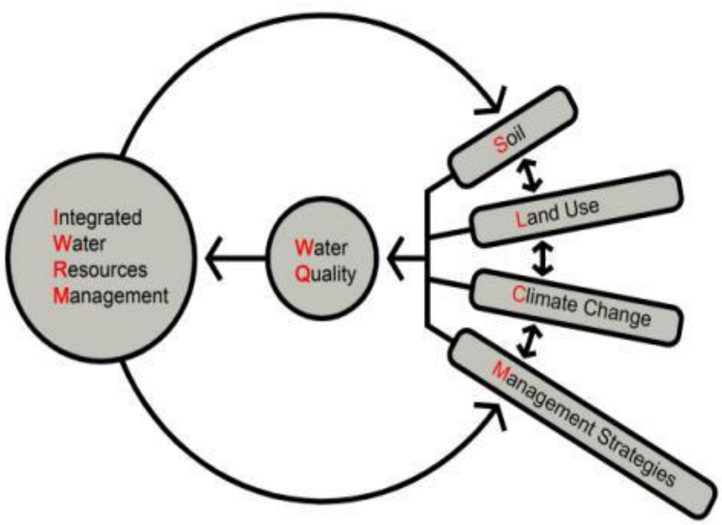

Figure 3: Concept of integrated water resources management

Adapted: http/ www.sswm.info/category/concept/iwrm (2017)

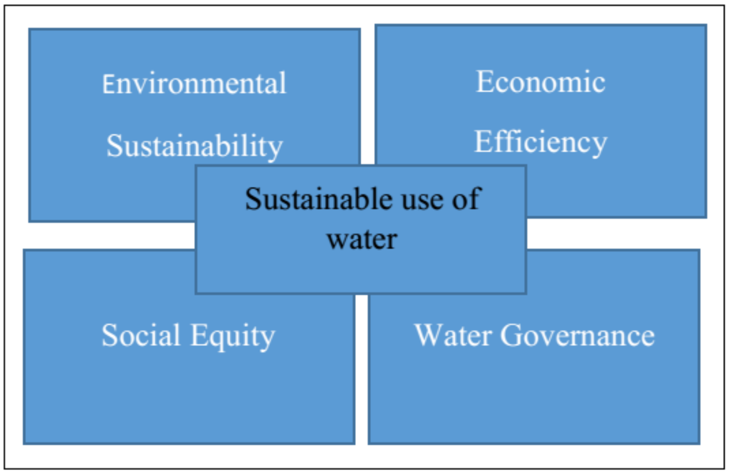

Figure 4: Framework for sustainable use of water

Adapted: http://www.thewaterchannel.tv/gender/content/chapter1/1_1.html (2017)

Simonovic (2009) suggests seven guiding principles as a practical guiding rule for scientific investigation of IWRM. They include:- ‘systems view, integration, partnership, participation, uncertainty, adaptation, and absolutely reliable data’. Each principle intends to bring further clarity to the IWRM process; however, the underlying basis that encompasses them all is the ‘systems concept’.

Ross (2014) arrived at the following definition of a system after aggregating nine different definitions: ‘‘A system is a group of elements, either physical or non-physical in nature, that exhibit a set of interrelationships among themselves and interact together towards one or more goals, objectives or ends’’. Sustainable water resources allocation planning views the catchment unit as a system mechanism, described by many phenomena. A system may be displayed as shown in Figure 5.

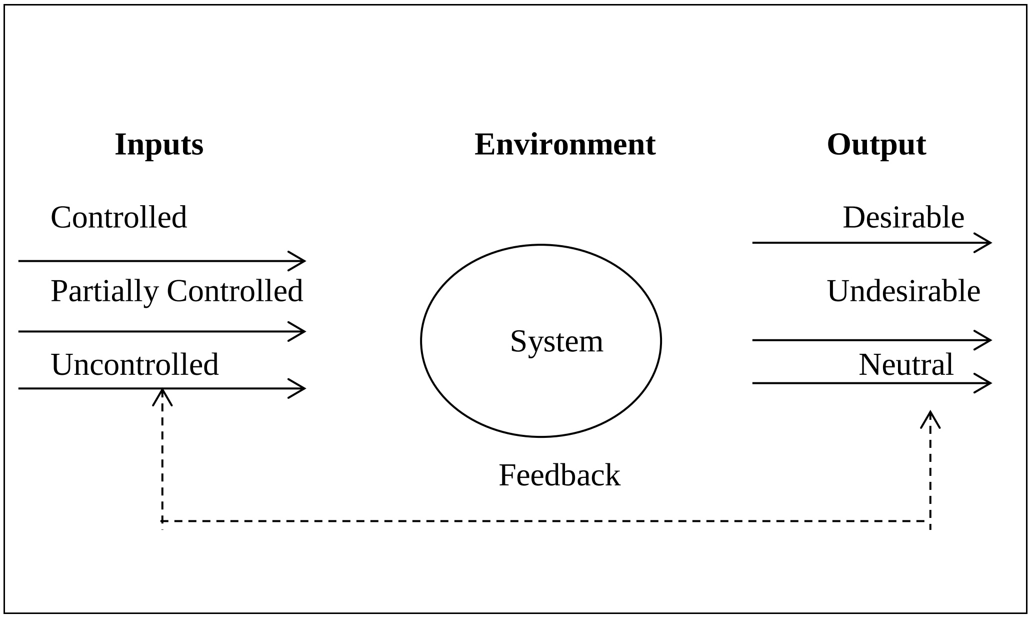

Figure 5: Model of the system

Source: Nandalal and Simonovic (2002)

As shown, the system is carved out of its environment. The feedback shows a possible external interaction between inputs and outputs. This concept is applied to the socio-hydrological response of a river basin and the interrelations between water uses and basin water users. A system analysis brings clarity in value estimation for water users in the system (Heinz *et al.* 2007). It makes the concept of modelling to be an interacting component of Hydrology, Environment, Life (aquatic), Policy and Sensitivity (HELPS) and a collective response of the basin (Sokile, Kashaigili and Kadigi 2003; Sivapalan, Savenije and Blöschl 2012; Bergstrom and Randall 2016).

The Pressure-State-Response (PSR) framework (Figure 6) also expatiates the system modelling of the socio-hydrologic interaction elements. It views the non-directional cause and effect of various human and natural activities on the environment. The exerted pressure on the environment reciprocates through administrator sectorial policies reform and a behaviour awareness campaign.

Thus, it helps both decision makers and the public in recognising environmental and other issues as interconnected. This framework approach addresses many complex aspects such as feedback, nonlinearity, heterogeneity and emergence behaviour (Bonabeau 2002; Matiwane 2012).

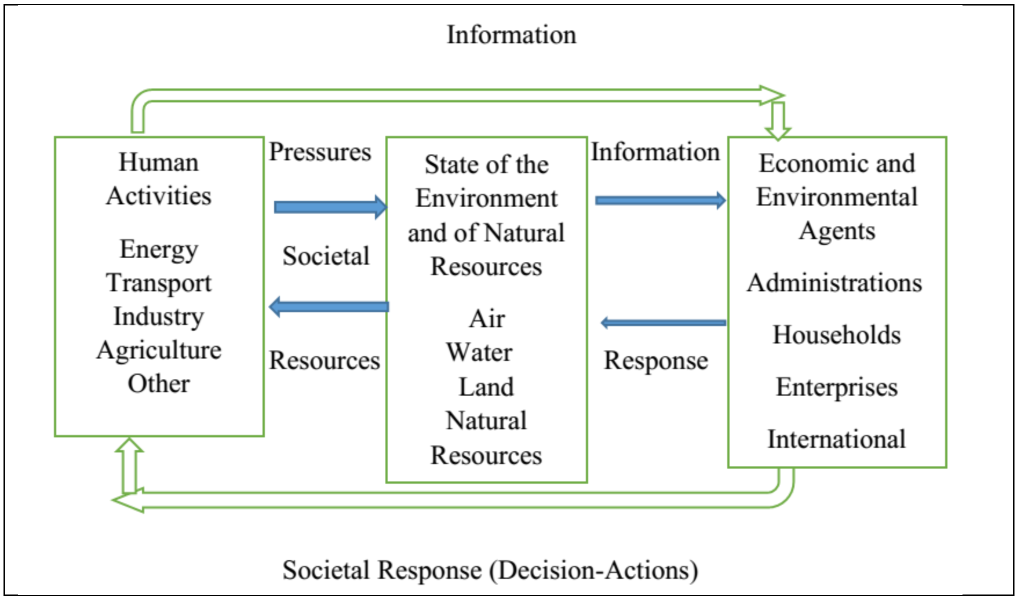

Figure 6: Schematic element of pressure - state-response model

Source: Kristensen (2004)

2.3 The importance of water allocation and water rights

The necessity for water allocation processes arises when there is a shift in balancing the growing needs with the limited/insufficient water availability in a basin without jeopardizing the eco-system's survival (Perry and Easter 2004). Prior engineering approaches looked only at one side of a tossed coin, either through augmentation of the supply-side, notably by the building of new storage capacity or through inter-basin transfer to meet increased demand.

However, new methods seek to balance the two sides through a multi-disciplinary multi-stakeholder process of managing water withdrawal and supply (Prodanovic and Simonovic 2010). Effective water allocation mechanisms take centre stage when efficiency and technology transfer in the prudent management of the scarce resource is employed to ensure sustainability of the water allocation and water right plan (Quesne *et al.* 2010b).

United Nations (2000) defines the roles and importance of water right both in the public domain as well as in the market. Water right is defined as a formal or informal prerogative, which grants the holder the right to withdraw water. It can also be referred to as the entire water allocation process (Bruns, Ringler and Meinzen-Dick 2005a). Water right refers to the legal system for allocating water from a source to water users. The nature of water right could be a natural (customary) or legal (positive – granted by law), individual or group right, a positive (having an obligation on others to do something) or negative (obligation to refrain from doing something) right and a riparian right. As per common law, every riparian owner has a natural right to use the water of a stream, which flows past his land with consideration of other riparian owners.

There are more than one methods for water allocation process, which is usually in operation in a basin system. This may be due to changes in priority of use, and/or the need to maintain efficient reallocation of water right (Freebairn 2003). Consequently, water right concept evolves and changes over time (Bruns, Ringler and Meinzen-Dick 2005a). Inappropriate or ineffective approaches to water allocation drive water stress. Thus, solutions to global water stress entail a proper understanding of water right and water allocation. Among the evolving philosophies and concepts in riverside modelling are included:

2.4 Water price, ownership and market mechanisms concept

The recent transition of water right to markets or other trading mechanisms is likely to increase and improve overall economic efficiency (Bruns and Meinzen-Dick 2005; Bruns, Ringler and Meinzen-Dick 2005b). Historical ownership of right plays a major role in determining access to water and establishing water-trading patterns. During a water allocation process, decisions are made over 'Who, How and On what basis' should water be abstracted. Bruns and Meinzen-Dick (2005) state that water allocation ownership processes are embedded in the following terms:

1- Automatic entitlement: - Entails water set aside for basic social purposes, or the maintenance of minimum environmental requirements.

2- Administrative entitlement: - This term describes water that was given by some authority, either through the state agency or through a user group (e.g. an irrigation board). This is the most widespread formal type of allocation process.

3- Communal or traditional processes: - Entails conventional, non-state law involvement. It is a customary form of water allocation.

4- Market allocation: - This exists in some parts of the world where both informal and formal water markets exist.

5- Ownership of land: - This involves ownership of surface or groundwater through sale or inheritance of landed property. It implies transfer of the water right to landowners.

Most surface water sources in Southern Africa have many riparian users (Schulze and Pike 2004) with conflicting interests for water use. This challenge has brought about the formation of River Basin Organisations (RBOs) whose objective is to arrive at an equitable, efficient, and sustainable distribution of these scarce resources for optimal societal benefits.

However, the heterogeneous nature of human demand for water resources calls for the use of a shared water plan. A shared water allocation plan is a set of rules for the sustainable use of water resources. It is an economic efficiency mechanism for allocating limited water resources and its management between two ends ─ the need for accessibility and the reliability of its supply (Rahaman and Varis 2005).

A widely-accepted criterion for evaluating water allocation policy is economic efficiency (Dinar, Rosegrant and Meinzen-Dick 1997). This criterion enables re-allocation of water from low efficient uses to highly efficient uses. When all the water in a river basin is efficiently allocated, the marginal benefit should be equal across all water use sectors. There are examples from the developed world where water allocation based on the principle of economic efficiency has worked successfully (Carraro, Marchiori and Sgobbi 2006). In addition to economic efficiency, there are other criteria that need to be considered in multiple user environments. Equity, predictability, strategic considerations, flexibility, technical feasibility, political and public acceptability are all considered as acceptable criteria for evaluating water allocation (Dinar, Rosegrant and Meinzen-Dick 1997; Carraro, Marchiori and Sgobbi 2006).

In the developing world, some of these criteria may play a dominant role in selecting water allocation policies and mechanisms, and sometimes they may transcend the use of economic efficiency (Rasi Nezami *et al.* 2013).

2.5 Water allocation mechanisms and policies

There exist various formulated water allocation policies and mechanisms that have been implemented globally. The currently observed water allocation mechanisms can be broadly categorised into three groups:1) Public (administrative) allocation 2) User-based (user managed) allocation, and 3) Water markets (Meinzen-Dick and Mendoza 1996; Dinar, Rosegrant and Meinzen-Dick 1997; Peralta, Forghani and Fayad 2014). It is common to find combinations of these mechanisms both in the developed and developing countries of the world. These mechanisms are briefly discussed below.

Under the public allocation mechanism, the state manages water allocation. The allocation volumes are defined based on quantity (quota-oriented) or based on a marginal cost pricing method (Dinar et al. 1997). This allocation method has been applied at river basin level, at water user systems level or at an individual water user level.

Public water allocation is commonly practised in large-scale water projects managed by the state sector. The state usually enforces public allocation using a system of regulations and sanctions. Among the challenges confronting public water allocation are: lack of political will to implement the existing legal framework; dual institutional responsibilities; inadequately trained staff; ubiquitous systems of water right and inadequate monitoring and evaluation agencies (United Nations 2000).

In general, the water allocations from public systems are heavily subsidised and do not reflect the actual supply cost. Therefore, water users are inclined to receive water exceeding their allocation. This leads to a range of management irregularities including the practice of rent-seeking by agency staff responsible for irrigation operations, which seriously disrupts the official allocation schedules (Repetto 1986; Meinzen-Dick and Mendoza 1996; Johansson 2000).

The response to the public allocation system challenge ushered in the user-based water allocation (Van Koppen et al. 2007). This method allows stakeholders and users to participate in decision-making, knowledge modification and adaptation to suit local conditions (Merry 1996). Many public irrigation systems have adopted a user-based allocation approach by establishing water user associations (WUA) at secondary and tertiary levels.

The above two methods have long been criticized for locking the water resources into uses that have diminishing value to the economy. Water markets introduce flexibility in water allocation by allowing trade of water right across sectors, across locations and across time.

A market approach allows the water users to seek the highest value application of scarce water through voluntary exchange and generation of information about scarcity and demand. It also creates an incentive to conserve water and invest in water saving technology. Despite these positive characteristics, formal water markets have not evolved in many of the developing world river basins (Rosegrant and Binswanger 1994). For a water market to function in a river basin, its user water right must be well-defined, enforceable and transferable (United Nations 2000; Howe and Koundouri 2003). Moreover, markets require third-party effects such as return flows, pollution, water-logging, and overdraft of groundwater, environmental impacts etc. to be fully quantified and associated costs to be incorporated in the exchange (Wurbs 2003).

Transaction costs (information gathering, conveyance losses, monitoring, enforcement etc.) should be lesser than the benefits earned from the trade of water right (Rasi Nezami *et al.* 2013). Many developing countries do not possess the capital, technology or the institutional structure needed to establish these conditions. The absence of water laws and clear jurisdiction over water and water markets has impeded the reallocation of water to efficient uses in the developing world (Howe, Schurmeier and Shaw 1986; Thobani 1998). However, in some developing world irrigation systems, the emergence of formal and informal water markets has been observed due to significant efficiency gains from the water right transfers (Rosegrant, Schleyer and Yadav 1995).

2.5.1 Priority-based allocation

Another important concept in both public and market methods are the allocation priority. Allocation priority comes into existence when the full water right of all water users cannot be supplied. In such a situation, the preferential order comes into play through 1) Natural priority (allocation from upstream to downstream order) 2) Assigned priority (3) Same priority (proportional allocation) (Wurbs 2003; Wurbs 2005).

Priority-based allocation could be used to address some specific issues faced by the water users in the developing world as described below. Traditionally, water resources projects in the developing world have one major goal, and all other uses of water have a secondary nature (Shah and Kumar 2008; Weragala 2010). Most of the projects were aimed at achieving food security, employment generation, hydropower generation, flood control and drought mitigation. In a water-scarce situation, the important water use can be guaranteed by prioritising its water right.

In public allocation systems, prioritisation is often used to attain social objectives such as redistribution of income, protection of the environment and ecology, provision of self-sufficiency in food, power generation, protection of cultural and religious values, ensuring employment opportunities etc. It has been used to prevent extreme loss to sensitive users under drought conditions. It allows recovery of capital costs of public investments. Prioritisation can be used to mitigate the return flow effects as well. It is also used as an instrument to protect the poor against the development of market power (United Nations 2000).

In a water market, a water right is transferable among users and they will be reallocated from low to high added value uses. Theoretically, the final equilibrium allocation of water rights will not be affected by their initial distribution. However, this holds true only when ideal market conditions (zero transaction costs, full information, many buyers and sellers etc.) exist. In practice, the initial allocation of water rights significantly affects the outcome of market allocation (Moffatt 2000). Proportional allocation gives an equal starting ground for all users in a subsequent water market, while prioritisation places preferred users in a privileged position. This inequality may prevent users from achieving economic efficiency in water allocation, but at the same time, it may be used to safeguard public interests (Ahmad and Prashar 2010).

The above discussion and subsequent discussion below highlights some of the important factors that affect water allocation of river basins in the developing world. The limitations in the capital, technology and legal frameworks, as well as social and environmental specifics in these countries, pose problems in establishing a fully market-based allocation; rather, a priority-based allocation has served as a veritable method in achieving basin water development objectives, while adjusting to the basin-specific socio-economic conditions of the region. The indicators of priority based allocation are measured from a performance index number of the allocation scheme or the allocation of simulation processes (Jain and Singh 2003).

2.6 Operational outline for effective water allocation planning

The effective allocation of water and its regulation are usually built around three key areas as illustrated in Figure 7 below, namely:- policy and legislation, management strategies and institutional capacity.

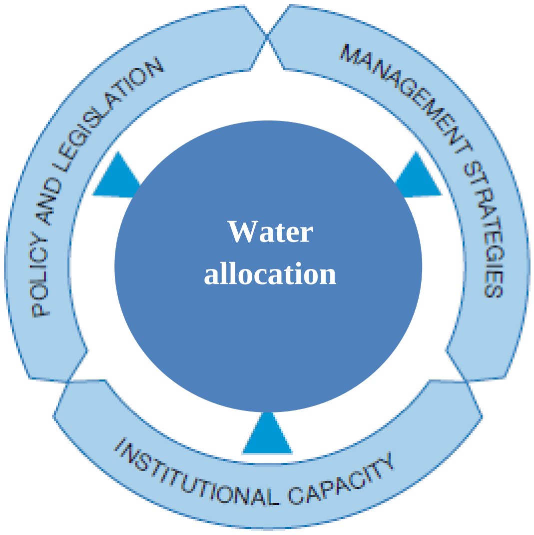

Figure 7 The three key focus areas of water allocation

Source: Speed *et al.* (2013)

The three key focus areas together determine the functioning of a water allocation system and the associated protection of the resources at a catchment level (Moore 2013). In cases where any one of these three is inadequate or not consistent with the other two, the successful implementation of the system is jeopardised. Without the legislation and policy level, there is no clear understanding of the 'rules' for water use. Without good management strategies, the conversion of these rules into sustainable allocations is limited. Likewise, without institutional capacity, the ability to ensure that these allocations are made and enforced is poor.

Förch and Schütt (2007) emphasised the involvement of various disciplines in integrated watershed management. In such a context, the plan, design and management of water resource management inevitably adopt a multidisciplinary, multi-participatory approach based on strong system analysis.

2.7 Sustainable watershed management model

Droogers and Aerts (2005) states that the most significant aspect of the model application lies in their utilisation in exploring different circumstances. These circumstances can capture aspects such as climate change and population growth to serve as a decision support system (DSS).

Sustainable watershed management suggests an integrated approach to water management. Integration in this context refers to the incorporation of the different functions of the hydro-system, the spatial and temporal integration of the processes, determining these functions and the integration of the management objectives of the different actors and stakeholders (Hellegers and Leflaive 2015). Integrated hydrological models (IHM) have served as a useful tool in interpreting the basin’s natural phenomena; it has also aided in the evaluation of the expected consequence of proposed water policies (Madani and Mariño 2009; Tuppad *et al.* 2010; Belayneh *et al.* 2014). However, they still lack the ability to fully mimic anthropogenic activities and assessed their impacts on the water cycle dynamics. This integral part ushered in a new field called socio-hydrology.

Socio-hydrology uses the eco-hydrological approach in planning, managing and ensuring sustainable development of the environment. It has helped to view the water system in proper perspective. The concept considered the basin’s Hydrology, Environment, Life (aquatic life) and human Policies (HELP) as an effective method for water resources development (Winz, Brierley and Trowsdale 2009; Halbe *et al.* 2013; Wescoat 2013; Brown *et al.* 2015).

The new field provides a theoretical foundation for catchment water allocation evaluation in the dynamic societal and ecological systems. It comprises three principle whole system domains, namely historical (Wescoat 2013; Kandasamy *et al.* 2014; Liu *et al.* 2014), comparative (Zlinszky and Timár 2013; Hoyer and Chang 2014) and process (Di Baldassarre *et al.* 2013; Elshafei *et al.* 2014). Although these stages have been a challenge due to the inadequate scientific backing of the robustness, sensitivity and validation in parameterising the schemes (Bawden *et al.* 2014), they are the most valuable tools used presently.

2.7.1 Objectives of water allocation

Modern basin water allocation planning now makes a drastic shift from the traditional conventional emphasis on supply-side only (construction of new infrastructure) to a significant balance through effective demand management measures (Ding *et al.* 2016). Table 1 shows the main characteristic objectives of water allocation.

Table 1: Objectives of water allocation

Objectives	Outcome	Character
	(Provision of basic social needs)	
Social	Provision of domestic purposes	Equitable
	Provision of potable water	
Economic	(Optimal economic use)	
	Hydro-power generation	
	Development of industrial sector	Efficient
	Development of Agricultural sector	
	Strengthening of Grassroots' economics	
Environmental	(Sustainability of the ecosystem)	
	Maintenance of quality of water	
	Tourism and recreational activities	Sustainable
	Aquatic and instream life support	

Source: Kampragou, Eleftheriadou and Mylopoulos (2007)

Aside from the need to periodically characterize and assess the viability of the models/method used for sustainable water allocation development in a region. Kampragou, Eleftheriadou and Mylopoulos (2007) state that basin overarching policy objectives for water allocation plan must include:

- Supporting priorities infrastructure in enhancing socio-economic development. (Wescoat 2013).
- Avoidance of frequent or unexpected water shortfalls in balancing both demand and supply side in managing the natural variability (Collet *et al.* 2015).
- Ensuring the most economical water productive and efficient use.

2.8 Factors influencing catchment yield

Catchment yields are usually determined from hydrometric records (daily, monthly and aggregated monthly for short duration rainfall). In most countries, monthly rainfall values are readily available.

2.8.1 Factors that determine runoff in a catchment

The main factors that determine the runoff of a catchment can be a physiographic, climatic or anthropogenic effect, land use, soil type, vegetation, catchment topography, drainage network, slope, shape and size (Arun 2013; Amoo and Dzwairo 2017). Slope, shape and size of a basin area are a function of its drainage network. Areas of dense drainage work are found to have a high runoff volume; likewise, if the catchment slope is high the runoff distribution will be high and vice visa.

Chopra (2011) highlights four core factors influencing the slope of a watershed. They are inclusive of:- soil type, vegetation urbanization, land use and land cover. The soil type significantly influences the pace of permeability, infiltration rate and generation of interflow, while the aggregated effect of vegetation on runoff is comprised of individual effects on interception, evapotranspiration and soil moisture movement. Unprecedented urbanisation can lead to reductions in the infiltration capacity of the land surface, thereby resulting in low or high flows depending on the topography. Furthermore, the way land use and land cover significantly impact on the complex physical processes will adversely impact the watershed slope. Reliable information on all these geomorphology parameters will aid better development and understanding of runoff in a catchment, which will in turn influence water planning, management, and its allocation factor.

2.9 Existing hydrological model

There exists a plethora of river basin models (RBM) ranging from process-oriented models to fully data-oriented models. Hydrological models change from numerous points of view: time step, spatial scale, simulation either of single events or on a continuous basis, and how diverse hydrological parts are processed. As indicated by Singh and Woolhiser (2002), hydrologic models are grouped in view of (1) procedure depiction; (2) timescale; (3) space scale; (4) techniques of solution; (5) land use; and (6) model use. Figure 8 depicts the spatial scale and physical detail of some water allocation hydrological models. The green ellipses show the key strengths of some well-known models.

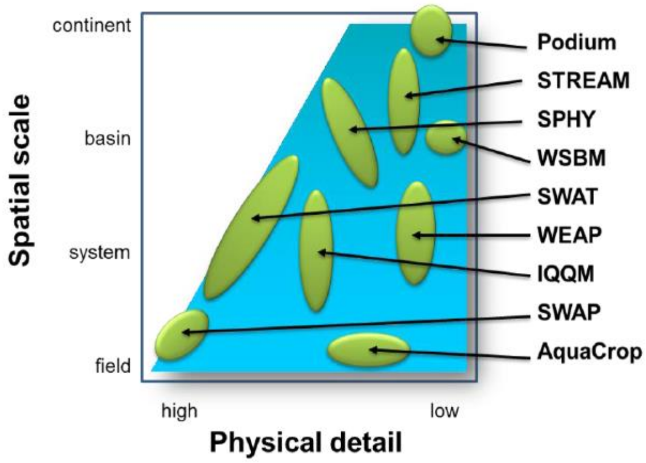

Figure 8**:** Relation between spatial scale and physical detail in water allocation tools

Source: Droogers and Bouma (2014)

George *et al.* (2011) postulate a whole-of-system approach in managing the intricacy involved in river basin water allocation to achieve an efficient, equitable and acceptable outcome. The whole-of-system approach works best when integrated hydrological modelling is employed at any level of the river basin. The term integration in the field of hydrological modelling connotes different meanings to different people (Jakeman and Letcher 2003). In the context of this study, it is a combination of two or more processes in a system or models of different systems. Flügel and Märker (2003) argue that in developing an integrated hydrological model (IHM), the first step is the understanding of the various hydrological processes that occur in the basin, followed by their interaction and contribution to the catchment yield. The process starts with gathering and processing of the collected data in arriving at a locus point of leverage for geo-informatic representation of the basin (Flügel *et al.* 2003).

The integrated watershed management model has been successfully classified into those that require compartment modelling and those that benefit from the comprehensive modelling method (Heinz 2006; Heinz *et al.* 2007; Harou Julien *et al.* 2009). The compartmental method consists of a loose assembly of the different models between the hydrological and economical components. In this type of model coupling, only output data are generally transferred between the mechanisms while under the comprehensive approach, the components are singly tight forming a consistent analytical model. Figure 9 diagrammatically illustrates the evolving trend in watershed models. This is largely attributed to the increasing capabilities and available spatial data.

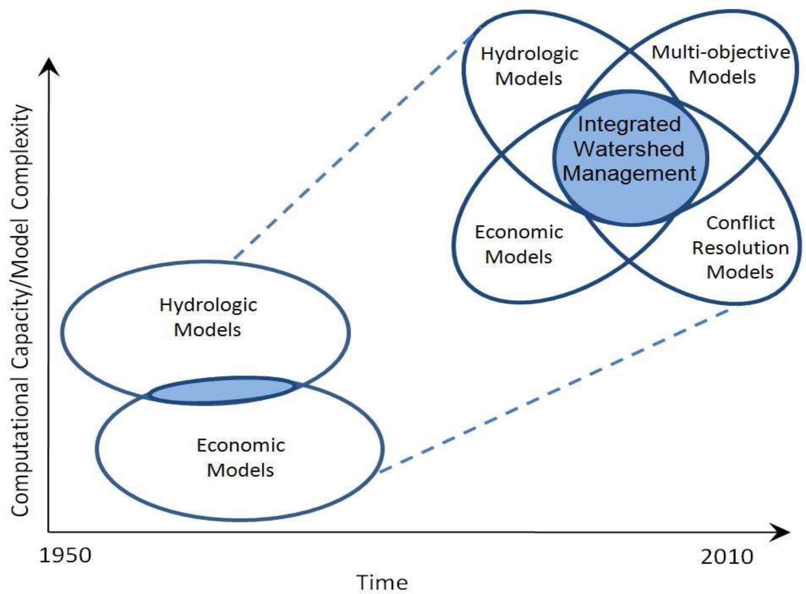

Figure 9: Evolution of integrated watershed modelling over time

Source: Mirchi, Watkins Jr and Madani (2010)

2.10 Assessment of future water resources

Multipurpose water resources planning has emerged as a result of an increase in competing and conflicting water uses due to rapid population growth and rising expectations of a better life (Johnson, Revenga and Echeverria 2001; Juízo and Lidén 2010). Water supply use needs to be met from either surface flow or groundwater resources or a combination of both for the riparian users. However, this study focussed on surface water only. Hence, future water resources demand by the end user for each category of water use was limited to surface water hydrology as a pre-requisite for its proper planning and management. The estimated future water use requirement can be projected based on population growth and development ((Roozbahani, Schreider and Abbasi 2013).

Future water use can be calculated by multiplying the corresponding per capita water use with growing population (Equation 1). The population can be calculated as follows:

$$P(t) = P(0) + \int [r_b - r_d] dt \qquad \textbf{Equation 1}$$

Where $P(t)$ is the projected population, $P(0)$ is the base year, the growth rate of population in the ith year. The South Africa Bureau of Statistics (2010) provides present populations in the province (in millions).

Furthermore, a reservoir system or storage basin is a necessary requirement for most water allocation planning (Howe and Koundouri 2003). King and Brown (2010) concluded that it is very important to generate synthetic streamflow sequences to analyse alternative designs, operation policies and rules for water resources systems and that the dependence structure of streamflow sequences is often assumed to be Markovian; that is, dependent on only a fine set of prior values. Thus, inflow hydrology is an important aspect of water allocation planning and reservoir operation studies. Seasonal demand may be relatively fixed, but in contrast, variation in natural streamflow between seasons may be highly variable.

Stochastic streamflow models are flexible tools that can be used to circumvent the shortcomings of the use of historically required storage alone (Wang, Robertson and Chiew 2009). The Stochastic probability distribution functions of Normal, Log-Normal (LN), Pearson III, Log-Pearson type III (LP3), Gumbel extreme value type1 (EVI) and Log-Gumbel (LG) offer a long-term time series of projected available water for allocation.

These probability distribution functions are in the form of Equation 2 and Equation 3:

$$Q = Q_{ave} + Z\sigma$$ **Equation 2**

The Log-Normal distribution is of the form:

$$LogQ = \overline{LogQ} + Z\sigma_{\log Q}$$ **Equation 3**

While Pearson III and Gumbel are of the form Equation 4 and Equation 5

$$X_T = X_{ave} + ZK$$ **Equation 4**

$$Q_T = Q_{ave} + Z(0.78Y_T - 0.45)$$ **Equation 5**

Where $Y_T = -\ln(-\ln(1 - \frac{1}{T}))$

The value Q_{ave} or X_{ave} is the mean annual flow; Z is the standard deviation; σ is the normal distribution percentage coefficient; K is the Pearson type III coefficient while G or G_x is the skewness or log G skewness coefficient; and Y_T is the variate at the time (T). The parameter Z, σ, K and G can be found in a standard normal distribution table in statistical and hydrology textbooks (Karamouz, Szidarovszky and Zahraie 2003).

2.10.1 Seasonal pattern analysis and forecasting hydrological flow regime

Monthly-varying environmental flows and seasonal water allocation require projected streamflow based on available past data for forecasting future hydrologic flow regime for various design purposes (Jakob 2013). Seasonal fluctuations are commonly observed in a quarterly or monthly hydrologic flow regime. As seasonality is a dominant feature in time series (Sultan and Janicot 2000), hydrologists have developed methodologies to routinely de-seasonalize data for modelling and forecasting different annual conditions.

The great variation inflow from one season to another mainly reflects the climatic variability, i.e., seasonality of rainfall and amount of evapotranspiration which is dependent on air-temperature, as well as precipitation in the basin (Ufoegbune *et al.* 2011). The understanding of this hydrological dynamics alteration in a basin is crucial for sustainable water allocation planning and management.

Quantitative forecasting models can be grouped into two categories: the time series models and the causal methods (Benkachcha, Benhra and El Hassani 2013). The time series models have been employed in the past to explain historical events in data and forecast them into the near future based on the naïve belief that what is happening now is a replicate of the past. The various quantitative time series forecasts include exponential smoothing, naïve method, trend curve analysis, moving average and the autoregressive integrated moving average (ARIMA) models (Chen, Bloomfield and Fu 2003).

However, this time series general pattern does not consider factors affecting the variable to forecast (Sahn 1989). Likewise, many of the ARIMA models employed do not really represent real-world problems (Zhang 2003). To overcome this limitation, the field of artificial intelligence (AI) models such as Fuzzy logic, and neuro-fuzzy logic has emerged. Genetic algorithm (GA), as a nonlinear regression model, ANNs, and support vector machines (SVM) have also proven to be effective (Hinton, Krizhevsky and Wang 2011).

Many of these tools can handle noisy data and address non-linear and complex dynamic systems. These tools are of immense importance when it is difficult to explain the physical relationships explicitly and thus serve as a substitute for modelling hydrologic flow regime systems (Rumelhart *et al.* 1986; Roozbahani, Schreider and Abbasi 2013).

2.10.2 Artificial neural networks

Artificial Neural Networks (ANNs) have been used often in time series forecasting (Benkachcha, Benhra and El Hassani 2013). However, few researchers have tested its capability in forecasting seasonal time series in non-stationary data.

Model Development

By considering different inputs (Equation 6), the following model is finalised using the correlation matrix method to maintain the parsimony of the model.

$$Q_t = f\left(R_t, R_{t-1}, Q_{t-1}, Q_{t-2}\right) \qquad \textbf{Equation 6}$$

Where Q_t represents the runoff at the time (t) and R_t represents rainfall at the time (t). The suffixes t-1, t-2 corresponds to the lagged values of hydrological variables.

We can forecast the future pattern by decomposing the original series into seasonal trend classification. This is represented by the input nodes, hidden nodes and activation functions for forecasting purposes (Shahid 2011; Hu *et al.* 2014). The transfer function in ANNs is the key factor determining the outcome solution. The transfer function can be a non-linear hypothesis, where the sigmoid (logistic) function Equation 7 is best used. It has a range of [0, 1].

$$f(x) = (1 + \exp(-x))^{-1}$$ **Equation 7**

On the other hand, the hyperbolic-tangent function Equation 8 is most appropriate for non-linear problems with negative and positive outputs.

$$f(x) = (\exp(x) - \exp(-x) / (\exp(x) + \exp(-x)$$ **Equation 8**

The output value (or activation) of the neuron is given by Equation 9:

$$a_i = f(n_t) = f \sum (w_{i,j} x_j)$$ **Equation 9**

where $f(n_i)$ is the transfer function - $w_{i,j}$ is the connection weight between node j and node i, x_j the input signal from the node j.; - a_i is the output of the neuron i.

Multilayer Perceptron (MLP) has been the most frequently used class of ANNs for backpropagation and feedforward algorithm employed in time series (Hornik, Stinchcombe and White 1989; Zhang, Patuwo and Hu 1998).

The MLP training is a supervised one in that the derived response of the network (target value) for each input pattern is always available. The algorithm used an activation function (transfer function) to limit the amplitude of the output of a neuron to some finite value. The individual inputs $x_1, x_2 \ldots\ldots X_n$ are multiplied by the corresponding elements $W_{i1,} W_{i2} \ldots\ldots W_{in}$ of the weight matrix W. The schematic diagram of the Multilayer Perceptron (MLP) configuration is shown in Figure 10.

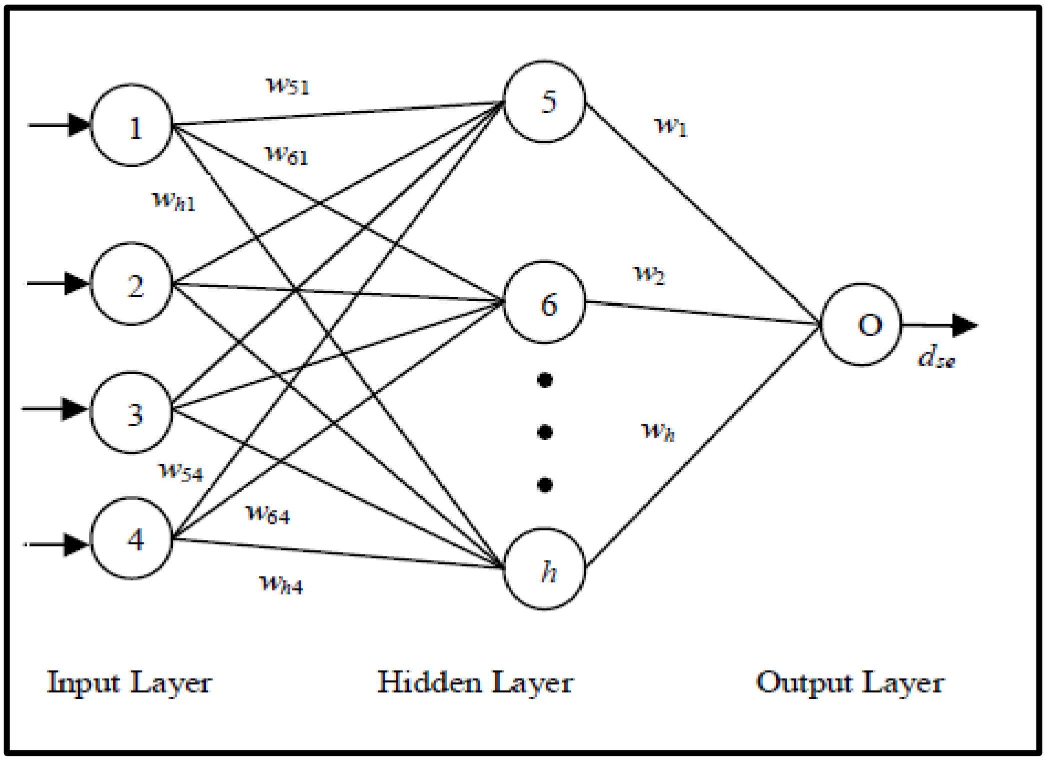

Figure 10: A simple 3-layer feedforward neural network

Source: Terakawa (2003)

The internal algorithm of ANN's back-propagation can improve the performance of the neural network. Equation 10 shows how the reduced total error can be calculated:

$$E = \frac{1}{2}\sum_{p}\sum_{j}\left[O_{jp} - d_{jp}\right]^2$$ **Equation 10**

Where E is the square error, p the number of applied patterns, djp is the desired output for J_{th} neuron when p^{th} the pattern is applied and O_{jp} is the J_{th} neuron output.

2.10.3 Mann-Kendall trend analysis and Sen's method

This test review was necessary for asserting factors that influence future water resources fluctuation pattern. The heterogeneous nature of meteorological data trend pattern brings about conflicting weather changes that result in significance occurrence and the movement changes witnessed in the actual volume of available water.

The Mann-Kendall trend analysis and Sen's method have proven to be reliable tools for detecting and estimating trends in hydro-climatic data (Mitrea, Lee and Wu 2009). Both methods represent a non-parametric test for identifying trends in time series data. Mann-Kendall compares the relative magnitudes of sample data rather than the data values (Kendall 1976) while Sen's slope estimator is used to estimate the true slope of an existing trend such as change per year, where the trend can be assumed to be linear (Sen 1968). Sen's and Mann-kendall sensor trend detection are used for trend analysis in forecasting basin hydrologic flow regime.

The major benefit of this test is that the data need not conform to any non-parametric distribution with assumed constant variance in time. The initial value of the Mann-Kendall statistics (S) is assumed to be 0 if there is no trend. If a data value from a later period is higher or lower than a data value from an earlier period, S is increased or decreased by 1. The net result of all the increased and decreased yields the final value of S. A very high positive value of S is an indication of an increasing trend while a very low negative value indicates a decreasing trend. However, it is important to compute the probability associated with S and the sample size n in order to statistically quantify the significance of the trend (Yue and Wang 2004). The model is as represented in Equation 11 (Mann 1945a).

$$X_i = f(t_i) + \ell_i$$ **Equation 11**

where f(t) is a continuous monotonic increasing or decreasing function of time and the residuals ℓ_i can be assumed to be from the same distribution with zero meanwhile the Sen's estimator of the slope is the median of the N values of Q_t (discharge at time t). The N values of Q are ranked from the smallest to the largest. Sen's slope Equation is given in Equation 12 if N is odd or Equation 13 if N is even (Mann 1945b).

$$Q = Q_{(N+1)/2}$$ **Equation 12**

$$Q = \frac{1}{2}\left(Q_{[n/2]} + Q_{[(N+2)/2]}\right)$$ **Equation 13**

Regression analysis represents a monotonic parametric trend (Montgomery and Peck 1982). It provides a measure of significance based on a hypothesis test on the slope coefficient (or alternatively the correlation coefficient) and a measure of magnitude. The non-parametric approach would be to use the Mann-Kendall test for trend (Mann 1945b; Hamed 2008) which is functionally identical to Kendall's (tau) test for correlation (Kendall 1976) and the associated slope estimate developed by Sen (1968). Detailed procedural steps for the trend analysis and expression are given by Yue and Wang (2004).

2.10.4 Multivariate PCA and FA component

Principal Component Analysis (PCA) has enjoyed wide usage in multivariate analysis of correlated variables (Lee and Dinar 1996; Lee and Vanrolleghem 2004). It is useful for reducing and interpreting large multivariate data sets, and for discovering previously unsuspected relationships.

PCA aims at extracting the most important information from the data set from the compress data size (Costa, Alves and Ferreira 2009). It works by rotating the original dataset space in such a way that they possess a new data point in the direction of the highest variance of the data (Gill 2014). The first principal component (PC1) denotes the direction of the highest variance of the data while the second principal component (PC2) accounts for most of the remaining variance under the constraint to be orthogonal to the preceding component PC1(Lennox and Rosén 2002).

2.10.5 Dependable water allocation

Dependable water allocation refers to the amount of water present at a place/ gauging station. It is the estimated water for a basin or gauging site to assist the existing utilisation pattern and practices. Its analysis helps in optimal allocation of water in the basin for different purposes and the design of water resources structures (Blöschl 2013). This is useful for water management and planning studies, water transfers, reservoir operation, and conjunctive water analyses (Mwelase 2016).

Dependable water availability to a different degree at a specific basin is usually estimated from the flow duration curve (FDC) at that site. Detailed procedural steps for FDC application can be found in the literature (Vogel and Fennessey 1994, 1995; Karlberg *et al.* 2007; Westerberg *et al.* 2011; Blöschl 2013).

Water availability at different reliability in a specific basin is usually used in establishing rules for sharing limited water resources and maintaining environmental quality for sustainable development (Punithavathi, Tamilenthi and Baskaran 2012).

2.10.6 Methods for estimating allocable water

Basically, there exist different methods for estimating allocable water, even though many of them still require greater modelling techniques (Speed *et al.* 2013; Butler and Adamowski 2015). However, the primary methods include annual or seasonal average estimation, use of hydrological modelling software and yield estimation based on the system operating rules. In all these methods, Mean Annual Runoff (MAR) provides the building unit for naturalised, or artificially created, equivalent of the average total quantity of surface water available in a year at a certain point in a river. It serves as a fundamental way of assessing how much water is available in a catchment.

The mean annual runoff (MAR) provides a reliable means of developing operational rules in maximising allocable water (Singh and Woolhiser 2002; Speed *et al.* 2013). The MAR may be estimated either through hydrological modelling of rainfall-runoff relationships or catchment yield simulation from observed data by taking the average of the total annual runoff values over a certain period (usually more than fifty years). It can also be estimated by using the data-mining technique.

Innovative data-mining techniques for modelling rainfall-runoff that are receiving favourable attention in the hydrological community range from the very simple models such as linear regression, autoregressive moving-average (ARMA) or lag models to complex ones such as ANNs Networks, singular spectrum analysis (SSA), and Standardised Anomaly Index (SAIs) (Maity and Kashid 2011). More recently we have seen the use of ANNs (Barua *et al.* 2010; Gosasang, Chandraprakaikul and Kiattisin 2011; Dorofki *et al.* 2012; Paswan and Begum 2013).

ANNs are non-linear data-driven networks which are opposed to the traditional model-based methods (Morimoto et al. 2007). They have been widely adopted for predicting and forecasting in diverse fields of research such as finance, medicine, engineering and sciences. They have also helped to solve an extraordinary range of problems (Maier and Dandy 2000). ANNs are specifically useful when the relationship between both input and output variables are discrete (Jha 2007).

ANNs perform well as a statistical and data analysis method because it was discovered that they improve model performance when adopted (Maier and Dandy 2000). They are also capable of predicting the outcome of an input set under time-series applications (Chang and Chen 2003; Barua *et al.* 2010; Maier *et al.* 2010).

2.12 Emerging modern approaches to basin water allocation

Modern approaches to basin water allocation require a structured analysis. The structural analysis depicts the watershed hydrologic dynamic in relation to balancing the societal net benefits without exposing ecosystems depletion. Emerging solutions define the allocation boundary and their associated interconnectivity pattern among the riparian users (Koundouri 2000; Yu C *et al.* 2009).

The study plans to use modern allocation planning of these models. The difference between traditional and modern methods lies in the fact that a modern allocation plan seeks to reallocate water for future development considering projection on socio-economic development and likely effect of climate change (Brouwer and Van Ek 2004; Britz Wolfgang, Ferris Michael and Kuhn Arnim 2013). Furthermore, Lee and Dinar (1996) state that previous approaches and methods in deciding how water resources are allocated are based on historical and future projection use among the different administrative regions that are entitled to use the water.

Recently, allocable water, or reserved water, is now increasingly being determined using equity, or priority, purposes (Rahaman and Varis 2005). Priority purpose allocation satisfies certain users before the water is shared between different regional interests to satisfy the various demands including environmental requirements for aliens' plants, tourism, and recreational activities. In resolving the water allocation dispute during the consultation, decision-makers now set out fair and equitable pre-agreed rules or processes, which reflect the wishes of the affected users. Paternalistic systems of operation and management, which do not involve consultation about how water is allocated, are becoming less and less acceptable (Pearson *et al.* 2010).

2.12.1 Decision support system in water resources

The decision support system with the aid of computer-based tools has supported IWRM in making quick and efficient decisions (Cheng *et al.* 2016). It has assisted in analysing the impact and vulnerability of water resources. Both the spatial-temporal changes in a river basin can be calibration and validation to predict future scenarios (Chien, Yeh and Knouft 2013; Zuo *et al.* 2015). Recent developments in computer science allow complex models to simulate the behaviour of environmental systems. They have helped in aggregating several models into integrated software (a knowledge-based Decision Support System (DSS). These tools use simulation or optimisation techniques to estimate the best allocation schedules between competing water demands.

Water resources management optimization can be classified into economic-driven optimisation models (Draper *et al.* 2003; Draper *et al.* 2004; Letcher, Jakeman and Croke 2004; Cai, Ringler and Rosegrant 2006; Ward, Booker and Michelsen 2006) and priority-driven optimisation models (e.g. CALSIM of Draper *et al*. 2004; WEAP of Stockholm Environment Institute (Yates *et al.* 2005b); WRMM of Alberta Environment, 2002 cited in Hassanzadeh *et al.* (2014).

Economic-driven optimization strives to maximise the net accrued benefit through the cost of its use over a planning period while priority-driven optimization sees water as social goods, which must be accorded higher weight with minimal cost. It usually consists of institutional rules and an economic incentives component (Ringler and Nguyen 2004). The node-like representation of the physical entities in a river has been a viable technique for solving both economic-driven and priority- driven optimization problems. This technique has been best used in solving Genetic Algorithm, Network Flow, Dynamic Programming, Linear and Non-Linear Programming among others (Robertson and Wang 2012).

Most river basin management is confronted with the challenge of how to satisfy the users' conflicting objectives and constraints amidst a series of possible solutions to the problem. This leads to making models (lump based, physical based and semi-distributed based models) to find an emerging solution in assisting limited human thinking. These models are often built on the conservation of mass principle using optimization and simulation techniques in solving the unit building blocks of the system. Krause *et al.* (2010) believe simulation models are best suited for assessing system performance while optimization models are intended to achieve system improvement.

2.12.2 Simulation and optimization approach: strengths and weaknesses

Simulation implies the imitation of original water resources behaviour based on a set of rules, while optimization tends to maximise allocations based on an objective function and the associated constraints. This method is most appropriate for 'what if' questions asked in investigations under different circumstances. The model accepts as input engineered strategies, physical constraints and/or management plans in generating comprehensive predictive outcomes (Mirchi, Watkins Jr and Madani 2010). Simulation is the preferred method for assessing water system responses to risky and non-equilibrium situations, such as droughts. It perfectly suits system components that are easily prone to failure (Kragt *et al.* 2011). Figure 11 below depicts applied methodology trends in water management scenarios.

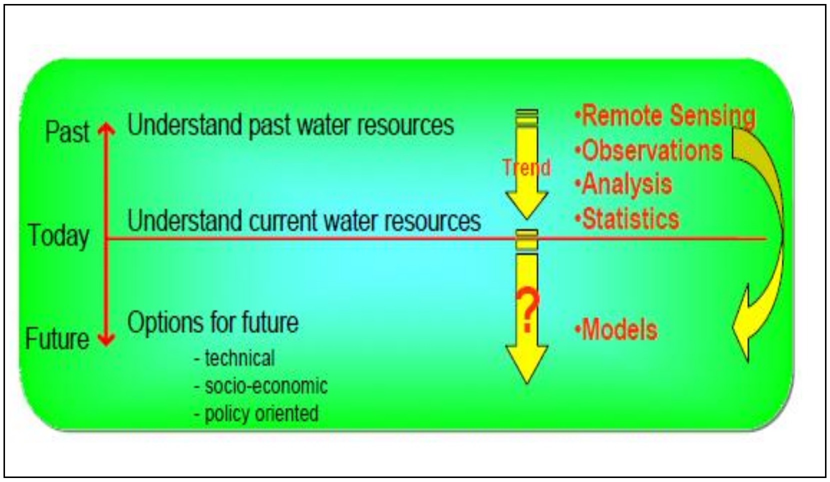

Figure 11: Simulation models concept in scenario analysis

Source: Laniak *et al.* (2013)

2.12.3 Advantages and disadvantages of simulation models

Simulation approaches offer some benefits over optimization allocation models because they typically solve the coupled grid system, partial-differential forms of the flow equations, and allow for detailed physically based solutions. However, they can be limited by computational expense and reliance on a predetermined set of operating policies (Condon and Maxwell 2013).

Optimization models

Optimization techniques select the best values for decision variables among alternative objective functions, that are subjected to a set of mathematical constraints in arriving at a feasible solution (Mirchi, Watkins Jr and Madani 2010). The objectives of water resources system optimization are to maximise benefits, minimise costs, and meet other related constraints (Rani and Moreira 2010). Optimization inclusive simulation is an alternative technique in handling large-scale river basin challenges (Loucks and van Beek 2005). It offers watershed management operations some sort of optimization techniques to exploit satisfaction of net demand while adhering to a variety of system-specific rules and priorities. Table 2 illustrates the main differences between simulation and optimization models.

Table 2: Simulation vs. optimization methods

Comparison	Simulation model	Optimisation model
Suitable for	‘‘What if’’ questions	‘‘What’s the best’ questions
Computational efficiency	High	Low
Transparency/acceptability to the stakeholders.	High	Low
Development effort	Low	High

Source: Harou Julien *et al.* (2009)

2.12.4 Advantages and disadvantages of optimization model’s application

The main advantage of optimization models over simulation models lies in their ability to screen many potential alternatives and provide new options that otherwise may have been over-looked. They are better suited for stochastic analysis, thereby making it easy for users to quickly adjust parameters and evaluate a range of intuitive trade-off analyses whose outcomes may not be practically achievable.

However, one drawback to these efficiency tools is that optimization models tend to rely on simplified physical relationships and are therefore limited in their ability to simulate interconnections within complex, conjunctively managed systems. Also, the linear nature of network flow model optimization is problematic when aspects of the water system display non-linear behaviour. They are generally data-driven and solve simplified forms of the governing equations. They often lack the ability to simulate feedbacks within the physical system that may result from management decisions (Condon and Maxwell 2013).

2.13 Review of some simulation river basin modelling tools

This section reviews the most common river basin modelling tools that are related to water allocation planning and sustainable watershed management. Examples of these type are: VENSIM-DSS (Dai and Labadie 2001), MODSIM-DSS (Azevedo *et al.* 2000; Labadie, Baldo and Larson 2000), CALSIM (Draper *et al.* 2004), Waterware (Wooldridge 1999), Riverware (Zagona *et al.* 2001), HEC-family of models (HEC-3, HEC-5 and HEC-ResSim) (Fereidoon, Koch and Mousavi 2014) , RIBASIM (Tiwary, Jha and Venugopalan 2010), and Mike Basin, (McKinney 2004; Warer 2004). Others are WEAP (Yates *et al.* 2005a; McCartney and Arranz 2007); REALM (Perera, James and Kularathna.M 2005), and OASIS (Bangash *et al.* 2012).

Most, water allocation simulation’s models are based on mass balance principles, using a node-like linear network with user-defined priorities to allocate resources. Table 3 depicts some of the hydrological models, their characteristics, areas where they have been applied, and input and output parameters. Table 4 shows a comparison of the integrated hydrological models. This table can be used as a guide in selecting an appropriate integrated hydrological model suitable for application in the study.

Table 3: Characteristics of hydrological models

Model	**Area applied**	**Inputs**	**Outputs**
MIKE SHE (Refshaard, Storm and Singh 1995)	Europe, USA (Magombeyi 2010); Semi-arid regions (e.g. South Africa) (Prucha *et al.* 2016)	Topography, soils, land use, hydraulic conductivity (aquifer), Manning's roughness, coefficient, evapotranspiration, drainage time and weather data	- Streamflow - Soil water balance
ACRU (Smithers 1995; Schulze and Smithers 2004)	Southern Africa, USA, Germany, New Zealand and Canada. (Warburton 2010)	Rainfall, temperature (max and min), land cover, soil properties, catchment characteristics and climatic data	- Runoff - Crop yield, sediment, and reservoir) - Soil water balance - Irrigation demand (Secretariat 2008; Magombeyi 2010)
SWAT(Arnold *et al.* 1998)	Global (Douglas-Mankin, Srinivasan and Arnold 2010)	Terrain data, soils, DEM, land cover/use, weather data, agricultural practices data, and reservoir and aquiver characteristics.	- Streamflow - Soil water balance - Crop yield - Nutrient balance - Climate data - Losses (percolation and channel)
Hydrological Simulation Program in FORTRAN(HSPF) (Donigian Jr *et al.* 1995)	The USA, Turkey (Magombeyi 2010)	Meteorological data, DEM, soil characteristics, land use/cover, meteorological data.	- runoff - sediment load

			- Nutrient and pesticide concentrations, time history of water quantity and quality at any point in a watershed. (Daniel *et al.* 2011)
TOPKAPI (Topographic Kinematic Approximation and Integration) (Liu and Todini 2002)	Italy, Spain, China, South Africa, Chile, USA.	DEM, soil, land cover, channel and surface roughness.	- Runoff - Subsurface, Overland, and channel flow - Soil water balance
HEC-HMS (Feldman 2000)	Humid, tropical, sub-tropical and arid regions (Abushandi and Merkel 2013)	Soil, land use, physical characteristics of catchment, channel geometry, topography, potential evapotranspiration, geological data, meteorological data.	- Runoff - Soil balance - Groundwater flow - Channel flow - Evapotranspiration
PyTOPKAPI (Sinclair and Pegram)	South Africa	DEM, soil, land cover, channel and surface roughness, meteorological data, evapotranspiration (Actual and Reference)	- Runoff - Subsurface, Overland, and channel flow - Soil water balance

Table 4: Comparison of integrated hydrological models for application in the study

Model name	**GIS Capability**	**Application**	**Advantages**	**Disadvantages**	**Remarks**
MIKE SHE	Yes	- Water quality - Surface and groundwater movement - Irrigation management - Water use management	- Large spatial scale range (Butts *et al.* 2005) -	-Model use requires technical expertise -Requires huge amount of input data, -Takes long computational time -Base flow overestimation -Real complexity of hydrological systems (Unbearable below ground scale of representatives and) Approximation of processes involved and numerical solutions)	Not selected; model accuracy in an ungauged and gauged catchment is not guaranteed.
ACRU	Yes	- Land use - Crop yield - Irrigation - Sediment yield - Water resources assessment - Design hydrology - Climate change	- Confidence in assessing climate and land use change - Good structure for hydrological responses and sediment mechanism	-Model availability and support is difficult. -Requires huge amount of input data. - Data pre-processing and GIS analysis are difficult. (Beckers,	Not selected; default values are based on South African dataset

		- Impact analysis - Environmental flows estimation - Risk analysis		Smerdon and Wilson 2009) - Not robust in semi-arid regions (Magombeyi 2010)	
SWAT	Yes	- Agricultural purposes - Subsurface drainage - Irrigation and reservoir operation - Water quality - Hydrological studies - Land use - Climate change - Sediment yield - Pollution loading	- Automatic calibration - Well adopted using remotely sensed data. - Flexible and robust	-Does not simulate single-event storms adequately. -Non-spatial aspects of the Hydrologic Response Unit (HRU), which does not provide an explicit spatial representation of riparian buffer zones, wetlands. -Limited ability to account for targeted placement of grassland or other land use and ignores flow and pollutant routing within a given sub-watershed. (Daniel *et al.* 2011)	Selected, due to its robustness and accessibility
HSPF	Yes	- Hydrological studies - Water quality - Pollutant analyses - Sediment transport	- Gives a detailed representation of land and watershed land, stream	- Huge amount of data input for setup -Not fully physically based	Not selected; will be difficult to set up in gauge

		- Agricultural practices	processes, and watershed pollutant sources. - Flexibility and adaptability to most watershed conditions - Well-designed code modularity and structure	- Not user friendly -Difficult to calibrate	and ungauged watershed
TOPKAPI	Yes	- Catchment hydrology - Water resources management - Reservoir management - Flood forecasting - Land use change - Climate change - Irrigation and drought	- Easy to calibrate - Run segment and continuous event simulation - Low computational time	-Expensive -The model fails to account for infiltration into the soil layer.	Not selected, due to infiltration process limitation
HEC-HMS	Yes	- Water balance - Water resources management - Flood hydrology - Urban drainage - Stream restoration - Urbanization impact - Reservoir operation	- User friendly - Auto calibration - Low computational time - Can be applied in a lake	-High complexity due to broad functionality in representing both watershed and river processes -Required high number of parameters -Can't simulate in large watershed scale	Not selected, as it requires many parameters to be available.
PyTOPKAPI	Yes	- Catchment hydrology - Water resources management - Reservoir management	- Well adopted using remotely sensed data - Ease of use	-Requires large data input	Not selected, as it requires large input of input data

		- Flood forecasting - Land use change - Climate change - Soil moisture estimate	- Robust in ungauged catchment - Simulate at hourly time scale - Less computational time		

2.13.1 Dynamic simulation model (DSM)

DSMs have a long history of application to river basin modelling. They connote conceptual simulation and numerical methods that are used to understand the structure and behaviour of complex systems. The system dynamics modelling method stems from 'Dynamo' invented by Forrester at MIT in the 1960s (Forrester 1961; Forrester 1981). System dynamic environment includes STELLA (Forrester 1992; ISEE Systems 2016); POWERSIM (Matondo 2002); GOLDSIM (Frontini and Burns 2003); Simile (Muetzelfeldt and Massheder 2003) and VENSIM (Winz, Brierley and Trowsdale 2009; Ventana Systems Inc 2016). Figure 12 depicts an example of land use and irrigation water demand in STELLA environment.

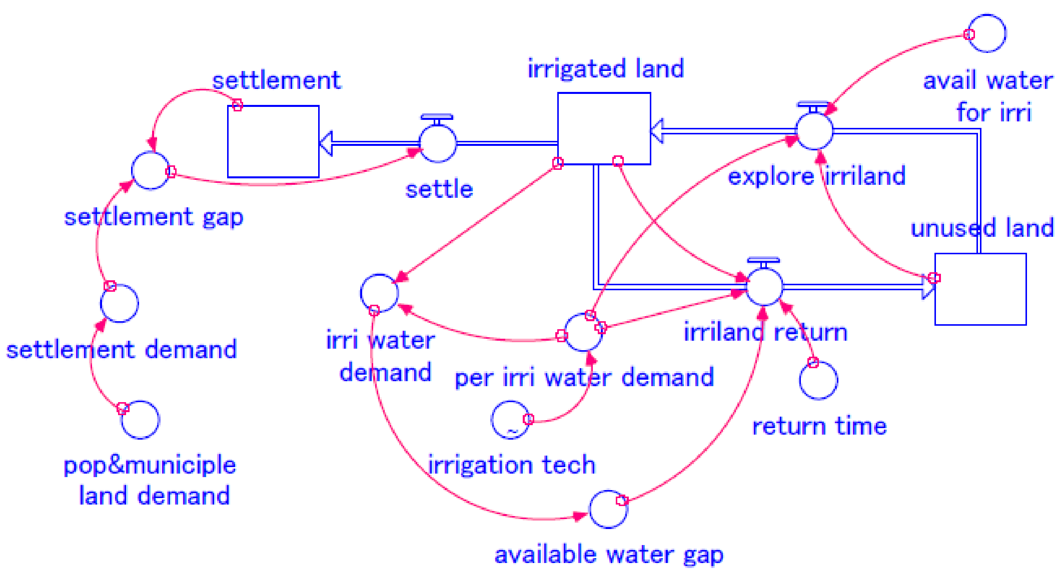

Figure 12: The land use and irrigation demand

Source: Laniak *et al.* (2013)

A system dynamic (SD) model offers a robust hypothetical level to conventional simulation or optimization models in arriving at a management decision for a problem. It offers a systematic and efficient analysis of relevant information useful to many organisations (Fang, Bao and Huang 2007). However, these advantages are still not fully employed in water resources (Ahmad and Simonovic 2000; Ahmad and Simonovic 2005). Conventional optimization deals with oversimplified systems, aside from not indicating how different basic elements such as feedback affect the dynamics of the system in the future.

The **systems dynamics simulation approach** resembles a complex phenomenon from a smaller, readily understood interdependent sub-system using feedback and delay processes that allows conservation of energy, time and funds in deriving maximum net societal benefit (Stave 2003; Sterman 2012). They are built from connectors, modifiers, flows and stocks. Figure 13 shows the STELLA schematic representation of the water demand by the industrial workforce and its population projection ahead of the scarcity of water resource.

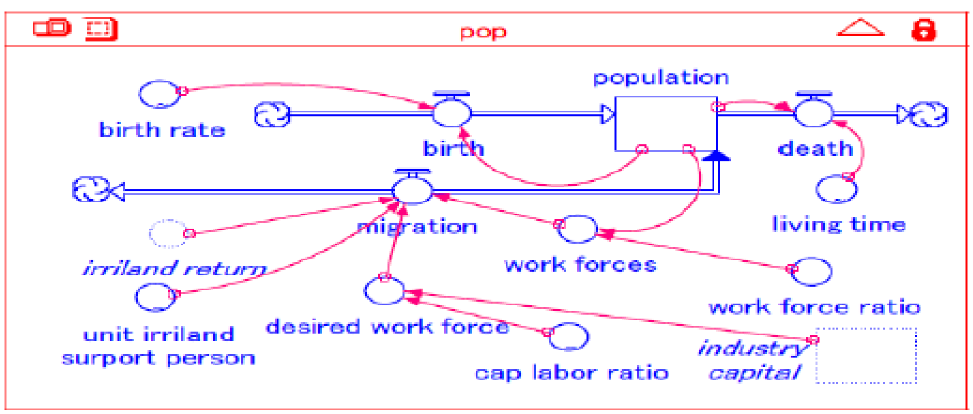

Figure 13: Dynamic model for population demand

Source: Maani and Cavana (2007)

The SD rational approach in its application helps decision makers to appreciate the structural behaviour of complex systems. It simulates and optimizes the overall water system behaviour, including economic growth, cost, future scenarios of population and climate change consideration (Prodanovic and Simonovic 2007; Null and Prudencio 2016).

The simulated environment creates difference equations from the on-user input variable. The sequential flow chart identifies the stock and flow, followed by its graphical representation in a simulated computer environment. Most of the dynamic models are created by connecting icons together in different ways, so much so that the structure of the model determines its behaviour in a transparent way. The applied technique consists of three key principles: feedback control theory, understanding the system structure behaviour, and the use of a computer-based simulated environment in formulating policies (Lane and Oliva 1998).

System Dynamic applications in water resources have been comprehensively reviewed by different authors (Simonovic 2009; Winz, Brierley and Trowsdale 2009; Mirchi, Watkins Jr and Madani 2010; Davies and Simonovic 2011; Mirchi *et al.* 2013; Gain and Giupponi 2015; Sivapalan 2015). Figure 14 illustrates the STELLA model for the natural river system modelling.

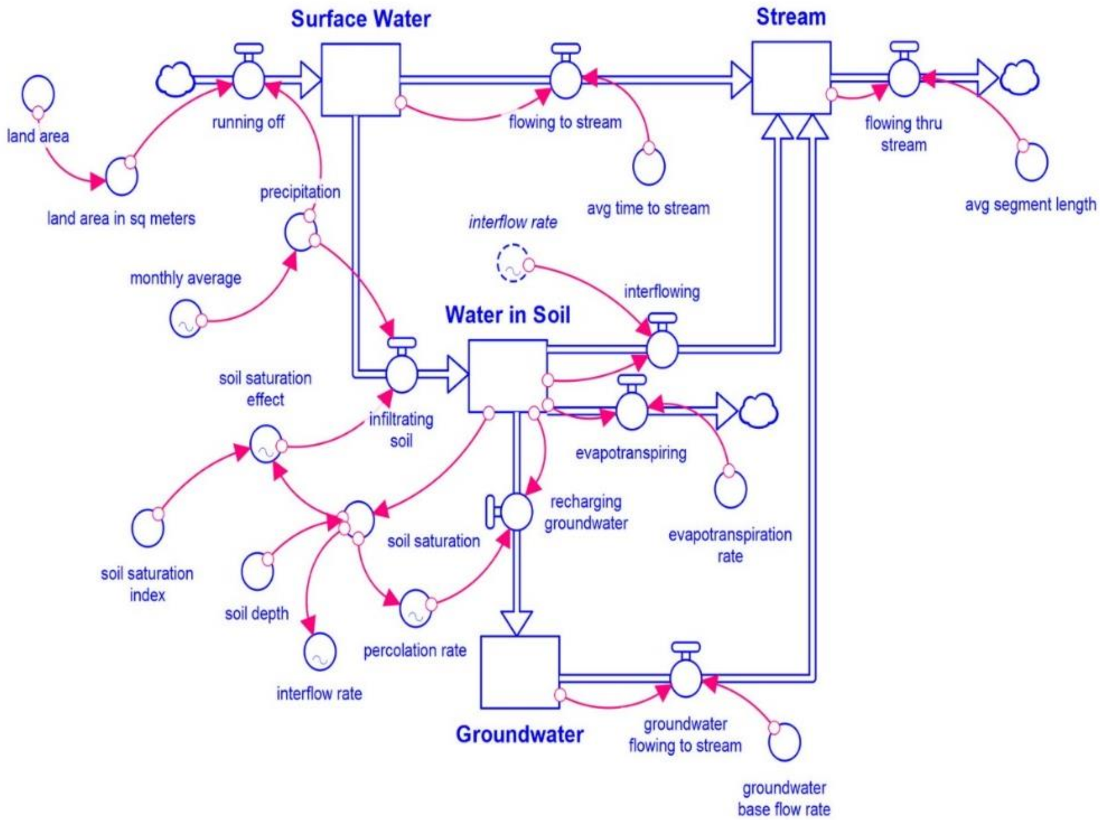

Figure 14: The natural river system modelling

Source: Johnson, Revenga and Echeverria (2001)

2.13.2 Some applications of the system dynamic approach

Many researchers have affirmed the superiority of the system dynamic approach in addressing both interactive and non-linear relationships in solving water shortage concerns (Simonovic S and Fahmy H 1999; Turton and Meissner 2002; Xu *et al.* 2002; Tidwell *et al.* 2004; Winz, Brierley and Trowsdale 2009). The dynamic simulation technique has been applied in many fields such as the carrying capacity of water resources (Ahmad and Prashar 2010) and land resources (Dai *et al.* 2013); simulating problems in water use (Simonovic 2012); and environmental impact (Deaton and Winebrake, 2000).

In addition, the dynamic simulation technique has been applied to other areas such as global modelling of water resources (Simonovic 1996; Simonovic 2009); interrelationships between environmental, ecological and economic resources (Costanza et al., 1998). It also include: reservoir operations (Ahmad and Simonovic 2006); flood management (Simonovic and Ahmad 2005); sustainable development (Xu *et al.* 2002); garbage disposal (Cai, 2006); water resources planning (Zhang et al., 2008); as well as water quality management (Gastélum Pérez 2006).

2.13.3 Advantages and disadvantages

Among SDM's advantages is the holistic view of water resources problems. This is captured in the Closed Loop Diagram (CLD) and Stock Flow Diagram (SFD). Its simulation approach helps in prioritising information gathering and provides a more holistic inquiry into their sub-system interactions. Also, it can assess different scenarios and evaluate long-term-run behavioural patterns (Ahmad and Simonovic 2000).

SDM has proved proficient in simplifying clear communication of model structure and results. It has also promoted shared vision planning, enhanced participatory modelling, and shared learning experiences. SDM offers a user-friendly interface suitable for sensitivity analysis for decision-making and policy assessment. According to Madani and Mariño (2009) its major pitfall includes the inappropriate application of the method without proper regard for its philosophy; speculative quantification of some subsystems such as socio-economic and political subsystems; and the ease of erroneous CLDs and SFDs conceptualisation.

It requires experience and expertise to develop a sufficiently detailed, insightful and representative description of the system dynamic hypothesis. It requires substantial interdisciplinary knowledge to generate meaningful quantitative predictions due to its complexity and assembly of subsystems (Madani and Mariño 2009).

2.13.4 The SWAT model

The Soil and Water Assessment Tool (SWAT) model has been in use globally for over 30 years (Arnold *et al.* 2012; Bieger *et al.* 2015; Daggupati *et al.* 2016). The semi-distributed physically based simulation model can serve as a strategic planning tool. SWAT can predict the impact of land use change and management practices on hydrological regimes in a basin (Sun *et al.* 2016).

This river basin model (SWAT) can quantify the impact of land management practices in large complex catchments. The model operates on a daily time step with up to monthly/annual output frequency on a continuous time basis (Arnold and Fohrer 2005; Coffey *et al.* 2013). The model was conceptualised to include:- agricultural management, reservoir/stream routing, weather forecasting, plant growth, nutrients, pesticides, hydrology, erosion and sedimentation. It works by distributing a watershed into sub-catchments, through a connected stream channel base on a unique grouping of vegetation type and soil which form the Hydrologic Response Units (HRUs) (Coffey *et al.* 2010; Sun *et al.* 2016).

Furthermore, the SWAT model works in a geographic information system (GIS) environment, with the capability of automating data entry, communicating and running the hydrologic model (Romanowicz *et al.* 2005; Daggupati *et al.* 2016). The modelling process with SWAT is as shown in Figure 15 while Figure 16 represents a schematic diagram of the Hydrological cycle in SWAT.

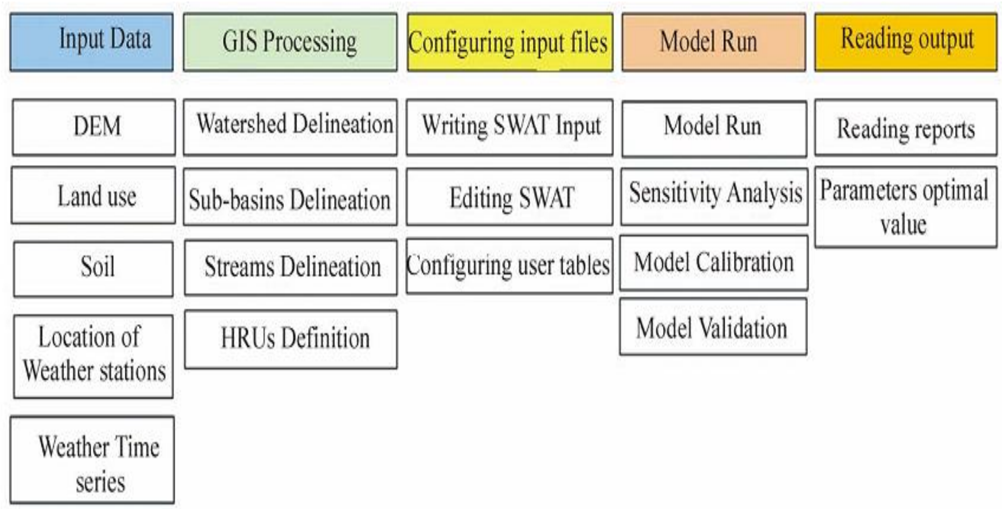

Figure 15: Components of SWAT model

Source: Fadil *et al.* (2011)

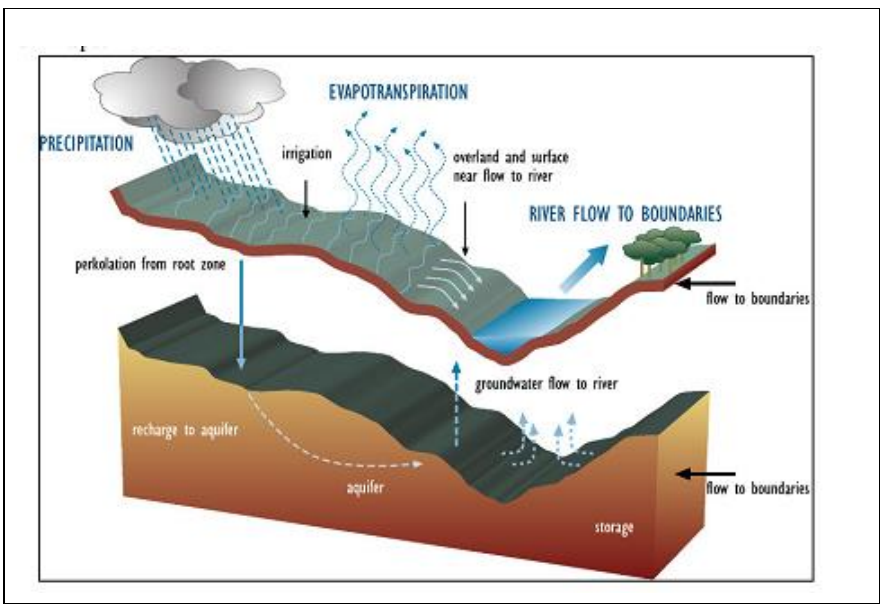

Figure 16: Scheme of the Hydrological cycle in SWAT

Source: Neitsch *et al.* (2011)

The SWAT model was built on the water balance principle. It uses Equation 14 in simulating the hydrologic cycle, which considers both the shallow aquifer above the impermeable layer and the unsaturated zone as a unit.

$$SW_t = SW_o + \sum_{i=1}^{t}(R_{day} - Q_{surf} - E_{\mathrm{a}} - W_{seep} - Q_{gw})_i$$ **Equation 14**

Where SW_t is the final soil water content (mm water), SWo is the initial soil water content in day i (mm water), t is the time (days), Rday is the amount of precipitation in day i (mm water). Qsurf is the amount of surface runoff in day i (mm water), Ea is the amount of evapotranspiration in day i (mm water), Wseep is the amount of percolation and by-pass flow exiting the soil profile bottom on day i (mm water), and Qgw is the amount of return flow in day i (mm water).

River transport

SWAT models the mass flow of water in the river channel as well as processes in the water and sediments such as evaporation, transmission through the riverbed, sedimentation, re-suspension, and organism die-off. For further information on factors in Equation 14 and calculations behind it, refer to the SWAT theoretical documentation (Nietsch et al. 2011).

The model uses SCS curve number and the A_{mpt} infiltration method in the generation of surface runoff (Neitsch *et al.* 2011; Dile *et al.* 2016). The SCS curve number describes surface runoff Qsurf as in Equation 15.

:

$$Q_{surf} = \frac{\left(R_{day} - 0.2S\right)^2}{\left(R_{day} + 0.8S\right)}$$ **Equation 15**

Qsurf is the accumulated runoff or rainfall excess (mm), R_{day} is the rainfall depth for the day (mm), S is the retention parameter (mm). Equation 16 defines the retention parameter.

$$S = 25.4\left(\frac{100}{CN} - 10\right)$$ **Equation 16**

Where CN= curve number, S=retention parameter; the total amount of water exiting the bottom of the soil profile on day i, (Wseep) is calculated from Equation 17.

$$W_{seep} = w_{per.ly=n} + w_{crk.btm}$$ **Equation 17**

Where W_{seep} is the total amount of water exiting the bottom of the soil profile on day i (mm H_2O), $w_{per.ly=n}$ is the amount of water percolating out of the lowest layer, n, in the soil profile on day i (mm H_2O). $w_{crk.btm}$is the amount of water flowing past the lower boundary of the soil profile due to bypass flow on day i (mm H_2O). The estimation of the base or return flow is done using Equation 18.

$$Q_{gw} = \frac{8000.K_{sat}}{{L_{gw}}^2}.h_{wtbl}$$ **Equation 18**

where Q_{gw} is the groundwater flow, or base flow, into the main channel on day i (mm H_2O), K_{sat} is the hydraulic conductivity of the aquifer (mm/day), Lgw is the distance from the ridge or sub-basin divide for the groundwater system to the main channel (m), and hwtbl is the water table height (m).

Among the significant parameters needed for efficient water planning and management is the water yield. Water yield is the total amount of water leaving the HRU and entering the main channel during the time step. The catchment prediction of water yield refers to the estimation of available water at a point in the basin with a certain degree of dependability (Martin *et al.* 2016). This can be evaluated using Equation 19 (Neitsch *et al.* 2011; Dile *et al.* 2016).

$$WYLD = SURQ + LATQ + GWQ - TLOSS \quad \textbf{Equation 19}$$

Where: WYLD is the amount of water yield (mm H_2O), SURQ is the surface runoff (mm H_2O), LATQ is the lateral flow contribution to streamflow (mm H_2O), GWQ is the groundwater contribution to streamflow (mm H_2O) and TLOSS is the transmission losses (mm H_2O) from tributary channels in the HRU via transmission through the bed.

2.14 Components of river basin models

The most used river basin management model comprises two main units: the hydrologic unit and the economic unit. The hydrological unit relates to the water balance in the hydrologic process, while the economic unit allocates water to different users based on criteria of maximising cost/gain. It determines and estimates the net salvage return for the different water users (Ahmad and Prashar 2010; Adams, Cowie and Van Niekerk 2016).

2.14.1 Hydrologic component

At the on-source, the river basin model consists of a node-link network (Awotwi *et al.* 2015). The nodes include the supply part: reservoirs, rivers, and groundwater aquifers; and the demand part: domestic use, industrial plants, and agricultural fields. Each of the delivery nodes is diagrammatically represented in Figure 17 and Figure 18.

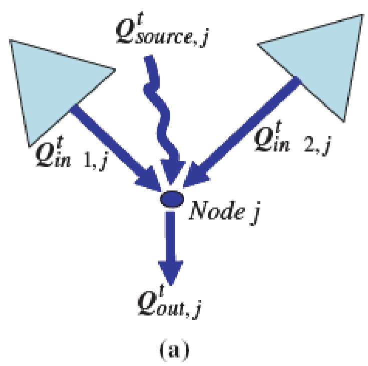

Figure 17: Diagram of a river confluence flow at source

Source: Cosgrove and Rijsberman (2014)

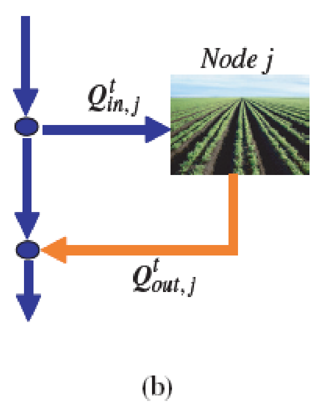

Figure 18: Diagram of agriculture water return-flow from the user

Source: Cosgrove and Rijsberman (2014)

At the confluence of rivers, Equation 20 represents the inflow and outflow for each time *t* for each node *j*

$$\sum_{out} Q^t_{out.j} = \sum_{in} Q^t_{in.,j} + Q^t_{source,j}$$ **Equation 20**

Where

$Q^t_{in.j}$ = inflow to the node j in period t (million m^3);

$Q^t_{out.j}$ = outflow from the node j in period t (million m^3); and

$Q^t_{source.j}$ = source of water for node j in period t (million m^3);

While, for the different water users, return flow from their diversion can be estimated using Equation 21.

$$Q^t_{out,j} = r_j * \sum_{In} Q^t_{deI,j}$$ **Equation 21**

Where: 0 $0 \le r_j \le 1$ is the return flow coefficient at node j (dimensionless).

The arrangement of the river reaches is illustrated in Figure 19.

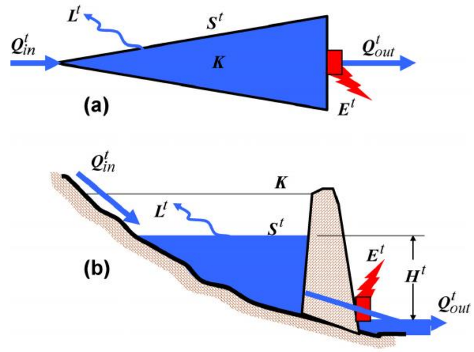

Figure 19: Arrangement of river reaches (a) and (b)

Source: Cosgrove and Rijsberman (2014)

For every river reaches and reservoirs site (Figure 19), water balances are calculated as represented in Equation 22. The water balance considers the seepage, evapotranspiration, outflow, precipitation and inflow (Arnold *et al.* 2012). The reservoir water balance can be:

Equation 22

$$S_j^t - S_j^{t-1} = Q_{in.j}^t - Q_{out.j}^t - L_j^t$$

Where

S_j^t = The volume of water in reservoir *j* at time *t* (million m^3);

$Q_{out.j}^t$ = release from reservoir *j* in period *t* (million m^3);

$Q_{in.j}^t$ = inflow to reservoir *j* in period *t* (million m^3); and

L_j^t = loss from reservoir *j* over time *t* (million m^3) from seepage or evaporation.

It should be noted that, for allocation based on efficiency, the economic component needs to be added.

2.14.2 Economic component

There exist different methods for evaluating the net economic return to domestic irrigation site, industry, and power generation site depending on the basin sector composition (Cai, Ringler and Rosegrant 2006).

The Net Economic Benefit (NEB) in a river basin is the summation of all component maximum net benefits from the supply of water to irrigation site, domestic and industry (D&I) water uses, and hydropower generation (if it exists), which are subject to operational, physical, and other constraints (Equation 23).

NEB is the summation of all the products of allocable water and the economic return of the sectors (Azevedo *et al.* 2000). Where the individual objective function (OF) is defined by Equation 24:

$$MaximiseZ = \sum_{j-Ag} NB_{Ag,j} + \sum_{j-M\&I} NB_{NB\&I,j} + \sum_{j-power} NB_{power,j}$$ **Equation 23**

The objective function is denoted as:

$$OF = \left[\frac{\sum_{i=1}^{n} S_i * NER_i}{AW_{(total)} * NER_{\max}} \right]$$ **Equation 24**

Where OF = objective function of maximisation of NER; Si = water supplied to sector i (m^3); NERi = net economic returns per unit volume of water from sector i (ZAR/m^3); AW

= available water (m^3); NERmax = maximum net economic return of a sector among the sectors considered (ZAR/m^3).

The constraints of the optimization problem are formulated as in Equation 25 to Equation 28:

(i) Water availability constraint:

$$\sum_{i=1}^{n} S_i \leq AW$$

Equation 25

(ii) Water demand and supply constraint:

$$D_{nori} \geq S_i \geq D_{\min i}$$

Equation 26

Where: D_{nori} =Normal or estimated water demand by sector I; $D_{\min i}$ = Minimum demand by sector i.

(iii) Non-negativity constraints:

$$S_i \geq 0, D_{nori} \geq 0, and D_{\min i} \geq 0$$

Equation 27

Limits on reservoir storage:

The storage volume in the reservoir can vary only between the minimum and maximum permissible storages (Equation 28).

$$S_{\min} \le S_{End} \le S_{\max} \qquad \textbf{Equation 28}$$

Where S_{min} (Mm^3) is the minimum permissible storage volume and S_{max} (Mm^3) is the reservoir capacity.

2.15 Performance evaluation, calibration, and validation of models

2.15.1 Model performance and evaluation measures

Studies centred around hydrology are highly significant as they aid the understanding of processes controlling water movement thus inversely impacting on quality and quantity of water (Abbaspour *et al.* 2014). Hydrological models often do not accurately depict the movement of water in a natural setting. Hence, for this reason, they are calibrated using past observed measured data (Arnold *et al.* 2012).

In line with this, the hydrological parameters alongside the temporal and spatial variability of river basins are perceived as integral towards the management and planning of water resources (Harmel and Smith 2007; Moriasi *et al.* 2012). The ‘deterministic’ approach to calibration is now outdated and unacceptable. It involves the optimization approach of ‘trial and error’.

In matching the simulated data with the observation data, the adjustment of parameters is required until some kind of reasonable match between simulation and observation are achieved. The SUFI2 algorithm represents a modern optimization tool for SWAT model calibration and validation (Abbaspour, Johnson and Van Genuchten 2004; Abbaspour 2007). This stand-alone model runs on a grid network for measured river discharges and quantification of the uncertainty in model outputs. The interface is independent of GIS and enables the processing of watershed delineation, and manipulation of the tabular and spatial data (Moriasi *et al*. 2015).

2.15.2 Criteria for model testing and performance evaluation

Different scientific efficiency criteria in evaluating a sound model calibration and validation have been suggested (Krause, Boyle and Bäse 2005; Krause *et al.* 2010). Manual performance of the SWAT model output can be assessed by comparing the model's ability to match monthly values of observed flow (mean monthly discharge).

A novel auto calibration program SUFI2 algorithm (Schuol et al. 2008), a sequential procedure of the SWAT Calibration and Uncertainty Program (SWAT-CUP) was used for the model sensitivity analysis, calibration and validation (Abbaspour *et al.* 2014). The SUFI2 algorithm uses different statistical efficiency criteria inbuilt into the programs to evaluate model performance.

It includes: the coefficient of determination, R^2 (Willmot 1981; Legates and McCabe 1999); the percentage bias measures, PBIAS (Gupta et al. 1999); the Nash-Sutcliffe efficiency coefficient, NSE (Nash and Sutcliffe 1970); and the root mean square error (RMSE) of observations standard deviation ratio. The statistical equations are given as in Equation 29 to Equation 32 respectively, where Yi obs is the ith observed data point, Y_{obs} mean is the mean of observed data, Yi sim is the ith simulated value, Y_{sim} mean is the mean model simulated value, and N is the total number of events.

$$R^2 = \left(\frac{\sum_{i=1}^{n} \left(Y_i^{obs} - Y_{mean}^{obs}\right)\left(Y_i^{obs} - Y_{mean}^{sim}\right)}{\sum_{n=1}^{n} \left(Y_i^{obs} - Y_{mean}^{obs}\right)^2 \left(Y_i^{obs} - Y_{mean}^{sim}\right)^2} \right)^2$$

Equation 29

$$PBIAS = \left[\frac{\sum_{i=1}^{i} \left(Y_i^{obs} - Y_{mean}^{sim}\right) \times 100}{\sum_{i=1}^{n} \left(Y_i^{obs}\right)} \right]$$

Equation 30

$$NSE = 1 - \frac{\sum_{i=1}^{n} | Y_i^{obs} - Y_i^{sim} |^i}{\sum_{i=1}^{n} | Y_i^{obs} - Y_{mean}^{sim} |^i} withj\, \xi N$$

Equation 31

$$RSR = \frac{RMSE}{SD_{obs}} = \frac{\sqrt{\sum_{i=1}^{n-1} \left(Y_i^{obs} - Y_i^{sim}\right)^2}}{\sqrt{\sum_{i=1}^{i} \left(Y_i^{obs} - Y_i^{sim}\right)^2}}$$

Equation 32

Typically, values greater than 0.5 for R^2 are considered acceptable for the coefficient of determination. Model efficiencies for the Nash-Sutcliffe Efficiency Index were classified by Moriasi *et al.* (2007) as very good (NSE = 0.75 to 1), good (NSE = 0.65 to 0.74) satisfactory (NSE = 0.5 to 0.64), and unsatisfactory (NSE < 0.5). The NSE higher values indicate less error variance.

The coefficient of correlation (CC) and root mean square error (RMSE) is the most frequently used for ANN performance evaluation measures during testing and validation (Paswan and Begum 2014). They are defined as in Equation 23 and Equation 24

$$CC = \frac{\sum_{i=1}^{n}\left[\left(Q_i - \hat{Q}_i\right).\left(P_i - \hat{P}_i\right)\right]}{\sqrt{\sum_{i=1}^{n}\left(Q_i - \hat{Q}_i\right)^2 . \sum_{i=1}^{n}\left(P_i - \hat{P}_i\right)^2}}$$

Equation 33

$$RMSE = \sqrt{\frac{1}{n}\sum_{i=1}^{n}\left(Q_i - P_i\right)^2}$$

Equation 34

where O_i is the observed value at time i, P_i is the simulated value at time i and $\overline{P}$ is the mean for the observed values. Observed runoff is used for model calibration and validation. Correlations are useful for indicating a predictive relationship that can be exploited in practice.

2.16 Socio-hydrological approach to water resources management

The socio-hydrological approach expresses the human-ecosystem water relationship. This is borrowed from an eco-hydrological approach that views watershed management from the water flow and water use perspective in classifying them into Greens and Blues (Sivapalan 2015). The Green perspective views economic water use in the growth of biomass as well as the ecosystem while the Blue perspective views the economic use of water in society for industry, domestic and agricultural purposes as well as viewing it as ecosystem dependent.

The socio-hydrological approach views water crises from a different perspective not only about human use but also balancing humans' water and natural water demand from an ecological perspective (Liu *et al.* 2014). The socio-hydrological water balance concept modifies the storage continuity equation (Zhou *et al.* 2015). Besides defining the relationship between inflow and outflow variables, it considers water required for ecosystem sustainability.

The socio-hydrological water balance framework partitions the evapotranspiration (ET) into societal and ecological systems as defined in (Equation 35 to Equation 39) (Sivapalan, Savenije and Blöschl 2012):

$$P = ET + R + G + dS/dt$$ **Equation 35**

$$\mathrm{P = ET_s + ET_e + R_{out} + {}^{dG}/_{dt} + {}^{dS}/_{dt}}$$ **Equation 36**

$$\mathrm{ET_e = ET_{ep} + ET_{eR} + ET_{eG}}$$ **Equation 37**

$$\mathrm{ET_s = ET_{sP} + ET_{slR} + ET_{sH} + ET_{s,oth}}$$ **Equation 38**

Where

$$D_R + D_G = ET_{sIR} + ET_{sH} + ET_{s,oth}$$ **Equation 39**

Where P = precipitation, ET = evapotranspiration; R = surface runoff, G = groundwater recharge and dS/dt = change in soil water storage. Ecological evapotranspiration component (ET_e) includes evapotranspiration from precipitation ET_{ep}, surface runoff (ET_{eR}) and groundwater ET_{eG} , in virgin vegetation areas, while, the societal evapotranspiration (ET_s) system component includes evapotranspiration in croplands and grasslands arising from precipitation (ET_{ap}) and irrigation (ET_{aI}) and water directly consumed by society: household water (ET_H) and other industries (ET_{oth}). Where: water diversions from surface runoff (D_R) and groundwater (D_G) represent irrigation water supply to croplands, grasslands, households and industries. The leftover surface runoff is meant for ecological purposes, (ET_{eR}) and outflows to the sea (R_{out}).

Shah (2005) mentioned the following workable solutions for water resources management in a watershed:

i. Banning private wells is futile; crowd them out by improving public water supply.
ii. Regulating final users is impossible; facilitate mediating agencies to emerge, and regulate them.
iii. Pricing agricultural water use is infeasible; instead, use energy pricing and supply to manage agricultural water use overdraft.
iv. A better alternative to improved supply-side management includes rainwater capture and recharge, as well as imported surface water in lieu of groundwater pumping.
v. Grow the economy, take pressure off land, and formalise the water sector.

2.17 Sustainable development indicator

There are several frameworks around which sustainable indicators can be developed, classified and organised (Kundzewicz and Kindler 1995; Sandoval-Solis, McKinney and Loucks 2010; Asefa *et al.* 2014; Collet *et al.* 2015). Hence, there are no agreed indicators for every purpose. Therefore, indices are used in evaluating one or more variable severity impacts, which help to avoid a biased decision-making process in a complex task like IWRM.

Sustainable indices offer usefulness in diagnosing water scarcity and serve as the basis for analysing in detail, the capability of the employed framework to sustain the system in the medium and long term. Another way to express relative levels of sustainability is either to use separate or weighted combinations of reliability (I_1), resilience (I_2), and vulnerability measures (I_3) (Lakshimi and Mohideen 2013).

In the context of work by Sadeghi *et al.* (2015), assessing the water allocation performance could be as stated in Equation 40:

$$\mathrm{SI} = \frac{100}{M}\sum_{i=1}^{M}\left(\frac{S_i}{D_i}\right)^2$$ **Equation 40**

Where M= number of years in the planning and horizons

D_i = annual water demand in the year i

S_i = annual water supply in the year i

SI = sustainability Index1

Xi and Poh (2013) in their work identified adequacy of water, self-sufficiency in water and economic sustainability as the most major features required in evaluating sustainable water management. Equation 41 to Equation 43 denotes their hypothesis. In general, the higher the index value, the less cost-effective the investment plan is.

$$Adequacy(t) = \frac{Totalwater\,\sup ply}{Totalwaterdemand}$$ **Equation 41**

Equation 42

$$Self-sufficiencyIndex(t) = \frac{TotalWaterSupply(t) - \text{Im}\,portedwater(t)}{TotalWaterDemand(t)}$$

Equation 43

$$\text{Cos}\,tIndex = \frac{AnnualInvesment(t)}{TotalWaterSupply(t)}$$

The Cost Index quantifies the extent of economic sustainability in the water sector. It gives a sense of how much investment has gone into the water sector to achieve a specific level of water supply.

Also, based on a study by Hoque, Hantush and Govindaraju (2014), Reliability (REL) and Resilience (RES) are defined as in Equation 44 and Equation 45. They show the chances of the successful period to that of failure.

Equation 44

$$\text{REL} = 1 - \frac{\sum_{i=1}^{k} d(j)}{T}$$

Equation 45

$$\text{RES} = \left(\frac{1}{K}\sum_{i=1}^{k} d(j)\right)^{-1}$$

Where:

K = number of failure events

T = total number of time intervals

$d(j)$= duration of the j^{th} failure event.

Vulnerability (I_3) is the ratio of total summation of average water demand to the deficit i.e., failure recorded in the system (Sandoval-Solis, McKinney and Loucks 2010).

$$VulI_3 = \frac{\sum_{t=0}^{t=n} Df_{it}}{No.of time I_i < 1 occurred / C_{i,t}}$$ **Equation 46**

Where $Vul\ I_3$ is the vulnerability indices and the first index $C_{i,t}$ indicates the average-e water demand (m^3/month); Df_{it}= Deficit in the system.

Volume vulnerability V_v and Time vulnerability V_t are expressed by Loucks (1997) in Equation 47 and Equation 48.

$$V_v = \max(S_j)$$ **Equation 47**

$$V_t = \max(d_j)$$ **Equation 48**

Where: (S_j) and (S_j)= magnitude and the duration of the j^{th} failure event

Equation 49

$$SI_i = [\operatorname{Re} S_i * \operatorname{Re} L_i * (1 - Vul_i)]^{1/3}$$

Sustainability Index (SI) is used to analyse and compare different scenarios. It can be measured in terms of Reliability (REL) and Resilience (RES) as in Equation 49 which varies between 0 and 1 (Safavi, Golmohammadi and Sandoval-Solis 2016).

2.18 Need for sustainable water allocation planning in South Africa

South Africa has been classified as a semi-arid country and the 30th driest country in the world (Crowley and van Vuuren 2013) with varying seasonal classification across the country (Fatoyinbo *et al.* 2017). The country cannot be left out, in formulating a sustainable water allocation plan to sustain the economy. Furthermore, a recent study reveals that South Africa presents a population of about 60 million people that has only 1,200 kilolitres of fresh water that is available per person, per annum (Umgeni Water 2015a). This is insufficient. However, considering the scanty precipitation and its uneven distribution across the country has brought the reoccurring challenge on how to manage and sustain the growing needs and demand for water use. This is of paramount importance in promulgating a sustainable water planning and catchment water regulation Acts (Quesne *et al.* 2010b).

2.18.1 Prioritise basins in KwaZulu-Natal Province, South Africa

According to Archer *et al.* (2010), Southern Africa has witnessed consecutive rainfall deficits with its multiplying effect on both the quantity and quality of available water and in some regions the resultant drought is severe. Besides conducted past studies in KZN basin by Kjeldsen, Smithers and Schulze (2002) and Haupt *et al.* (2017), recently interactions and documented records with DWS stakeholders confirmed that most river basins in KZN are highly stressed. Table 5 presents the DWS (2016) varying degrees of priority stressed basins in need of a water allocation reform programme (WAR). Mkomazi River system was chosen over those rivers prioritise 1 and 2 categorised because it remains the most untapped available water resources with conflicting users. The water resources exist almost all the year round and has not been adequately harnessed for sustainable allocation among its competing beneficiaries (DWA 2009). This has been identified and proposed for the actualization of the Mkomazi-Umgeni water transfer scheme (DWA 1999a, 2004).

Table 5: Priority stressed basins in KwaZulu-Natal Province

STRESSED CATCHMENTS IN KZN			**Priority**
Quaternary Catchment	River	System Name	Category
U20A – U20K	UUmgeni River	UUmgeni System	1
U60A, U60D &U60E	Umlaas River	Umlaas System	2
U40A-J, U30A-E, U50A	Mvoti River	Mvoti System	2
U80F	Mvoti River	Mvoti System	-4
T51A-T51J	Upper Umzimkulu	Upper Umzimkulu	2
T40A-G	Umtamvuna River	Umtamvuna System	2
T52A-M	Umzimkulu River	Umzimkulu System	2
U10A-M,	Mkomazi River	Mkomazi System	3
U70A-B	Lovu River	Lovu System	2
U70C-F	Lovu River	Lovu System	3
U80B-D	Umzube River	Umzube System	4
U80A	Mhlangamkulu River	Mhlangamkulu System	4
U80E	Mgababa River	Mgababa System	4
U80G	Fafa River	Fafa System	4
U80H	Mzinto River	Mzinto System	4
U80J-K	Mpambanyoni River	Mpambanyoni System	4
U80L	Mahlongwana River	Mahlongwana System	4
V20A-V20J	Mooi River	Mooi System	3
V70A-V70G	Bushmans River	Bushmans System	2
V31A-V33D	Buffalo River	Buffalo System	2
V11A-M, V12A-G, V13A-E, V14A-E, V60A-J	Tugela River	Tugela System	2
W21A-W23D	Mfolozi River	Mfolozi	3
W12A – W12H	Mhlathuze River	Mhlathuze System	2
W41A- W44E	Pongola River	Pongola System	2

**Priority list is as follows 1 = very high, 2 = high, 3 = medium, 4 = low* Source: (DWS 2016)

2.19 National Water Act (1998) and water licensing in South Africa

The water legislation guiding the South African water resources recognises the inter-relatedness of the water system, which links the hydrological cycle with the physical characteristics of the basin. The purpose of the National Water Act No 36 of 1998 (NWA) as stated in section 21 (c) and (i) of the government gazette state that "impeding or diverting the flow of water in a watercourse and altering the bed, banks, course or characteristics of a watercourse" are in general refer to as water use. This water use must be licensed unless it is listed in Schedule I, as an existing lawful use, is permissible under a general authorisation, or if a responsible authority waives the need for a licence" (RSA 1998). The Act sets out the country's objective of water for all in a 'phased and progressive manner'. The Act permits water use to continue under existing conditions until it is formally licensed.

'The Act' mainly addresses three principles: sustainability, efficiency, and equity (DWA 2009). The Act intends to ensure that the country's water resources are managed, protected and used in a manner that promotes equitability and sustainability for present and future generations (DWA 1998). The Act allows for the protection of aquatic ecosystems,wetlands and other water demand users.

A completely new institutional framework has been created to oversee water regulation, based on the devolution of responsibility to the lowest possible level. This was published in the National Daily of 24th March 2017, which states that DWS is the government agency responsible for monitoring and guarding the nation's water resources. The government agency states the procedural requirements for water use licence applications and repeals government gazette no. 40713, regulation no. R. 267.

A summary of progress with the current water licence registration as a means for water regulation is shown in Table 6 (DWAF 2004).

Table 6: Registered licensed water users present at Mvoti-uMzimkhulu WMA

River	Registered (HA)	Still Registered (HA)	Total no Registered (HA)	Total Water Use (Mm^3/a)	Forest Registered (HA)	Forest Still to Register	Total Forestry to Register (HA)
Mngeni	3,361	1,377	4,738	22,764	2,457	1,045	3,502
Mvoti	2,639	617	3,256	7,859	18,398	4.717	23,115
Blovo	758	271	1,029	3,932	4,165	2,514	5,679
Mkomazi	2,065	691	2,756	16,274	4,006	1,225	5,231
Umlaas	1,820	2,730	4,550	7,020	1,500	700	2,200
uMzimkhulu	4,947	967	5,914	298,290	5,224	1,135	6,359
Totals	**11,707**	**3,923**	**17,693**	**80,658**	**34,250**	**10,636**	**44,886**

Source: DWAF (2004)

The Act categorised entitlement to use water as: Schedule 1 use; general licences authorisations; and Existing Lawful Use (ELU).

‘‘Schedule 1 use’’ allows users to use water for their personal household needs and non-commercial food gardens use and without having to register this use. The general authorizations permit the use of raw water without a license in specific areas, so that they can make use of certain water resources without having to apply for a license.

Existing Lawful Use (ELU) allows people or organisations who were using raw water for commercial purposes before the new Act came into effect in 1998 to carry on using that water until they are called upon to apply for a licence under compulsory licensing at the catchment.

2.19.1 Water allocation during apartheid era

The annual water allocation plan in South Africa has had a long history since the apartheid era (the 19th century,) when water allocation was based on an irrigation cycle of halfmonthly time-step, except the East that uses a decade time-step (Clark 1959; Baudoin *et.al,* 2017). White people are the major players in commercial irrigation farming, and accordingly determine allocation percentages. This is best captured by the slogan ‘Some for All Forever’ which favours the white farmer over the other race farmer.

The country’s constitutional reform in the post-apartheid period overhauls the country’s past water use regulations and has ushered in the new nation’s water policy that is of an international standard in addressing the past imbalances in respect of HDIs (Mackay 2001). The South African government made a concerted and successful effort to implement a governance structure that will provide secure and sustainable water supply services to all (DWS 2016). The nation’s water policy framework was completely reformed between 1994 and 1997, ushering in a new water policy termed the National Water Act of 1998. The new policy reform laws were aimed at ensuring equity and public trust over the use of water and towards developing greater sustainability (King and Brown 2010).

2.19.2 Water allocation post-apartheid era

The new National Water Act, which was promulgated in 1998 ushered in a completely new institutional framework, which is based on the devolution of responsibility to the lowest possible level, and organised around hydrological units through a series of catchment management agencies (DWA 2004, 2009).

It sets out the Water Allocation Reform (WAR) programme to be implemented by the Department of Water Affairs (DWA), which addresses the socio-economic needs of water allocation. The Act seeks, among other things, to correct the historical imbalance in the allocation of water in South Africa. It also contains a series of programmes intended to achieve the broad objectives, vision, and mission of NWRS-2. The NWA further stipulates equity, sustainability and efficiency as guiding principles of water resource management

(McDonald and Ruiters 2005). The Act stipulates that water should meet international obligations, and serve the basic human consumption need, without neglecting the protection of the environment for ecosystem preservation. It has drawn on world's best practice.

2.20 Water allocation reform (WAR) programme

The toolkit for the WAR programme states how to achieve sustainability in water use. It provides an enabling environment for the efficient and the most beneficial use of water (Department of Water Affairs and Forestry 2004; DWS 2016). The potential for economic growth in KZN lies in two sectors, namely, Agriculture and Industry. In both sectors, WAR is fundamental to ensure that the region changes the landscape of water allocation and ensures that water is made available to HDIs. This will then contribute to the way water is allocated to address both the social need for redress and to grow the economy, which is vital to South Africa's future (King, Tharme and De Villiers 2000).

The WAR programme also recognises the previous limitations in developing and implementing new dams and water transfers. It now makes provision for a policy for future water management in South Africa. This includes the guidelines stated in Gillham and Haynes (2001) work:

- 'There shall be a certain "reserve" of water required to meet basic human needs, and maintain environmental sustainability;
- Water Allocation must promote and accomplish equitable and sustainable economic and social development;
- The binding general water use must include conservation and protection policy for all users;
- The recognition of river catchments as the basis for the establishment of catchment management agencies.

These (National and Basin) agencies implement the IWRM principles to integrate water demand from different sectors of society and to balance this with water availability. They see to the coordination of up-stream and down- stream uses (Pegram *et al.* 2013)'. The WAR programme states the procedural stages of implementing the integrated water resources management plan. The development of the IWRM plan starts with the identification of the basin goals, water resources issues assessment, climatic and demographic assessment, proposal of the IWRM plan, formulation of water resources policy and strategies, involvement/ participation of stakeholder and evaluation of the IWRM plan.

2.21 Benefit generation and sharing

Presently, there is no clearly defined framework which exists for benefit generation and sharing (Pallett *et al.* 1997). Most pilot-scale studies are based on trial and error identification and use in hydro-politics (Turton and Henwood 2002; Eriksson *et al.* 2015). Benefit generation and sharing is a concept, which seeks agreement among common river basin major users. It is meant to achieve equitable sharing based on understanding, transparency and an improved mutual symbiotic relationship especially for the transboundary countries (Turton *et al.* 2004).

It can be achieved through water demand management that aims to increase the efficient use of water and optimise the net economic returns for water use (Gupta and van der Zaag 2008). However, national and regional policies have to date neglected the issue of optimal water allocations across economic sectors (Mackay 2001; Kragt *et al.* 2011).

2.21.1 Environmental consequences of water regulation

The need for detailed basin-specific environmental assessment and verification of environmental flow requirement is of utmost importance in water regulation. Water regulation permeates needful use of water and its movement among various sectors' uses. It takes care of spatial-temporal change toward ensuring water availability (King, Tharme and De Villiers 2000).

Environmental Flow Requirement (EFR) is the minimum water required to maintain a healthy ecosystem including endangered fish species and the riparian corridor in a river basin. It varies between 15%-20% of the mean annual flow as recommended by United Nations (2000). A lesser percentage may be a detriment to the river's health. In addition, a reduction in the EFR of river flows decreases the ability of the river capacity to cope with pollutant loadings (Freebairn 2003). Sustainable use of water provides minimum EFR for a healthy river, economic development, and poverty alleviation. It ensures the continued availability of many benefits that healthy rivers and groundwater systems bring to society (Kandasamy *et al.* 2014). The health status of most of South Africa's river basins is a call for concern (Richter *et al.* 2003).

It is widely recognised that water allocation for aquatic ecosystems should take the natural variability of hydrological conditions into consideration because they are deterministic factors influencing geomorphology, habitat quality, water quality, as well as biodiversity of lakes (Smakhtin, Revenga and Döll 2004; Mitsch and Gosselink 2007). Water allocation for a river basin/lake is a means to allocate water as closely as possible to its natural regime to maintain particular ecological/wetland characteristics which are able to provide important goods and services (Gardner and Davidson 2011).

In recent years, many studies related to water quality assessment have been carried out using four main approaches which consist of: (1) water quality index (2) trophic status index (3) statistical analysis approaches and (4) biological analysis method e.g., Genetic Algorithms method and other different biological indices (Elshemy and Meon 2011). Cluster analysis (CA), factor analysis (FA) and principal component analysis (PCA) are multivariate statistical methods used for simplifying complex data matrices which aid the understanding of ecological dynamics and water quality (Jolliffe and Cadima 2016). They facilitate the identification of probable constituents that influence environmental systems of water while offering invaluable mechanisms for sustainable water resource management (Simonovic 2009; Shrestha and Kazama 2007; Praus 2005).

A variety of other studies have equally used this technique (Boyacioglu and Boyacioglu 2008) to identify the latent pollution source, and for classifying, sampling sites. Further to this, Gupta et al. (2013), equally utilise the CA in pinpointing the core pollutant. Against this background, it can be deduced that these techniques can be utilised to establish the relationship between variables and possible trends in the distribution of measured data.

2.21.2 Policies and legislations guiding water regulation

The Southern African general framework for resource allocations, benefit generation and benefit sharing; proposed a toolkit guiding water resources allocation and benefit (Grey and Sadoff 2003). The proposed regulations should include precautionary principles, a cooperative manner; economic benefits and costs. It is summarised below:

1. Resource allocations must be considered at the primary basin, secondary basin and tertiary basin level.

2. Transboundary resource management needs to be based on cooperative rather than confrontational management.

3. The need to prioritise shared water, meeting basic needs and ecological water requirements before considering other uses.

4. Information acquisition and data sharing which are essential for operationalisation of the benefit must be made available in a friendly environment.

5. Cooperative management of shared water resources. Data must also be available to the relevant stakeholders, including civil society.

2.22 Rules for water allocation planning

A variety of authors has postulated many water allocation-planning rules (Boland and Whittington 2000; Mokorosi and van der Zaag 2007; Gupta and van der Zaag 2008; Falkenmark and Jägerskog 2010). Majorly all these authors, address water sharing to be on the basis of precautionary principle and segmented development phased manner of integrated water resources management. This study, however, states Speed *et al.* (2013) eight 'golden rules' for basin water allocation planning. These are outlined in Table 7 below.

Table 7: The eight 'golden rules' for basin water allocation planning

S/n	Theme	Key message
1	Interbasin transfer	Where inter-basin transfers are proposed, water allocations should be planned and implemented with consideration for segmented development.
2	Institutional capacity	A strong institutional support is required in achieving a sustainable basin allocation process.
3	Reflect the main constituents	A sustainable water allocation plan should incorporate the core challenges and complexities of the basin.
4	Quantifying reasonably	Water should be apportioned reasonably from the onset, as reallocating in future can pose a financial, social, economic and political impasse challenged.
5	Sustaining the ecosystem	A good water allocation plan should put the ecosystem as a core priority.
6	Prioritisation by necessity	Water should be allocated to prioritised basic needs such as domestic and agricultural usage before being allocated to aesthetics and tourism concerns.
7	Efficiency	Water allocations should be based on an understanding of the relative efficiency of different water users particularly in a water stressed basins.
8	Seasonal and equitable considerations	Consideration should be given to seasonal variability while upholding equitable and a clear concession among users.

CHAPTER 3: STUDY AREA

3.0 Introduction

In this section, the physiological characteristics of the basin in relation to the study aim and objectives were examined. It begins with the study area digital elevation model (DEM) analysis in understanding of the river hydrological mechanism. The effect of hydro-climatic variables as they affect the quantity and quality of available water was subsequently examined. Also, the morphological and hydrological characteristic of the underlying geological strata on the basin lateral flow was equally discussed. Furthermore, the influenced of the vegetation cover, soil relief, soil type, land use, and land cover as part of environmental factors that greatly hinder the flow of water and the implementation of sustainable water allocation planning was discussed. The basin unique characteristics and its peculiarities as they mar or made the water quality to be safe for aquatic survival and preservation of their public benefit value were also examined. The section concludes with an exploration of the synthesised impact of climate change and human policy on the Basin.

3.1 Digital elevation model of the river

This session provides the necessary background for environmental consequences of water regulation and modality for water allocation planning. Digitizing is one of the most time-consuming tasks required to create vector layers from a raster data. The extracted DEM of Shuttle Radar Topography Mission (SRTM) 30 m resolution satellite imagery for the study area was digitized in QGIS environment in creating digital hydrological surface and watershed modelling. This help to provide a good and clear understanding of the catchment characteristics. The physiological source of the river starts in the upper Drakensberg mountains and discharges into the Indian Ocean, draining an area of about 4 400km^2 (Figure 20).

The river is approximately 170 km in length with an elevation at about 3 400m above sea level stretching from the north-west to the southeast region. The Mkomazi Catchment 'supports extensive agriculture (principally livestock grazing and sugarcane), intensive agriculture (citrus and vegetables), commercial forestry and subsistence agriculture'(Taylor 2001; Taylor *et al.* 2013). The headwater main-stream, as well as most of its tributaries, is characterised by steep gradients of altitude under present climatic conditions. This may have resulted in making land uses highly variable, which in turn affects the perennial nature of the intra- and inter-annual streamflow (Oyebode, Adeyemo and Otieno 2014). The digital elevation model analysis of the river provides the needed platform to investigate the applicability of an integrated hydrological model in a Geographical Information Systems (GIS) environment for sustainable water allocation planning and management.

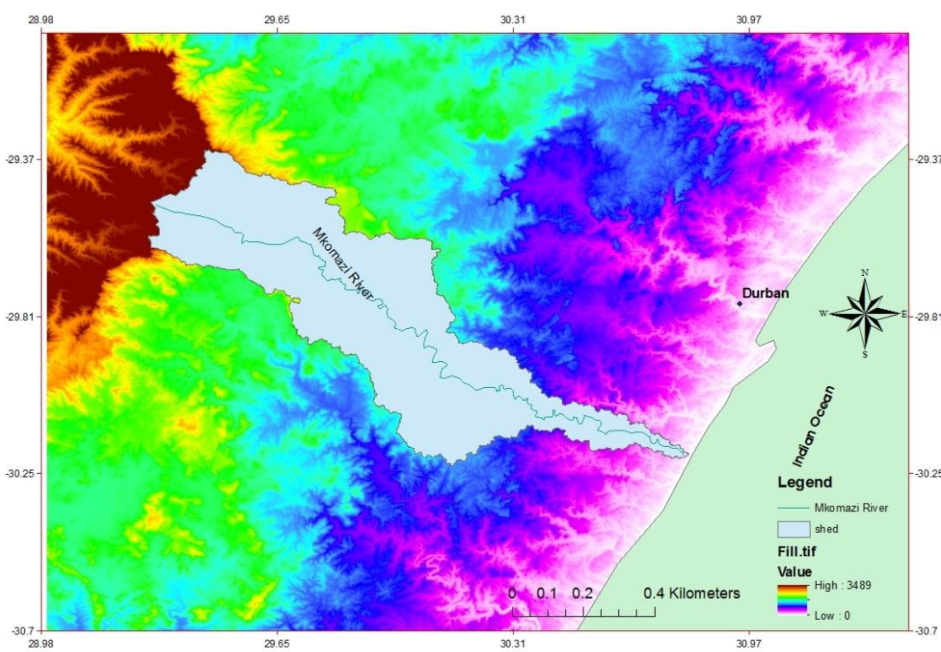

Figure 20: The location of Mkomazi Basin in KwaZulu-Natal Province

Source: ESRI ArcGIS 10.3.1 Software and online SRTM DEM Raster image

3.2 The Mvoti-uMzimkhulu water management area

The Mvoti-uMzimkhulu water management area (WMA) hosts the study area. It is among the three WMAs situated in KwaZulu-Natal Province (Figure 21). The water management area is home to the eThekwini Municipality, and includes industrial complexes of the greater Pietermaritzburg (PMB) and Durban areas.

Due to the high demand for water in the PMB and Durban regions, it was concluded from a pre-feasibility study conducted by the Department of Water and Sanitation (DWS) that two potential impoundment sites (Impendle and Smithfield) be located in the upper-middle part. Thus, the Mkomazi catchment was identified and proposed for the actualisation of the Mkomazi-Umgeni water transfer scheme (Department of Water Affairs and Forestry 1999, 2004).

Figure 21: The three WMAs situated in KwaZulu-Natal Province

Source: ESRI ArcGIS 10.3.1 Software and Department of Water and Sanitation GIS shape files

The catchment area is currently being used for commercial forestry and irrigated farming. Among the central towns, include Bulwer, Richmond, Ixopo, Impendle and the Sappi Saiccor paper industry near the coastal town of Umkomaas (Figure 22).

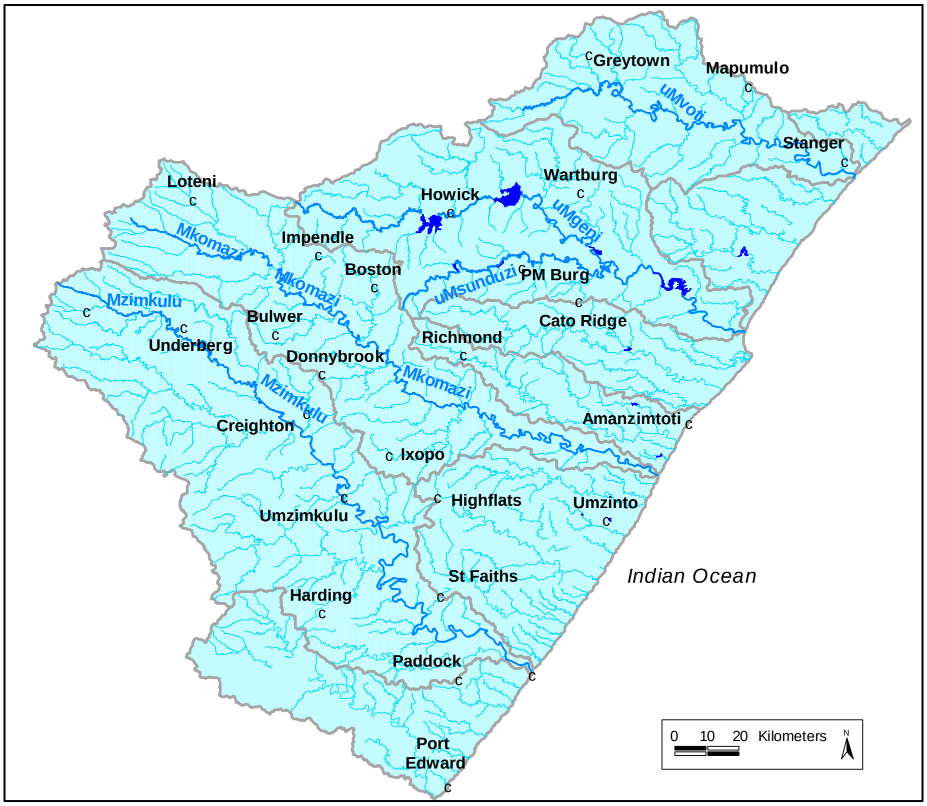

Figure 22: Umvoti/Umzimkulu WMA rivers and major towns around the catchments

Source: ESRI ArcGIS 10.3.1 Software and Department of Water and Sanitation GIS shape files

The physiographic factors include both the watershed and channel characteristics. A large watershed takes longer time for draining the runoff to outlet when compared to smaller watershed and vise-versa. Rivers with larger drainage areas tend to combine the flow effects of numerous conditions found throughout the basin.

3.3 Physiographic description of the study area

The Mkomazi River can be sub-divided into five physiographic zones (Figure 23):

i) The coastal lowlands up to 620 m (mean annual sea level - m a.s.l.);

ii) the interior lowland area ('middle berg area') from 620 to 1079m (m.a.s.l.);

iii) lowland area up to 1494m (m.a.s.l.);

iv) the mountain area up to 2011m (m.a.s.l.); and

v) The highlands, with elevations up to 3342m (m a.s.l.).

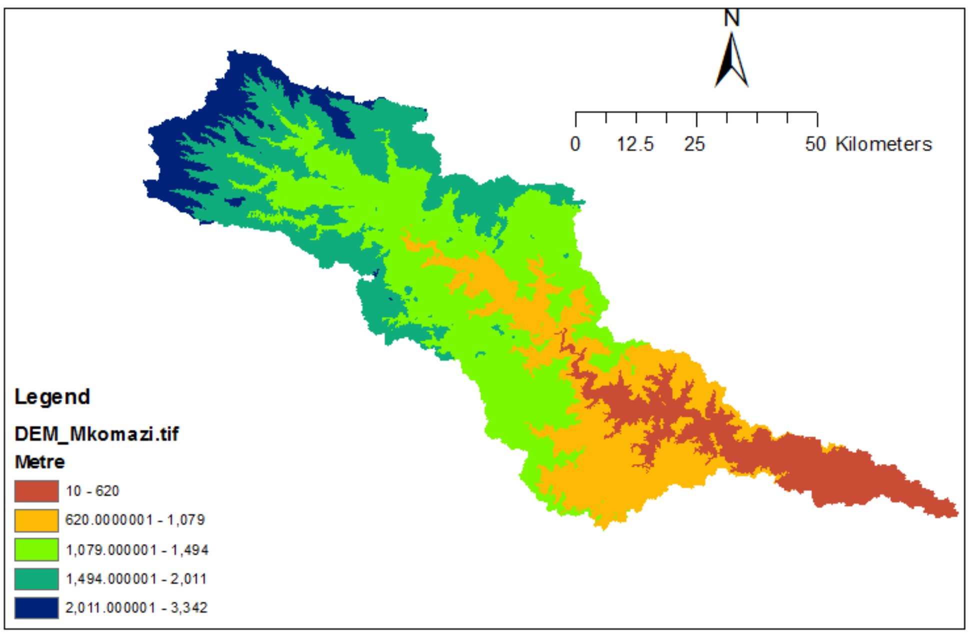

Figure 23: Mkomazi stream network with elevation zones

Source: ESRI ArcGIS 10.3.1 Software and online STRM DEM Raster image

The channel characteristics information can be used to generate a synthetic unit hydrograph based on known physical properties of the basin. The climatic condition of the study area varies with the seasonality of dry winters and wet summers (Flügel *et al.* 2003). Rainfall distribution is inconsistent along the catchment, ranging from nearly 1200mm per annum at the headwaters to 1000 mm p.a. in the middle and 700mm p.a. in the lower reaches of the catchment with highly intra-and inter-seasonal streamflows (Flügel and Märker 2003; Taylor, Schulze and Jewitt 2003 ; Oyebode, Adeyemo and Otieno 2014).

3.4 Hydrogeological potential of the study area

The basin has a potential source of groundwater yield that has not been fully utilised (Umgeni Water 2015a). The lithology stratification of the basin consists of sandstone, tillite and mudstone/shale. These lithologies (gneisses) support marginal to poor borehole yields (0.1–0.5 ℓ/s) with a median value of 0.3 ℓ/s (Umgeni Water 2015b). Its geology is predominantly intercalated arenaceous and argillaceous strata. Principally argillaceous strata and tillite interspersed characterise the middle part. The undifferentiated assemblage of compacted sedimentary extrusive and intrusive rocks forms the lower part while the assemblage of tillite and shale with basic/ mafic lavas form the remaining remnant upper part (Figure **24**).

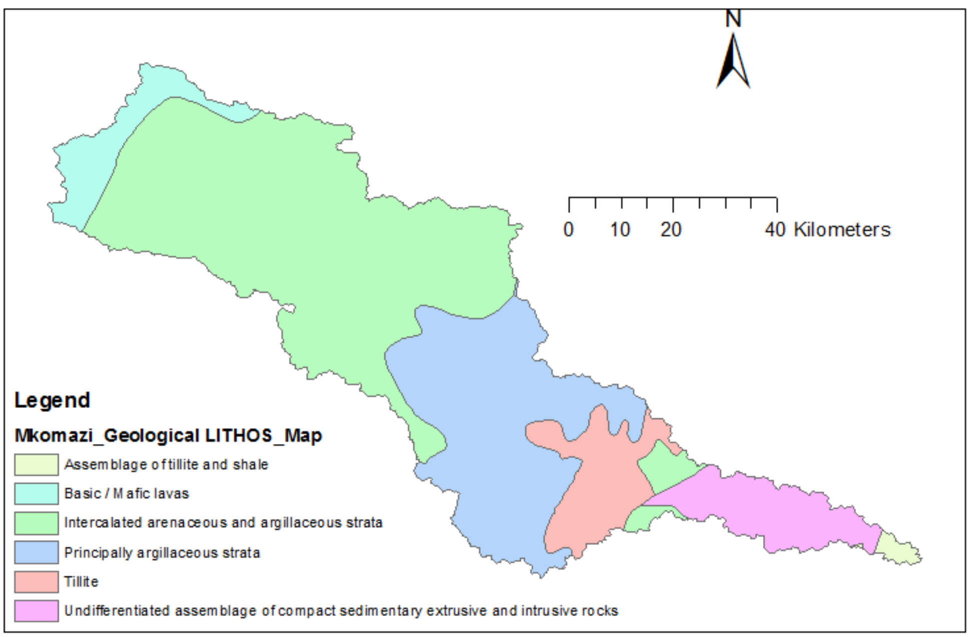

Figure 24: Mkomazi Basin Geological map

Source: ESRI ArcGIS 10.1 Software and Department of Water and Sanitation GIS shape files

The similar condition of lithology and geologic structures suggests the semi-arid regions have poorly permeable sub-soil with finer drainage density texture to warrant almost the same natural runoff across the basin.

3.5 Vegetation cover

Vegetation cover influences water flow within channels and on floodplains. Vegetation increases the flow resistance by producing flow separation and enhancing turbulence intensity (Blignaut, Ueckermann and Aronson 2009). As indicated in Figure 25, there exist five major vegetation belt types for the Basin – at the upper part exist the pure grassveld types; temperate and transitional forest and scrub types dominate the middle part; the lower catchment part consists of false grassveld, karoo and karroid types with coastal tropical forest type.

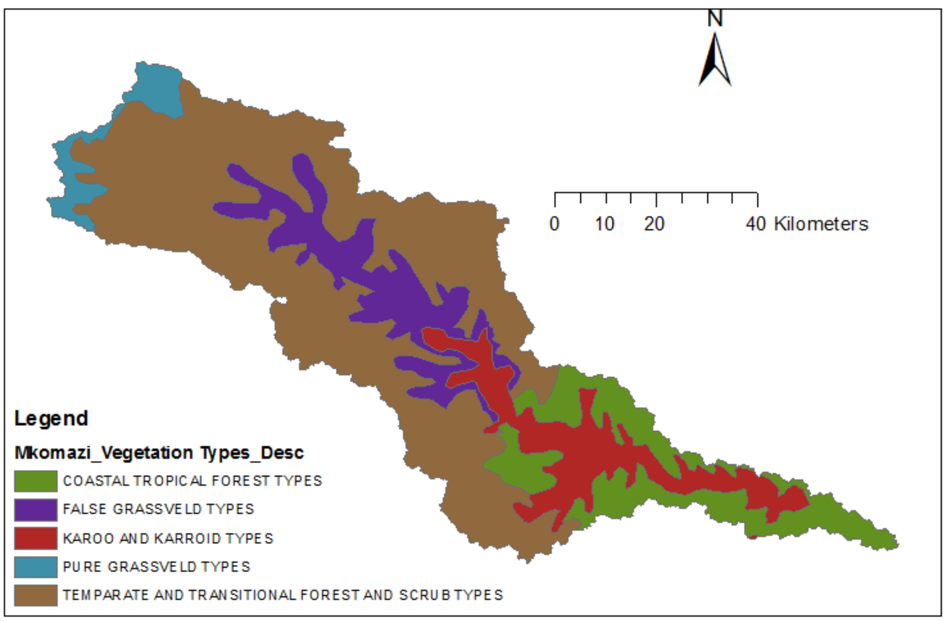

Figure 25: Vegeation types of Mkomazi Basin

Source: ESRI ArcGIS 10.3.1 Software and Department of Water and Sanitation GIS shape files

3.6 Soil relief and Soil type

Relief ratio measures the overall steepness of a drainage basin and is an indicator of the intensity of erosion process operating on the slope of the basin. The soil relief classification extracted from GIS shapefile for the basin (Figure 26) shows five categories ranging from 300-3000m. Based on MacVicar (1977) Dominant Soil ecotopes categories, the Basin was classified into 5 units of terrain namely: 1= crest, 2=scrap, 3=midslope, 4=footslope, 5=bottomland.

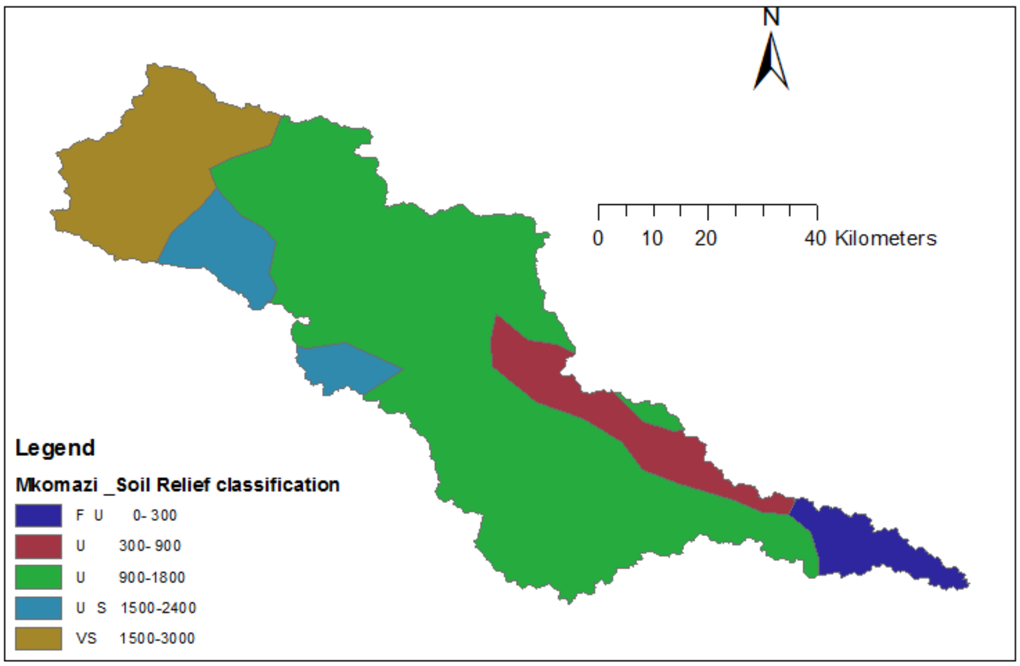

Figure 26: Mkomazi Basin soil relief classification

Source: ESRI ArcGIS 10.3.1 Software and DWS GIS shape files

The soil type and permeability rate are of considerable importance in the evaluation of watershed. They have a substantial influence on the rainfall-runoff process and the distribution of flow to the stream. Soil types like sandy soils are very easily drained whereas, soils containing clay can be almost impermeable and therefore, rainfall on clay soils will run off and contribute to flooding volumes. Extracted soil type from Food Agricultural Organisation (FAO) global data files from a harmonised digital soil map of the world (HWSD v1.1) (Nachtergaele *et al.* 2009) gives four main types of soil namely: sandy loam, loam, sandy clayey loam, and loamy soil for the processed soil raster image.

3.7 Land use and land cover (LULC)

The land is the most important natural resource, which embodies soil, water and associated flora and fauna involving the total ecosystem (Adams, Cowie and Van Niekerk 2016). The catchment land use is mainly grazing and commercial forestry (wattle, pines, and eucalyptus). The upper part is dominated by unimproved grassland with patches of agriculture and forest plantations while the middle and lower parts of the catchment have witnessed overgrazing and high population densities (Flügel *et al.* 2003). The land use pattern of any terrain is a reflection of the complex physical processes acting upon the surface of the earth. These processes include the impact of climate, geologic and topographic conditions on the distribution of soils, vegetation and occurrence of water.

The type of best management practices on land uses and land cover has a great effect on the runoff yield. An area with forest cover or a thick layer of mulch of leaves and grasses contributes less runoff because water is absorbed more into the soil. The changes in land cover/use have been most rapid on the foot slopes of the mountain where large commercial afforestation has been established (WR 2005). This has adversely affected the downstream and ecological systems leading to conflict over water demand, which calls for careful planning to alleviate the growing water challenges. The multifarious uses and demands have resulted in water stress situations particularly in times of drought, which has characterised the South African environment in recent times. Herrfahrdt-Pähle (2010) further states that conflict/ competition for water demand may arise due to:-

- Temporal variation in the climatic and hydrological regimes.

- Human-induced land use and management practices, which in turn are a determinant of environmental flow (e-flow).
- Insufficient water availability for riparian users particularly during the dry season.
- Illegal water abstraction leading to scarcity.
- Inefficient use of the scarce water resources (furrow irrigation).
- Inadequate enforcement of the water by-laws.

The underlying issue in all these factors is the incessant occurrence of water scarcity, and to maximise user benefits, efficient water resources planning and management in the basin is therefore crucial.

3.8 Hydrological and morphological characterisation of the basin

Timely and reliable information on the hydrological characteristic and geomorphological status of a basin is useful for better development and management of the watershed areas. They can be used in stage -discharge curve design to determine estimated depth of water 'y' in the channel or its present equivalent amount in quantifying the water accounting budget for the basin.

Table 8 represents the basin's morphologic and hydrologic characteristics over the past 15 years as released by DWS (2016). The table shows a consistent amount of evaporation (1300 mm), with a gradual variation in the amount (399-124 mm) of natural runoff that has been witnessed across the basin. This characteristic feature portrays the extent of temporal variation in the climatic conditions and hydrological regimes witnessed in the basin, which no doubt will affect the distribution and availability of water resources of the basin (Taylor *et al.* 2013; Umgeni Water 2015a).

Table 8: Basin morphologic and hydrologic characteristic parameters

Region	River(Watershed)	Incremental area (km^2)	Evaporation (mm)	Rainfall (mm)	Natural Runoff (mm)	Mm^3/yr.
Mkomazi	Impendle	1,422	1,300	1,138	399	568
	Smithfield	632	1,300	1,017	258.2	163.2
	Ngwadini	2,242	1,200	875	144.7	324.5
	Mkomazi Estuary	91	1,200	855	124.2	11.3
	Luhane	46.3	1,361	980	161.9	7.5

Source: DWS (2016)

The unique characteristics and peculiarities of the basin for aquatic survival and preservation of their public benefit value was examined in subsequent session 3.9 as part of water quality indices.

3.9 Mkomazi surface water quality and ecosystem survival

The water quality concern is more obvious amongst the rural settings which are mostly dependent on the raw water for their domestic use (DWAF 2014). Similar challenges regarding water quality have existed between the mainstream Mkomazi River and its lower tributaries. Over the years, the increasing human population concerned with agricultural activities alongside the river has significantly contributed to the contamination of the Mkomazi River, - mainly through the presence of faecal waste (DWAF 2014). Besides the inland town of Ixopo, the coastal region of Mkomazi and the Sappi Saicorr industrial region, most of the other areas are less developed with only a few economic activities. The water quality may also have been impaired because of prevalent sewerage problems in the catchment. The sewer network has continued to lose much of the sewage generated in the town of Ixopo to the catchment upstream of the Solly Bux Dam. This has polluted the water, thereby increasing the cost of treatment of the water at the Ixopo plant (Schulze and Pike 2004; Umgeni Water 2015b).

The main source of information for determining the water quality requirements for the protection and maintenance of healthy aquatic ecosystems is well documented in The South African Water Quality Guidelines volume 8. It is a compilation of all the different Targeted Acceptable Water Quality Ranges (TWQR), which have been previously discussed in volume one to seven of the gazette.

3.10 Mkomazi River and aquatic benefits

The Mkomazi River Basin's natural assets and cultural values are of immense value to all the riparian users. They are essential for domestic supply, irrigation, tourism, and industry. They have also served as a means of livelihood for subsistence farming and fish production (Zhang *et al.* 2009; DWAF 2014). In their work, Richter *et al.* (2003) and Tyson (1986) identified the aquatic community that exists in the study area to include: **Flora-** *Avecinnia marine, Rhizophora mueronata, Ceriops-candoleana, Tamarix spp, Salvadosa spp.;* and **Fauna:** Hydropsychidae and Simuliidae, as well as Elmidae and baetid mayflies, dominated the hydro-pneumatic groups (DWAF 1986; Adams, Cowie and Van Niekerk 2016). The Scaly Yellowish (*labeobarbus natalensis*) is the fish that is mostly found in the Mkomazi River system as well as in the Umgeni, uMzimkhulu, Thukela and the Umfolozi area (Schulze 1995; Department of Water Affairs 2013).

Umgeni Water (2015a) also indicated other fish species to include one red data species and three South African endemic species. Of the latter, the (*barbus natalensis*) fish species is the most endemic, common to both the Mkomazi and uMzimkhulu rivers in the KwaZulu-Natal Province region. Generally, the basin has a healthy, rich heterogeneous environment that supports a wide range of ecological species. This is evident from the abundant pest and invasive alien species which have become problematic in the river (Umgeni Water 2015a).

3.11 Socio-economic characteristics and beneficiaries of the river

The socio-economic characteristics of the study area reveal the agricultural sector as a vital player in the province's economy (Statistics SA 2010). The water resources in the catchment are widely utilised for many activities such as agriculture, drinking water, tourism, and the paper industry. According to the analysis made by Sutherland *et al.* (2014), the basin's problem related to water resources is mainly attributed to the insufficiency of water for agricultural and domestic use, which is diminished because of the temporality and the quality of the resource. The existing socio-economic situation consists of mainly small-scale farming among less than one-fifth of the population (Flügel and Märker 2003). The archaeological and cultural background comprises of Ubuntu tradition with significant historical artefacts (Nkondo *et al.* 2012).

The Mkomazi River system consists of both reused water sources and freshwater (WR 2012). The demand for Mkomazi water is at its peak (Hassan and Crafford 2006) due to the increasing population. Table 9 shows the population distribution in the Mvoti-Umzimkulu water management area where the study area is located (DWAF 2004).

Table 9: Mvoti-Umzimkulu water management area population distribution

	Total population	Population density *people/km*^{2}	%Urban population	%Rural population
Mvoti to uMzimkhulu WMA	5.12 Million	188	57%	43%
Umgeni	1 627 000	366	74%	26%
Mkomazi	167 000	38	4%	96%
Mvoti	304 000	111	19%	81%
uMzimkhulu	327 000	49	5%	95%

Source: DWAF (2004).

Agriculture production has maintained a consistent growth throughout the quarters of the periods 2001-2010 (Statistics SA 2010). The report shows an average economic growth rate of 3.8% for the period with agriculture workers accounting for 78.3% of the province's total. Table 10 depicts the basin poverty index and per capita income distribution in the basin (DWAF 2004).

Table 10: The basin poverty index and per capita income distribution

WMA	**Average annual per capita income (R)**	**Households**	**Households with electricity (%)**	**Households with piped water (%)**	**Poverty index**
Mvoti to uMzimkhulu WMA	11,200	1,126,144	61	56	0.37
Umgeni	15,100	368,250	70	63	0.23
Mkomazi	5,200	30,339	22	26	0.57
Mvoti	6,100	62,115	34	32	0.59
uMzimkhulu	6,400	61,421	12	14	0.63

Source:DWAF (2004).

A cursory look at Table 10 shows that the Umgeni catchment closest to the coast has the highest per capita income. As we move further from Durban to Mvoti up to the Mkomazi catchments, the relative per annum capita income drops to a meagre R5,200 which shows the poverty level in the area (DWAF 2004). The Poverty Index has been used as the best way to measure the region's standard of living (DWAF 2004; Brown *et al.* 2015). Based on Water Services National Information System (WSNIS) database (2004-2010), reported by DWS (2016), the approximate number of people with access to water below the reconstruction and development programme (RDP) level per water supply is no match for the growing demand in the KwaZulu-Natal Province and the eThekwini municipality (DWA 2009). Table 11 shows the municipal population growth rate from 2001-2010 (Statistics SA 2010), the number of households and their accessibility to water delivery service.

Despite the province's abundant river water resources, the table clearly shows that many of its citizens did not have access to basic services water supply. Also, the most significant change that has occurred in the basin in the past 30 years is the conversion of grazing land, bushland and natural forests into small-scale croplands, resulting in resources use conflicts (Priscoli and Wolf 2009).

Table 11: eThekwini population growth and their accessibility to water

Year	**eThekwini municipal population (census 2011)**	**Population growth rate**	**No of households (IMP 2010:46)**	**No of people that have access to water delivery (WSNIS)**
2004	3,268,832		874,168	410,426
2005	3,345,733	0.233	894,717	360,640
2006	3,376,631	0.092	902,442	325,686
2007	3,395,671	0.056	907,844	272,218
2008	3,421,552	0.076	914,701	209,669
2009	3,442,070	0.06	920,179	157,044
2010	3,609,259	0.475	938,124	110,754
Average	**3,408,535**	**0.166**	**907,454**	**263,777**
Medium	**3,395,671**	**0.056**	**907,844**	**272,218**
Std. Dev	**105062.31**	**0.17**	**20209.55**	**109945.44**
Range	**340,427**	**0.419**	**63,956**	**299,672**

Source: Statistics SA (2010).

CHAPTER 4: RESEARCH METHODS

4.0 Introduction

The mixed design approach method was adopted in this research. It considered the theoretical aspects of the subject matter in conjunction with collected archive documentations from DWS officers and gathering of field data records (quantitative). Figure 27 represents an epistemology analysis of quantitative and qualitative research interpretation.

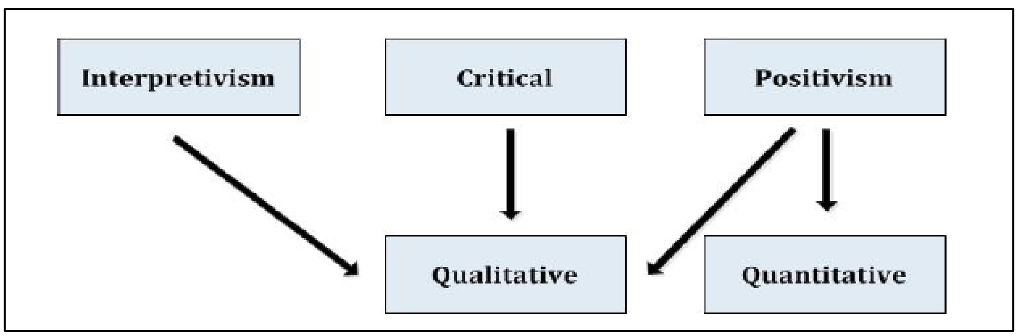

Figure 27: Epistemological assumptions for quantitative and qualitative research
Source: Onwuegbuzie, Johnson and Collins (2009).

4.1 Selection of an appropriate research approach

The quantitative data from the secondary sources agency (ARC, SWS) and satellite downscale image were used in the conceptual socio-hydrologic dynamic framework (HELPS) in addressing water resources management in a semi-arid region of South Africa. The applied research method was illustrated in Chapter One and below is the non-directional detail of the research methodology (Figure 28).

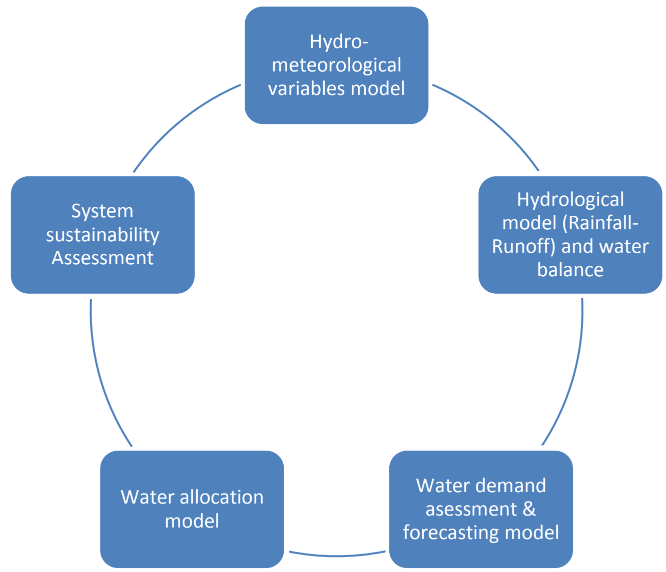

Figure 28: Schematised non-directional detail of the research methodology

The HELPS framework provides a chain of thought that analyses how structural changes in one part of a system might affect the whole system's behaviour.

4.2 Choice of integrated hydrological model

Based on Table 4 as discussed in Chapter Two, the SWAT model was considered appropriate for the study owing to the capability of the model, the type of available data which can be used to meet the study objectives, and its preferred treatment of uncertainty and spatial availability. The model has the ability to tackle a range of different problems related to water resources since the model is built in such a way that it covers more than one problem (e.g. water quality, soil erosion). Figure 29 presents an example of the possible modules included in one such spatially distributed model, SWAT (Arnold *et al.* 1998; Arnold *et al.* 2012).

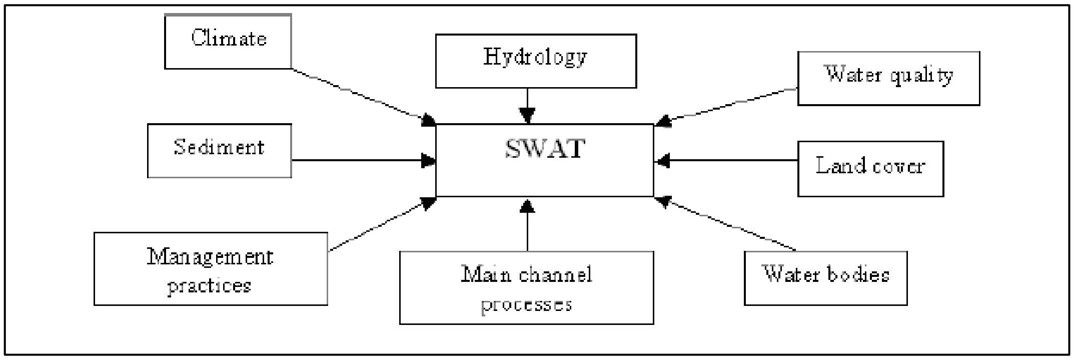

Figure 29: The Soil and Water Assessment Tool (SWAT) capability
Source: Neitsch *et al.* (2011)

As seen in Figure 36, the model addresses the various components of water management. Its effectiveness in handling different hydrological problems can be found in different studies (Birhanu 2009; Ndomba and van Griensven 2011; Arnold *et al.* 2012; Daggupati *et al.* 2016; Dile *et al.* 2016; Sun *et al.* 2016). The spatial heterogeneity in conjunction with its temporal hydro-climatic variability can be used to support any water allocation decisions in a deteriorated undeveloped river basin. SWAT has enjoyed a wide range of different users across the globe and it is well documented in the literature.

The model's ease of use and its adaptability to different watersheds in many countries and regions are a testimony to its efficacy. Based on these reasons, the SWAT model was chosen for the prefecture basin. Details of the applied methods used in achieving the specific objectives are discussed below:

4.3 Research methods for specific objective 1

To examine the trade-off among users by identifying the basin ecosystem dependants and analyse the surface water quality index rating into pollutant strength for their environmental and public values benefit preservation.

As a prelude to achieving this specific objective, the identify ecosystem dependent and other beneficiaries of the Mkomazi River was well described extensively in section 3:8-3:9 in Chapter Three. The water sampling design, the physio-chemical water quality data processing and analysis of the water quality index (WQI) rating were discussed subsequently WQI analyses are needed to balance both the temporal and spatial scales of the hydrological cycle with the ecological benefits for societal prosperity.

4.3.1 Water sampling design and parameters data

The collected dataset covering seven years (2012-2016) was extracted at the depository of South African water resources website (WR2012). The extracted data were analysed using the different multivariate statistical method to deduce similarities or dissimilarities between sampling sites, and their impact on the aquatic net benefit preservation. The sampling data sets of seven water quality parameters (pH; NO_3+NO_2-N; NH_4-N; F; PO_4-P; SO_4; and TDS (mg/l) were available at two monitoring stations 10E and 10M (WMS station 102619 and 102620, Camden and Shozi Delos Estate) along the river basins.

These data are available at varied percentile degrees of 5%, 50%, and 95% respectively. Therefore, the data range between the minimum and maximum value were used as a validity check and the reliability of such data. A cross-section of the sample water quality data set, is shown in Table 12.

Table 12: Cross-section of the min. and max. water quality data

Parameters		U10A	U10B	U10C	U10D	U10E	U10F	U10G	U10H	U10J	U10K	U10L	U10M
pH (Unit)	Min	7.68	7.68	7.68	7.68	7.68	7.68	7.68	7.68	7.68	7.68	7.72	7.72
	Max	8.03	8.03	8.03	8.03	8.03	8.03	8.03	8.03	8.03	8.03	8.03	8.03
NO3+NO2-N (mg/l)	Min	0.08	0.08	0.08	0.08	0.08	0.08	0.08	0.08	0.08	0.08	0.05	0.05
	Max	0.21	0.21	0.21	0.21	0.21	0.21	0.21	0.21	0.21	0.21	0.3	0.3
NH4-N (mg/l)	Min	0.02	0.02	0.02	0.02	0.02	0.02	0.02	0.02	0.02	0.02	0.02	0.02
	Max	0.11	0.11	0.11	0.11	0.11	0.11	0.11	0.11	0.11	0.11	0.09	0.09
F (mg/l)	Min	0.11	0.11	0.11	0.11	0.11	0.11	0.11	0.11	0.11	0.11	0.13	0.13
	Max	0.16	0.16	0.16	0.16	0.16	0.16	0.16	0.16	0.16	0.16	0.18	0.18
PO4-P (mg/l)	Min	0.02	0.02	0.02	0.02	0.02	0.02	0.02	0.02	0.02	0.02	0.02	0.02
	Max	0.06	0.06	0.06	0.06	0.06	0.06	0.06	0.06	0.06	0.06	0.07	0.07
SO4 (mg/l)	Min	3.00	3.00	3.00	3.00	3.00	3.00	3.00	3.00	3.00	3.00	7.75	7.75
	Max	9.49	9.49	9.49	9.49	9.49	9.49	9.49	9.49	9.49	9.49	13.94	13.94
TDS (mg/l)	Min	57.87	57.87	57.87	57.87	57.87	57.87	57.87	57.87	57.87	57.87	87.19	87.19
	Max	82.18	82.18	82.18	82.18	82.18	82.18	82.18	82.18	82.18	82.18	160.23	160.23
SO2-N (mg/l)	Min	0.16	0.16	0.16	0.16	0.16	0.16	0.16	0.16	0.16	0.16	0.18	0.18
	Max	0.02	0.02	0.02	0.02	0.02	0.02	0.02	0.02	0.02	0.02	0.02	0.02

While the descriptive statistical summary of the basin water quality was as presented in Table 13.

Table 13: Descriptive statistics of Mkomazi (U10) water quality variables

Statistic	pH (pH Unit)	NO3+NO2-N (mg/l)	NH4-N (mg/l)	F (mg/l)	PO4-P (mg/l)	SO4 (mg/l)	TDS (mg/l)
Minimum	7.680	0.050	0.020	0.110	0.020	3.000	28.080
Maximum	8.030	0.300	0.110	0.180	0.070	13.940	204.740
1stQuartile	7.680	0.080	0.020	0.110	0.020	3.000	57.870
Median	7.875	0.145	0.055	0.145	0.040	8.620	57.870
3rd Quart.	8.030	0.210	0.110	0.160	0.060	9.490	87.190
Mean	7.858	0.150	0.063	0.138	0.041	7.012	74.937
Variance	0.031	0.007	0.002	0.001	0.000	13.889	1476.368
Std_dev	0.176	0.081	0.045	0.027	0.021	3.727	38.424
Skewness	-0.011	0.293	0.039	0.042	0.052	0.148	2.032
Kurtosis	-1.987	-1.312	-1.959	-1.679	-1.916	-1.218	

4.3.2 The water quality index rating evaluation

In rating the surface water quality index into pollutant strength for their environmental and public values benefit preservation. The water quality assessment has been carried out using three main approaches, which consist of: (1) water quality index (2) trophic status index (3) statistical analysis approaches. Because of unit disparity, the normal and standardised representation of water sample analysis is required for effective statistical analyses. Figure 30 depicts the normal and standardised version of the water quality parameters.

Multivariate statistical methods consisting of Cluster analysis (CA), factor analysis (FA) and principal component analysis (PCA) are used for simplifying the complex data matrices. This aid the understanding of ecological dynamics and water quality as supported by(Jolliffe and Cadima 2016). They facilitate the identification of probable constituents that influence environmental systems of water while offering invaluable mechanisms for sustainable water resource management (Simonovic 2009; Shrestha and Kazama 2007; Praus 2005).

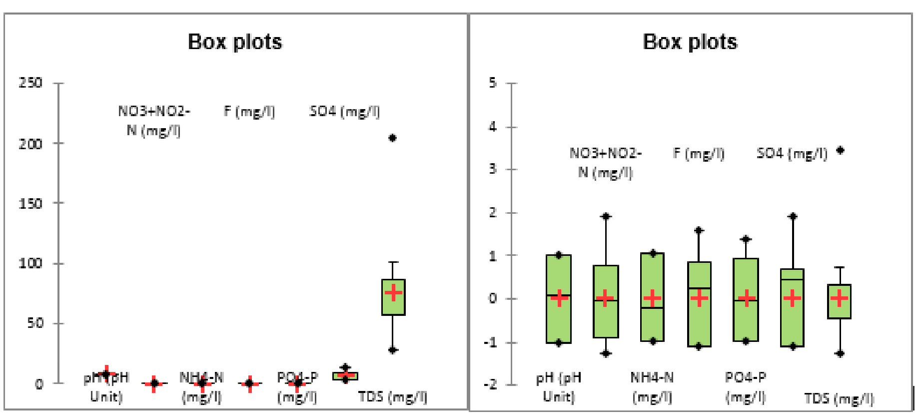

Figure 30: Normal and standardised representation of water quality data

The South African Water Quality Guidelines volume 8 serve as the primary source of information for determining the water quality requirements of different water uses and for the protection and maintenance of the health of aquatic ecosystems. These Guidelines were subsequently used in assessing the Mkomazi River status and its aquatic public benefits preservation.

The water quality index was evaluated by using the standard methods as per (DWAF 1996; APHA 1998, 2005), this was compared with standards prescribed by South African Water Quality Guidelines volume 8 WHO (2005). The weighted arithmetic index method has been used for the calculation of the water quality index (WQI). WQI calculation was done as outlined in the following steps by Abdul Hameed M Jawad, Haider S and Bahram K (2010):

1) Assign a weighting rate based on expert opinion
2) Calculate relative weight (RW) using Equation 50

$$RW = \frac{AW_i}{\sum_{i=1}^{n} AW_i}$$ **Equation 50**

Where, RW = the relative weight, AW = the assigned weight of each parameter, n = the number of parameters.

3) Thereafter, a quality rating was assigned to all the parameters except pH. This was achieved by dividing each sample water quality parameter obtained from the laboratory analysis by a standard recommended by the WHO (2005) or South African Water Quality Guidelines volume 8 DWAF (1996) based on drinking water guideline and the result was then multiplied by 100.

$$Q_i = \left[\frac{C_i}{S_i}\right] \times 100$$ **Equation 51**

$$Q_{pH} = \left[\frac{C_{i-} V_i}{S_{i-} V_i}\right] \times 100$$ **Equation 52**

Where, Qi = the quality rating, Ci = value of the water quality parameter obtained from the laboratory analysis, Si = value of the water quality parameter obtained from recommended WHO, V_i = the ideal value which is considered as 7.0 for pH. Equation 51 and Equation 52 ensures that Qi = 0, when a pollutant is totally absent in the water sample and Qi = 100 when the value of this parameter is just equal to its permissible value. Thus, the higher the value of Qi is, the more polluted the water is (Abdul Hameed M Jawad, Haider S and Bahram K 2010).

4) Finally, the computed WQI, (SI_i) were first calculated for each parameter using Equation 53 and Equation 54:

$$SI_i = RW \times Q_i$$ **Equation 53**

$$WQI = \sum_{i=1}^{n} SI_i$$ **Equation 54**

The computed WQI values could be classified as <50 = Excellent; 50-100 = Good; 100-200 = Poor; 200-300 = Very poor; >300 = Unsuitable (Shah *et al.* 2009).

Detailed results and analysis for the Basin WQI rating and categorisation for drinking, irrigation, and aquatic life utilisation are discussed in Chapter Five

4.4 Research methods for specific objective 2

To propose water allocation mechanisms in achieving equitable water distribution and large benefits from water uses across the basin's communities and users.

A methodological prototype framework model suitable for water resource allocation at catchment scale was developed from the literature review in Chapter Two section 2.1-2.6. The prologue in achieving this specific objective required reliable data and adequate information on water availability and water use. These serve as necessary input to water policies that aim to provide equitable and sustainable water use. As a result, this objective was further broken down into sub-objectives (A and B) to connote a logical scientific step towards its accomplishment. The sub-objective 2a involves the following:

- To evaluate techniques for data correction and verification for hydrological forecast study.
- To develop a reliable relationship between hydrological and climatic data.
- To use a data-driven method for rainfall forecasting.
- To determine a hydro-meteorological trend pattern and its implication for rainfall prediction.
- To examine how climatic-spatial and temporal changes affect stream flow patterns.
- To highlight the use of a flow duration curve in determining flow magnitude.
- To develop best-fitted probability distribution models for projecting water yield in a basin.
- To examine the impact of seasonal fluctuations in water allocations in non-stationary climates.
- To evaluate the use of machine learning technique (ANN, Mann-Kendall, and Sen's slope) in hydrological trend characterization based on different temporal scales.

While sub-objective 2b entails:

- To apply an integrated method for estimating actual water availability and use.

- To summarise this information in the form of water resource accounts and changes in the storage basin.
- To compute the basin water balance and distinguish between different components, such as green and blue water, non-beneficial consumption and beneficial consumption, non-recoverable fraction and recoverable fraction.
- To synthesise and summarise sustainable water allocation rules.

4.4.1 Collection and processing of data for models input analysis

The raw datasets required for the study were obtained from the South African Weather Information System (SAWs), the Agricultural Research Council (ARC) and the Department of Water Affairs (DWA), South Africa. The SAW_S provided corresponding climatic data such as daily and monthly precipitation sums (mm), relative humidity (%), wind speed ($m\ s^{-1}$), and mean, minimum and maximum air temperature for two independent weather stations, the Shaleburn and Giants Castle stations, located within the study area. ARC provided other meteorological datasets including Solar radiation (MJ/m^2), Sunshine duration (h) and Evapotranspiration (mm). Table 14 depicts a cursory variation in catchment location, daily and monthly related climatic data collected, while depicts the available climatic data stations.

Table 14: Catchment location and related years of available climatic data

Catchment no	Comp No	Lat	Long	Alt	Station Name	**Start Date**	**End Date**
U10J	19696	-29.933	30.15	1200	Richmond: Sapekoe Est.	10/1/1986	6/30/2005
U10L	30530	-29.948	30.315	841	Richmond; Burnside	1/1/2001	12/9/2015
U10J	30587	-30.011	30.238	389	Mkomazi valley; Crousaz	3/1/2002	6/29/2011
U10L	30813	-29.936	30.325	853	Little_Harmony	1/1/2008	8/15/2016
U10E	30914	-29.639	29.845	1355	Impendle: Sthunjwana primary shool	2/21/2011	8/15/2016
U10	[0237618 A9] &[026801 6AX] -	-29.29	29.59	1625	Shaleburn & Giants Castle (aws)	1/1/1990	12/31/2015

Figure 31depicts the location of the meteorology climatic stations.

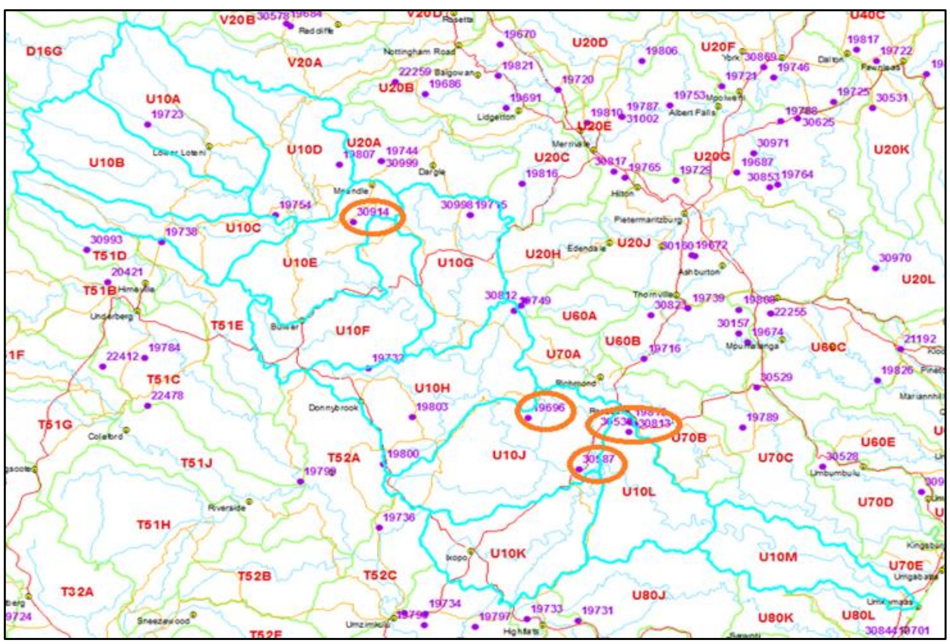

Figure 31: Mkomazi Basin screen meteorological stations used for the study

Source: Agricultural Research Council, South Africa.

The various stations' source data were processed and subjected to a rigorous scientific method to test their accuracy, reliability, homogeneity, consistency and localisation gaps. Only four stations met the above requirement. The year 2008-2015 represents the corrected available data used for this study (U10L 30530, U10J 30587, U10L 30813, U10 at Shaleburn, and Giants Castle stations).

4.4.2 Hydrological data source

The South African Weather Service (SAWS) provided complimentary historical monthly records of mean streamflow data for a period of varying years. Discharge data at four gauging sites with flow records dating back to as early as the 1960s exist in some parts of the catchment. Table 15 shows the observed data range for the River gauging stations.

Table 15: Observed Flow Data

Station Name	Frequency	Period
UIH006 @Delos Estate	Daily	1/11/1962 - 31/10/1982
UIH006 @Umkomaz Drift	Daily	1/11/1956 - 31/10/1957
UIH009	Daily	1/6/2005 - 30/9/2015
UIH005@Lot 93 1821	Daily	1/9/1990 - 31/08/1980

The site (U1H009) has the recently automated gauge equipment with adequate flow records. However, datasets from other gauging stations (U1H005 and U1H006 Mkomazi drift @ Dolas estate) located within the lower catchment of the river were relatively short and were not used. The resultant collated streamflow databases were carefully analysed and assessed using a frequency analysis-based spreadsheet.

4.5 Processing of rainfall data

Due to variability in the years of the creation of different rainfall stations and numbers of available historical meteorological data, there are some lost/missing values within the period of observation. Statistical correlation, regression and double mass curve have been employed for processing of rainfall data. Meteorological data corresponding to 1990-2015 was eventually selected for the analysis (15-years). The selected years cover an appreciable uniform length of rain gauge data with other meteorology data required in achieving the study's aim. These data were processed and they serve as the input vector space data for the study.

To start with, correlations were established among the various meteorological variables and later among the different rainfall stations to find those stations which have similar rainfall characteristics. Table 16 depicts the statistical summary of the dataset used while Table 16 contains the meteorological variables correlation matrix for rainfall-runoff.

Table 16: The statistical summary of the observation

Variables	Observations	Minimum	Maximum	Mean	Std. deviation
Solar	300	0.030	36.450	15.691	3.884
windsp	300	0.650	3.367	1.794	0.561
MaxRH	300	33.000	99.930	78.425	16.712
MinRH	300	3.000	66.340	32.765	15.144
Revo	300	9.000	194.550	97.307	30.259
Rain	300	0.000	353.200	64.394	61.918
Runoff	300	2.018	123.639	26.217	26.216

Table 17 contains the meteorological variables correlation matrix for rainfall-runoff while Figure 32 shows the hydro-meteorological variables map.

Table 17: Correlation matrix (Spearman)

Solar	windsp	MaxRH	MinRH	Revo	Rain	Runoff
1	-0.080	**0.254**	**0.300**	**0.594**	**0.436**	**0.393**
-0.080	**1**	**-0.545**	**-0.150**	**0.207**	-0.068	-0.087
0.254	**-0.545**	**1**	**0.777**	-0.077	**0.269**	**0.230**
0.300	**-0.150**	**0.777**	**1**	0.049	**0.364**	**0.363**
0.594	**0.207**	-0.077	0.049	**1**	**0.221**	**0.243**
0.436	-0.068	**0.269**	**0.364**	**0.221**	**1**	**0.340**
0.393	-0.087	**0.230**	**0.363**	**0.243**	**0.340**	**1**

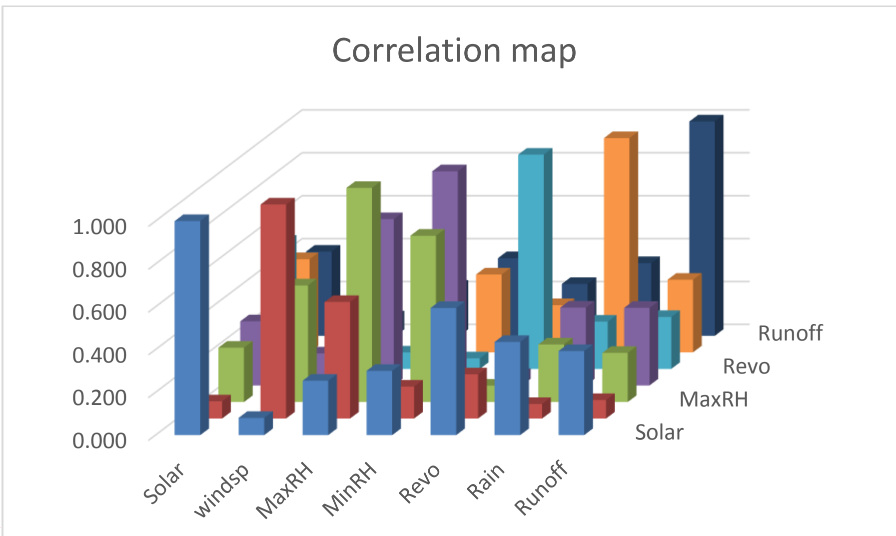

Figure 32: The meteorological variables correlation map

Furthermore, the worked-out correlation matrix was established between the different rainfall stations' distance and meteorological parameters in the form of their correlation coefficients. The stations corresponding to each rainfall reference station with average correlation (0.50), and which also lie within a specified distance (<50km) from the reference rainfall station, and whose average rainfall is close to ± 10% of the average rainfall of reference stations chosen for the analysis.

Table 18 depicts the results from the correlation coefficients distance matrix, and the average annual rainfall. The meteorological stations' variables that exhibited strong significance among the various stations mean that the stations have similar environmental characteristics. A value of 50 shows that the data stations' distance is close, fair and reliable to be used as a true representation of the basin's climatic condition.

Table 18: Distance matrix - values

Stations	1	2	3	4	Rainfall
1	14.200	29.667	20.616	38.587	38.300
2	38.300	98.960	78.949	16.878	98.960
3	3.520	64.550	53.472	75.207	78.949
4	19.910	183.510	103.046	28.851	56.878
Rain	32.000	179.800	68.659	52.473	59.373

The result reveals that stations 2, 3, and 4 correspond to stations U10L, No: 30187; U10J, No: 9696 and U70B, No31534 (as nearby stations) and whose data are highly correlated.

4.5.1 Double mass curve analysis

Thereafter, the consistency of rainfall data of all stations was checked using the double mass curve (DMC) method. The DMC uses the principle that the observed datasets coming from the same parent population are consistent (Equation 55). An index station A is selected to which cumulative yearly average rainfall dataset is plotted against accumulated values of nearby group stations (as a base). This is then arranged sequentially (starting from the most recent year to the earliest year's records) to cover the total periods of investigation. A break in the slope of the resultant plot shows a change in the precipitation regime of the index station. This is corrected using the prior value of the index station before the change is noticed.

$$P_m(i) = m \times C_A(i) - C_X(i-1)$$ **Equation 55**

Where $P_m(i)$ is the corrected rainfall at the index station A during year i; m is the initial slope of the line; $C_A(i)$ is the cumulative mean rainfall up to the year i; $C_m(i-1)$ is the cumulative rainfall at the index station A till the year i-1. Figure 33 shows the annual DMC for rainfall station at U1H001 Mkomazi.

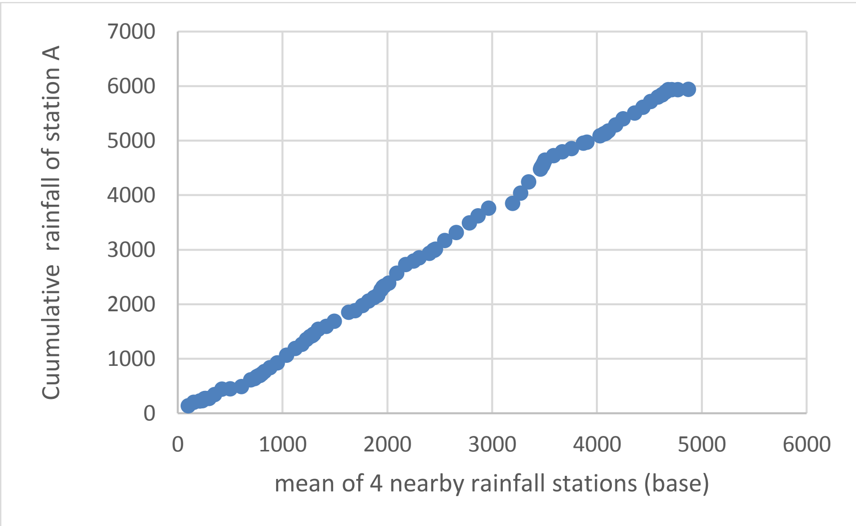

Figure 33: The annual DMC for rainfall station at U1H001

No significant change of slope is observed in the double mass curves for four out of the six stations. However, two stations, viz U10M and U10L, exhibited some inconsistency. The corrections for these stations were the slope of backward years before the changes were noticed.

Using the observed rainfall data of correlated stations and their average annual rainfall (shown in Table 19), the gaps in the observed rainfall series for all the chosen stations have been filled by using the normal-ratio method. The corrected complete dataset for rainfall is now available for the years 2005-2015. Table 19 depicts the catchment location, distance, and average annual mean rainfall value.

Table 19: Catchment location and average annual mean rainfall value

Catchment no	Station Name	Distance (Km)	**Average annual rainfall (mm)**
U10J	Richmond: Sapekoe Est.	32.00	1015.16
U10L	Richmond; Burnside	179.80	695.5
U10J	Mkomazi valley; Crousaz	68.65	538.44
U10L	Little _Harmony	52.47	801.363
U10E	Impendle: Sthunjwana primary school	59.37	674.54
U10M	Zz2_naturesfarmings	78.95	437.921

4.6 Hydrological variability of the basin to climate change

The growing number of signs indicates that global water yield at different basins has been negatively impacted by the postulated changes in climate (WMO 2007; IPCC 2008). Hydrological modelling for projected water allocation needs to consider non-stationary data for any hydrologic design, planning or management purposes. The consideration of this non-stationary data trend will help to justify the choice of model used and give insights into the basin's underlying physical mechanism that has been occurring.

The basin's response to climate change was studied in this section using an ombro-thermic diagram. This relates to the wetness and dryness period over time. It uses a simple line graph to show the relationship between rainfall and temperature as major climatic factors, which affect a place.

4.6.1 Ombro-Thermic Diagram of stations in the study area

Rainfall and temperature are the two important climatic parameters which determine the climatic situation of any place (Martin *et al.* 2016). The ombro-thermic diagram helps to identify the dry and wet months in a region (Sumathi *et al.* 2011). It uses a simple line graph of monthly average rainfall and means temperature or evapotranspiration plotted on both the Y-axis of the graph scale with months on the X axis respectively. It has enjoyed wide usage in a Mediterranean climate to establish the temperature - rainfall relationship.

However, some researchers may argue that the best method for defining the limits of the dry period in an erratic climate region is to use the ratio P/ETP (P= precipitation, ETP= potential evapotranspiration). A ratio of 0.35 is defined as the threshold below which dryness does not allow the growth of plants (Sumathi et al. 2011). However, the ratio gives very similar results to those of Gaussian's empirical system (Blondel 2010), where a 'dry' month is defined as one having precipitation less than or equal to twice the average temperature for the same month. The ombro-thermic diagrams across the basin stations are summarised in Figure 34, Figure 35, and Figure 36.The year 2008-2015 is used as a common base due to variations in stations' collected data.

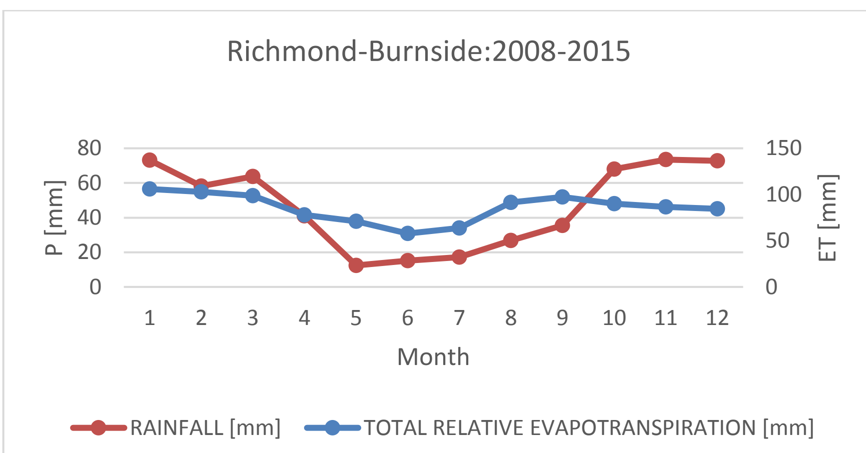

Figure 34: Ombro-thermic diagram for Richmond-Burnside station

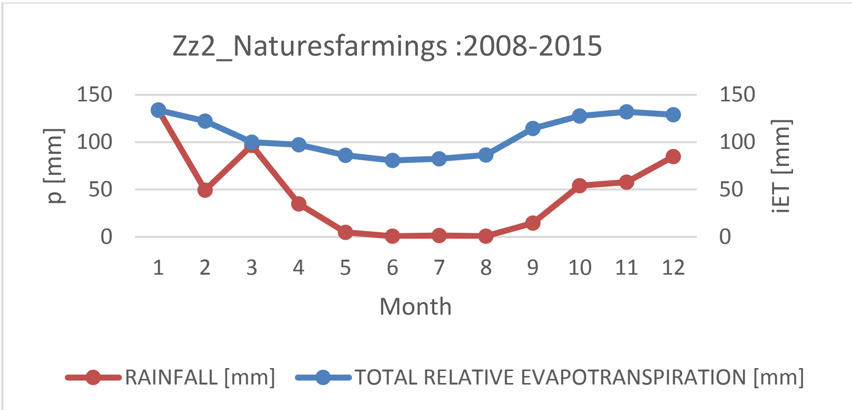

Figure 35: Ombro-thermic diagram for ZZ2_natures farmings station

It is evident from the above diagrams that the months March to September are considered as wet months as they fall above the mean temperature, while the other months are dry months as they fall below the mean temperature. These trends are also evident in the minimum and maximum Temperature and Rainfall relationship for Richmond Burnside 2008 - 2015 (Figure 36).

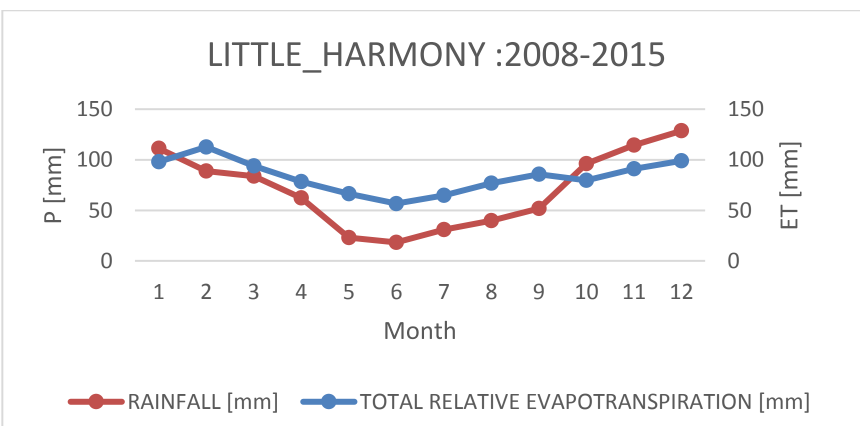

Figure 36: Ombro-thermic diagram for Little_Harmony station

4.6.2 Discharge variability frequency trend analysis

A frequency trend analysis of hydrological discharge variation of the basin helps in understand the prevailing underlying physical mechanism occurring in the basin. This can be used as a basis for adaptation strategies planning for a water allocation study. Four gauging sites with flow records dating back to as early as the 1960s exist in the catchment. Figure 37 presents the mean monthly and annual discharge for the various gauging stations collected data.

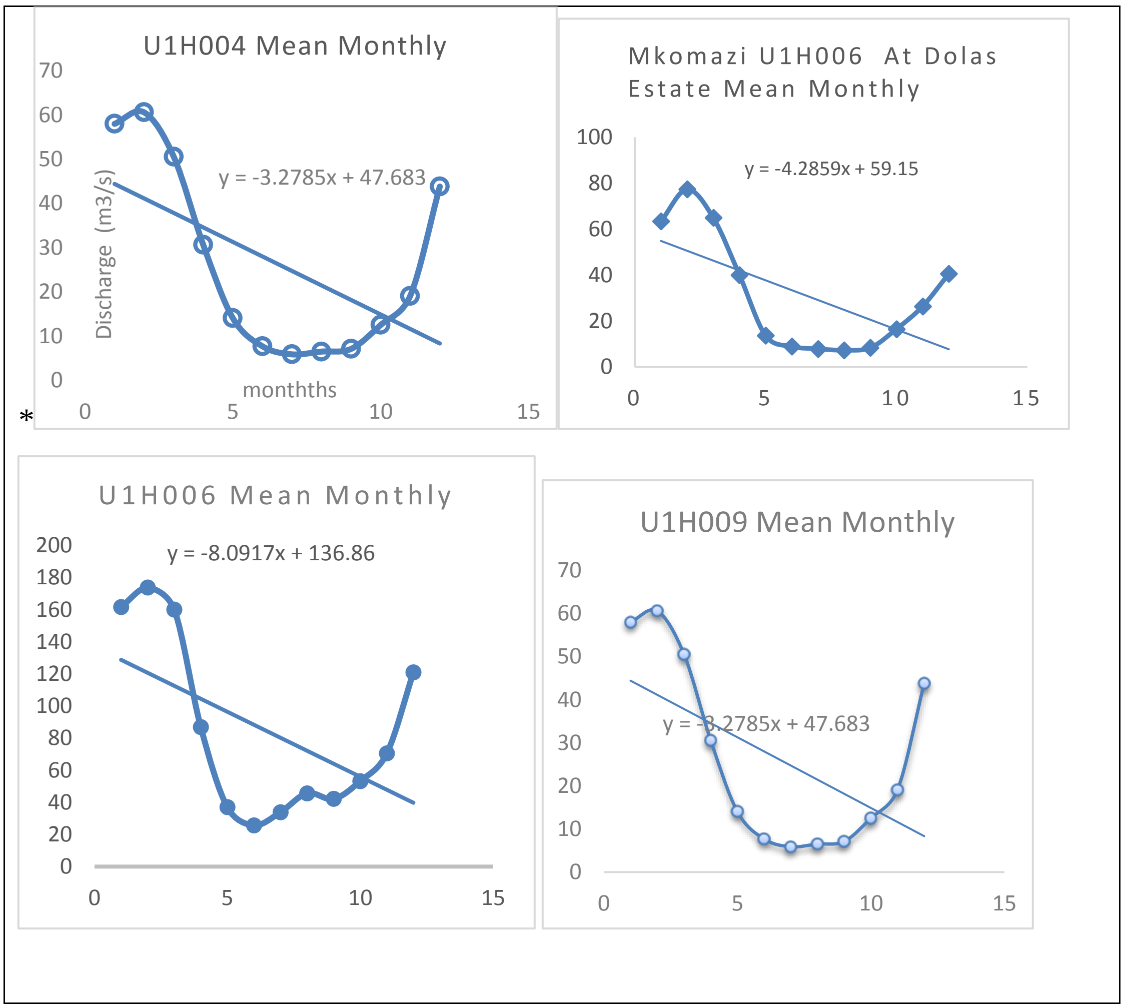

Figure 37: Mean monthly discharge at various gauging stations

It was observed that the region has been experiencing a decline in flow regime (Figure 39) with the lowest record between May and October and a gradual increase usually from November until January. The graphs of mean annual discharge variation at the different gauging locations also follow the same trend. Figure 38 presents the annual time series trend.

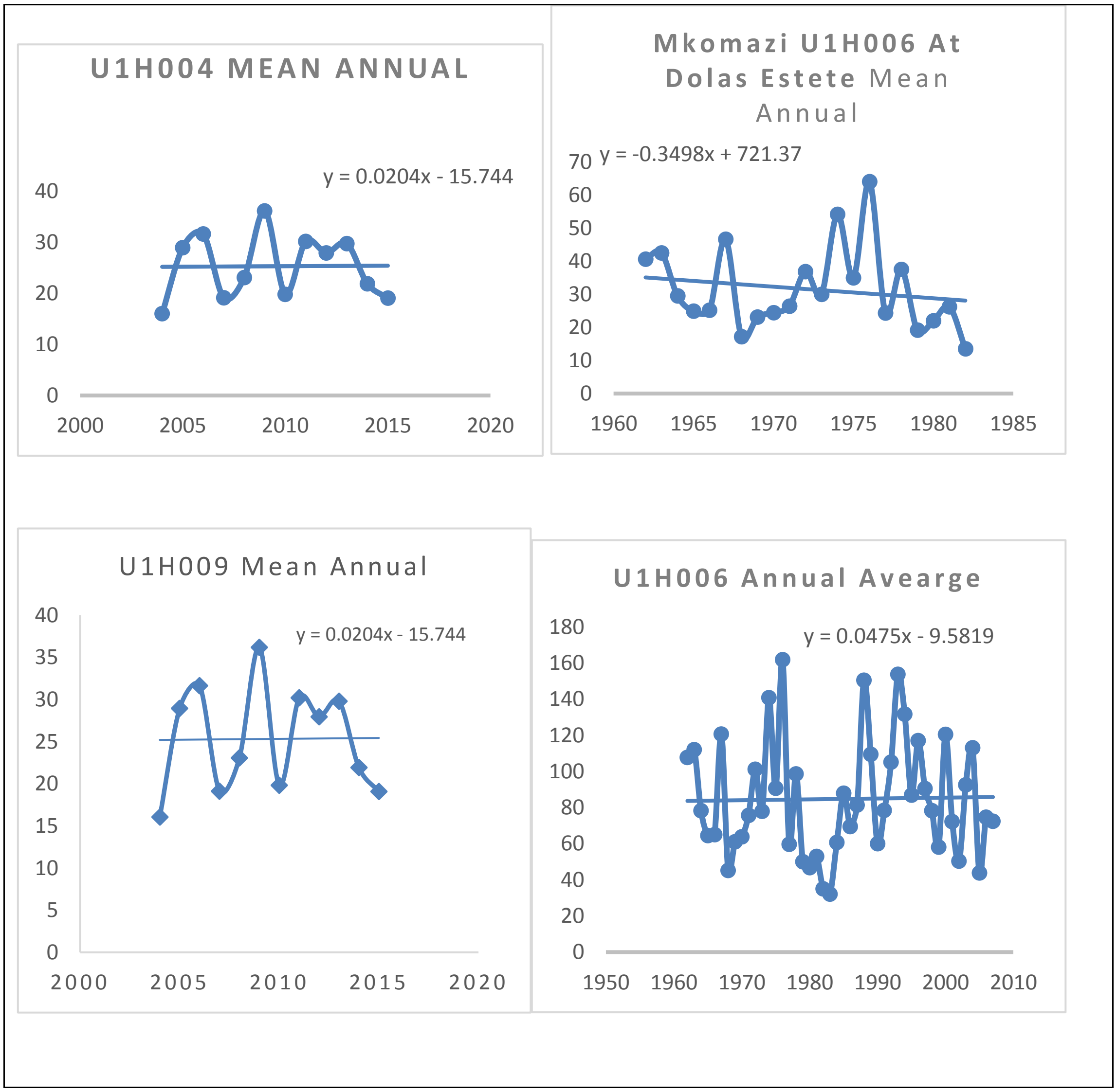

Figure 38: Mean annual discharge of meteorological weather stations

4.7 Methods for establishing rainfall and streamflow relationship

Modelling streamflow and rainfall have been explicably complex due to their dynamic nature and the non-linearity of its hydro-meteorological variables (Mugumo, Ndiritu and Sinha 2013).

In this section of the study, cross-correlation, exponential function, linear and non-linear statistical regression tools have been used to model the streamflow and rainfall relationship. The developed model closely mimics the basin's characteristics and establishes a network sectorial forecast between the upstream and downstream variables. This is useful to validate the streamflow forecast.

The correlation coefficient between rainfall and runoff for Mkomazi River establishes a relationship between the upstream (U10B) and downstream (U10M) which is shown in Equation 56:

$$r = \frac{\sum (P_{U10B} R_{U10M} - nP_{U10B} R_{U10M})}{\left(\sum P^2{}_{U10B} - nP^2{}_{U10M}\right)\left(\sum R^2{}_{U10B} - nR^2{}_{U10M}\right)}$$ **Equation 56**

Where n = number of years of record = 8 years; $\mathbf{P}_{U10B}$ = Mean Annual Precipitation for Sevav = 1225mm; $\mathbf{R}_{U10B}$ = Mean Annual Runoff of Mkomazi River at downstream = 443mm.

The correlation coefficient results of 0.825 imply that the basin lies in a hydro-meteorologically similar environment. Microsoft Statistical software XLSTAT by Addinsoft was used for the statistical time series analysis of linear, non-linear and cross-Exponential correlation to test the variability and homogeneity trend relationship between the rainfall and the streamflow series. The results analysis of the linear and nonlinear regression model of Runoff to Rainfall variables is as presented in Figure 39 and Table 20

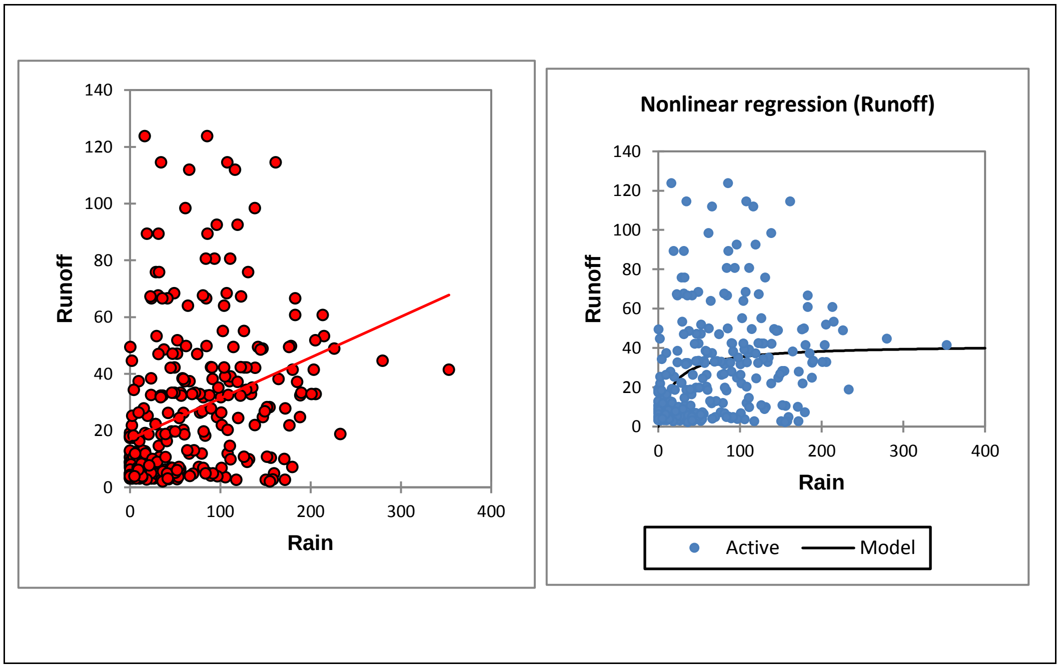

Figure 39: Linear and nonlinear regression of plot of rainfall-runoff variables

Table 20: The linear regression model parameters (Rainfall-Runoff)

Source	Value	Standard error	t	Pr >|t|	Lower bound (95%)	Upper bound (95%)
Intercept	16.952	2.059	8.233	< 0.05	12.9	21.004
Rain	0.144	0.023	6.238	< 0.05	0.098	0.189

Runoff = 16.9517180922342+0.143882932082037*Rain

While the Nonlinear Regression Equation model is of the form:

Y = 1 / (1+Exp (-pr1-pr2*X1) and it is given as Figure 40:

Runoff = 41.6748607391847*Rain / (17.876708256097+Rain)

The developed best-fit exponential equation (Figure 40) for the basin runoff-rainfall relationship is of the form $(Q_m) = \exp(\alpha) P_m^{\exp(\beta)}$. Where $\boldsymbol{Q_m}$ = Discharge; $\boldsymbol{P_m}$ = precipitation.

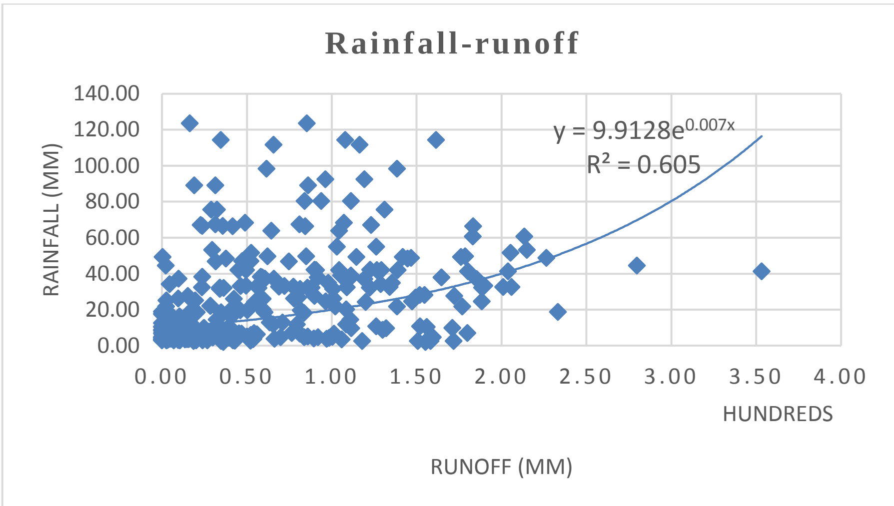

Figure 40: Exponential regression of plot of rainfall-runoff variables

The study area (MRB) has witnessed variation in climatic conditions and human activities, which have altered the hydrological regime. Mugumo, Ndiritu and Sinha (2013) argued that the conceptual South African water resource-planning model (WRPM) currently used to simulate stochastic streamflow into reservoirs is overly complex. Moreover, the estimation of the basin water resources has been based on various empirical relationships developed elsewhere, whose best value result can hardly be applicable and defended in this environment. The use of numerical modelling methods, including dynamic regression, conditional probability time series and Artificial Neuron Network has been investigated in this study for developing a rainfall case forecast model fed by environmental variables. A detailed analysis can be found in Amoo and Dzwairo (2016).

4.8 Method for determining seasonal streamflow forecasts

In assessing the basin hydrological runoff, the climatic conditions and latitudinal location of the study area are the main determining factors (Milly, Dunne and Vecchia 2005; DWS 2016). To date, no research has examined how climate-driven spatial and temporal changes to streamflows have affected the re-allocation of water among the contending users with seasonal-variability consideration. Hence, the CMA cannot afford the basin capacity to be stretched beyond breaking point before putting regulating measures in place. Hydrological variability trend characterization on different temporal scales based on available past data and rainfall variability is of utmost importance for sustainable water allocation planning and management.

In this section of the study, an Artificial Neural Network (ANN) pattern classifier was utilised for seasonal classification and hydrological flow regime prediction. Statistical factor and principal component analysis were used in data preparation as input for ANN forecasting.

The exploration in seasonal trend forecasting of storm runoff from rainfall anomaly investigates the year-to-year variation in sensitivity within each watershed characteristic. Sen's slope abrupt change detection and the Mann-Kendall parametric trend analysis were used to establish the relationship between climatic indicators and past catchment conditions. Beyond the long-term seasonal analysis, an inter-annual analysis was also performed to analyse historical rainfall and streamflow data in the river basin. The ANN input hydro-climatic data analysis covering the period 2008–2015 provides a likely forecast of high, near-median, and/or low streamflow. Table 21 gives the statistical summary of the selected station's data use, while Table 22 represents the result of the homogeneity test.

Table 21: Statistical summary of the selected station year (2008-2015) variables

Variables	Unit	Minimum	Maximum	Mean	Std. dev
MaxT	°C	14.400	33.170	24.408	3.442
MinT	°C	-5.000	20.620	10.392	4.942
Solar	MJ/m^2	0.030	36.450	15.691	3.884
windsp	[m/s]	0.650	3.367	1.794	0.561
MaxRH	%	33.000	99.930	78.425	16.712
MinRH	%	3.000	66.340	32.765	15.144
R Evap	mm	9.000	194.550	97.307	30.259
Rain	mm	0.000	353.200	64.394	61.918
Runoff	m^3/s	2.018	123.639	26.217	26.216

Table 22: The result of the homogeneity test

Variables	K	T	p-value (Two-tailed)	99% confidence interval on the p-value	
MaxT	2221.000	279	0.597	] 0.584,	0.609 [
MinT	3311.000	98	0.158	] 0.148,	0.167 [
Solar	3405.000	134	0.135	] 0.126,	0.143 [
Windsp	3710.000	64	0.080	] 0.073,	0.087 [
MaxRH	6690.000	156	< 0.0001	] 0.000,	0.000 [
MinRH	6066.000	156	0.000	] 0.000,	0.001 [
Revo	2824.000	182	0.298	] 0.286,	0.310 [
Rain	5358.000	148	0.003	] 0.001,	0.004 [
Runoff	2138.000	243	0.639	] 0.627,	0.651 [

A homogeneity test is used to check whether two samples are from the same population. The result of Pettit's Homogeneity test shows that the data is moderately uniformly distributed which depict a fair representation of the Basin stations. The p-value has been computed using 10000 Monte Carlo simulations. A 99% confidence interval and significant level alpha = 0.05 in Time elapsed: 0s form the XLSTAT statistical package. The risk is to reject the null hypothesis H_0 (that Data are not homogeneous) while it is true (59.65%).

4.8.1 ANN model input analysis

The studied variables input dataset have different variances and units of measurement. Thus, the dataset was standardised since the standardised results are needed for minimisation of bias and accumulation of predicted error from the observed data. This step was done by subtracting the mean data from the original data and dividing it by the standard deviation (Ikudayisi and Adeyemo 2016). At the end of the standardisation process, each variable in the dataset is now converted into a new variable of zero mean value and a unit standard deviation. The original and standardised variables are displayed in Figure 41 and Figure 42 respectively.

These data were further subjected to various tests/editing regarding homogeneity, consistency and gap closure before adaptation for model inputs. This helps to improve their predictive ability and reduce uncertainty in data usage.

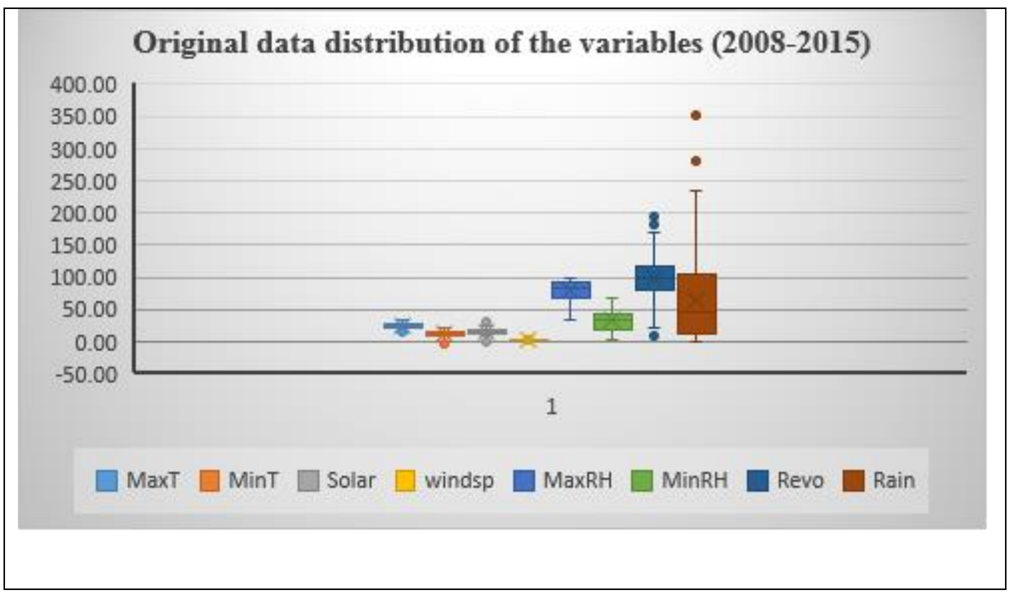

Figure 41: Original data distribution of the variables

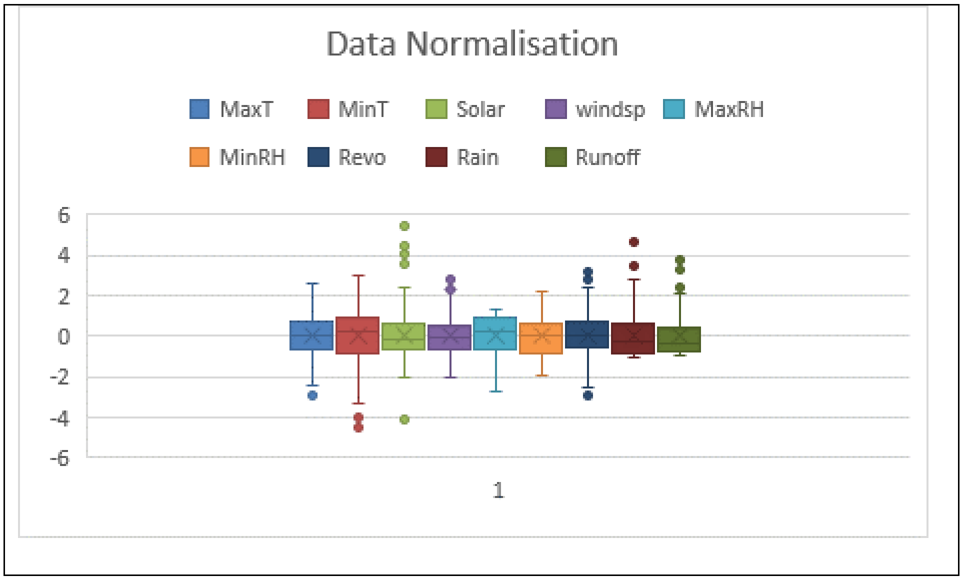

Figure 42: Data standardisation (normalisation)

4.8.2 Materials and methods for seasonal pattern classifier

The ANN pattern classifier was used to perform the experiments for predicting hydrological flow regime and seasonal pattern classification. This was done in the MATLAB 2015a environment. The gradient descent algorithm optimization technique in the neural network framework was used in determining the different combinations of functions for optimal performance. The normalised data were used for ANN input (seasonal forecasting and classification).

Microsoft Statistical software XLSTAT by Addinsoft was used for statistical analysis of PCA, FA, correlation, nonparametric Mann–Kendall test and Sen's trend Test. PCA was used to extract the most important data which influence streamflow, while FA indicates the degree of different percentages of each contributing element to the total streamflow volume (latent class). The correlation relationships between the collected hydro-climatic data were developed as scatter plots and correlated in order to determine their significant parameter sensitivity. Thereafter, Sen's and Mann-Kendall's sensor trend detection was used for the trend in forecasting the hydrologic flow regime.

Statistical data processing

Regional patterns from a pairwise combined series have been used to study cross-correlation coefficients to indicate similarities in the mechanisms that cause a phenomenon to be exhibited in the basin. Table 23 depicts the correlation matrix among the variables.

Table 23: Spearman correlation matrix

Variables	MaxT	MinT	Solar	windsp	MaxRH	MinRH	Revo	Rain	Runoff
MaxT	**1**	**0.809**	**0.645**	**-0.253**	**0.427**	**0.376**	**0.454**	**0.194**	**0.463**
MinT	**0.809**	**1**	**0.632**	-0.100	**0.625**	**0.749**	**0.373**	**0.463**	**0.545**
Solar	**0.645**	**0.632**	**1**	0.032	**0.234**	**0.330**	**0.628**	**0.526**	**0.506**
windsp	**-0.253**	-0.100	0.032	**1**	**-0.386**	-0.075	**0.223**	0.025	-0.096
MaxRH	**0.427**	**0.625**	**0.234**	**-0.386**	**1**	**0.800**	-0.085	**0.316**	**0.186**
MinRH	**0.376**	**0.749**	**0.330**	-0.075	**0.800**	**1**	0.084	**0.436**	**0.375**
Revo	**0.454**	**0.373**	**0.628**	**0.223**	-0.085	0.084	**1**	**0.257**	**0.277**
Rain	**0.194**	**0.463**	**0.526**	0.025	**0.316**	**0.436**	**0.257**	**1**	**0.441**
Runoff	**0.463**	**0.545**	**0.506**	-0.096	**0.186**	**0.375**	**0.277**	**0.441**	**1**

Values in bold are different from 0 with a significance level alpha=0.05

4.9 Research methods for sub-specific objective 2b

The second sub-objective deals with the evaluation of the basin water balance and its different component. It entails:

- Development of an integrated and consistent methodology for estimating actual water availability and use.

- Summarising this information in the form of water resource accounts and changes in storage basin.
- Computing the water balance and distinguishing between different components, such as green and blue water, non-beneficial consumption and beneficial consumption, non-recoverable fraction and a recoverable fraction.
- Synthesising and summarising available sustainable water allocation rules.

4.9.1 Assessment of water balance over the Mkomazi River Basin

A basin water budget is needed to give an overview of periodic water availability. The development of an integrated method for estimating actual water availability represents a crucial step in determining the water balance configuration towards integrated watershed management.

In doing that, it required the analysis of the individual components of the hydrological cycle, especially at the catchment scale. Accordingly, (a) morphometric and hydrological inventory of the watershed was performed; (b) a regional hydrologic water balance was developed from the inventory (c) quantification of river flows on the chronologically sequential water balances over the watershed was computed using Soil water assessment Tool (SWAT).

A ten-year period (2004 to 2013) was chosen for this analysis based on corresponding obtainable streamflow data. This period covers a mix of low- and high-water years. A descriptive statistical of mean, median, mode, standard deviation, skewness, and kurtosis were employed to simulate the basin’s hydrological process in evaluating the basin’s water balance.

The most important elements of water balance in a basin consist of precipitation, surface runoff, lateral flow, base flow and evapo-transpiration. All these elements, with the exception of precipitation have to be predicted using appropriate modelling tool as their quantification by measurement is not easy (Sathian and Syamala, 2008).

The SWAT model was parameterised using globally available digital elevation data (DEM), satellite derived land cover, soil type data, and processed hydro-meteorological data collected from various sources such as SAWs and ARC inter-government agency. This dataset serves as input data for the SWAT model. In addition, SWAT Error Checker was used for the hydrology and sediment output visualization.

4.9.2 Data collection and analysis

The quality of the available database influences estimation accuracy regardless of the method used (Archer *et al.* 2010). To this end, the challenge from multiple sources for data collection, data resolution, missing data and incomplete data from the local sources was overcome by using spatial source global weather data at the required (daily) resolution to parameterise the employed SWAT model. The collated resultant climate databases were carefully analysed and assessed using frequency analysis-based spreadsheet.

4.9.3 SWAT model setup/ model input

The Quick-Geographic Information System (QGIS) interface of the SWAT version (Di Luzio, Srinivasan and Arnold 2004) was used to develop the water balance model of the River Basin. SWAT is regarded as a versatile tool when it comes to physically based continuous -event watershed modelling. The modelling process involved in SWAT has been illustrated in Figure 15 in section 2.13.4 in Chapter Two. It required rigorous analysis of the digital elevation model (DEM), soil, and land use map. These were reprojected to

Universal Transverse Mercator Zone 34 South. All the input data used for this SWAT modelling part of the research are as shown in Table 24.

Table 24: Summary of SWAT model input data for Mkomazi Basin

S/N	**Data type**	**Description**	**Resolution**	**Remark**
1	Topography	Digital Elevation Model	30mx30m	Shuttle Radar Topographical Mission
2	Land Use Map	Land Use Classification	1km	Global Land Cover Classification,
3	Soil Map	Soil Types and Texture	10km	Digital Soil Map of the World
4	Weather	Daily precipitation, Wind speed, Solar radiation, Evapotranspiration, Min and max temperature, and Relative humidity.	Daily	Climate Forecast System Reanalysis (CFSR), Global weather data

Figure 43 shows the watershed model results with each sub-basin’s contribution to water yield. It shows the digitized elevation model, land use, soil type and streamflow network in the sub-basin’s delineation. A total number of 233 sub-basins’ delineation was arrived at for the watershed hydrological response unit. Detailed results analysis and discussion are given in Chapter Five.

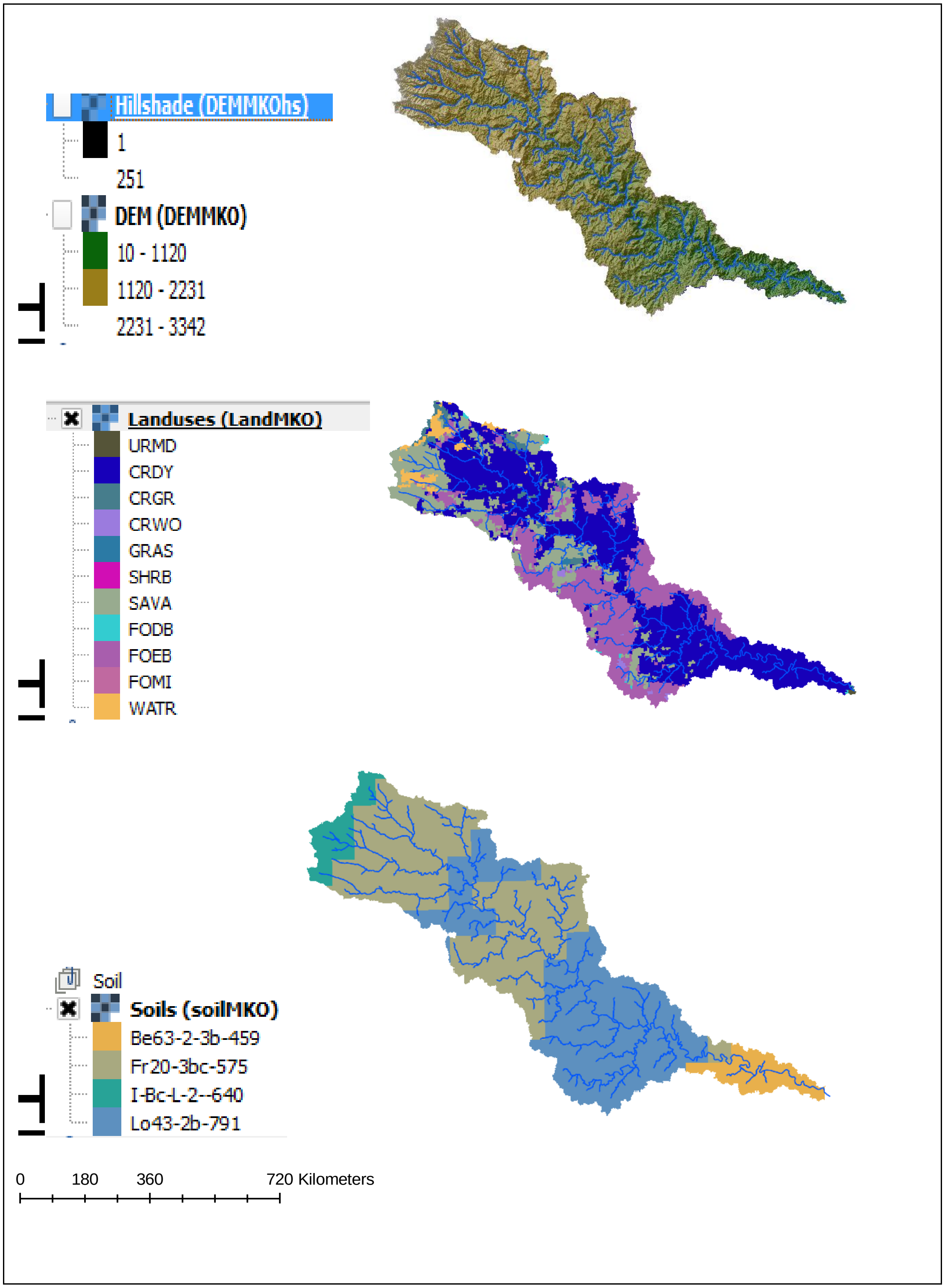

Figure 43: Digitized elevation model, land uses, soil type and streamflow network

Table 25 gives the QGIS_SWAT land use delineation from the Global Land Cover Characterization database. The table consists of land use descriptions, the area occupied and the percentage composition of different LULC, while Table 26 gives the soil data and percentage composition for the different classes of soil cover respectively.

Table 25: Information on land use of the Study Area

Sl. No	QSWAT Code	Description	Area(Ha)	% of Watershed
1	URMD	Urban and Built-Up Land	37.93	0.01
2	CRDY	Dryland Cropland and Pasture	219082.3	50.19
3	CRGR	Cropland/Grassland Mosaic	9103.77	2.09
4	CRWO	Cropland/Woodland Mosaic	2035.52	0.47
5	GRAS	Grassland	681.46	0.16
6	SHRB	Shrubland	80798.82	18.51
7	SAVA	Savannah	872.34	0.2
8	FOEB	Evergreen Broadleaf Forest	113008.9	25.89
9	WATR	Waterbodies	19.92	0
10	BSVG	Barren or Sparsely Vegetated	10495.84	2.4
	Total		436136.7	100

Table 26: Soil Data Information of the Study Area

Sl. No	EAWAG Code	Area	%age	Texture
1	I-Bc-L-2--640	23085	5.29	Sandy Loam
2	Lo43-2b-791	184987	42.38	Loam
3	Be63-2-3b-459	26975.3	6.18	Sandy Clayey Loam
4	Fr20-3bc-575	201090	46.07	Loam

4.10 Research methods for specific objective 3

The third research specific objective - *To synthesise rules for sharing limited water resources towards operational analysis for environmental flows estimation*

This objective was achieved through extensive literature review work in Chapter Two (session 2.20-22). It entails the review of South African water legislation Acts (NWA. 1998); the development and implementation of IWRM plan in South Africa; water reconciliation strategy study for the KwaZulu-Natal Province area among other efforts to coordinate land and water management. These rules were all drawn from similar world experiences for efficient and gainful utilization of water and other natural resources. The synthesised rules and principles were modified to suite KZN water allocation reform (see step-by-step procedures in session 2:22 in Chapter Two). The established water rules were subsequently adapted to the present Mkomazi case study area. The procedural practical application is detailed below:

A fair water resource allocation is especially important during the dry season especially in regions with a fluctuating climate, such as the KwaZulu-Natal Province in South Africa. The availability of water for irrigation during that season offers a prospect of growing a second crop in one year. The study area irrigation water use also affirmed agricultural activities has been the highest water use (60%), followed by urban water requirements (25%), while the remaining 15% is jointly shared by the other segment users (DWAF 1986; Adeyemo, Bux and Otieno 2010)

A water dependable allocation mechanism has been employed in this part of the study for the different riparian water demand. Based on the estimated available water, allocable water was made available based on percentage dependability of the Mkomazi water yield to the different users. It consists of the use of a probability distribution function for projected water availability forecast and the use of a flow duration curve (FDC) for the monthly flow magnitude quantification. The Weilbil ranking was used for choosing the dependable flow, based on a reliable agreed percentage value.

The environmental flow was calculated by subtracting surface water diversion and outflows into the sea from surface runoff or better still, through assuming 20% of the 75% dependable flows in each of the wet months or using 15% of the average monthly flows in different months for the dry months. The knowledge of the long-term time series of water availability is very important in water management and planning studies, water transfers, reservoir operation and conjunctive water analyses (Matondo 2002).

4.11 Research methods for specific objective 4

To establish a framework for water trading, which encourages water, use efficiency and allows the movement of water to new users.

The developed proposed water-trading framework uses a System Dynamic simulation technique to form composite supply side augmentations with a demand-side improvement system. It provides holistic assessment for HELPS conceptual sustainability evaluation in a basin. The System Dynamic tools in the VENSIM environment were used to map the interconnectivity between the hydrological simulation and economic values component as described by Zhou *et al.* (2015). The hydrological simulation component of the model reveals flow regime (available water) in physical terms while the economic component determines its effective cost (Zalewski 2000; Turton *et al.* 2004; Zhou *et al.* 2015).

Figure 44 depicts the conceptual causal-loop diagram while Figure 45 is the stock-flow diagrammatical representation of the SD conceptual framework development. The conceptual integrated model presented was developed in close cooperation with KwaZulu-Natal Province Department of Water and Sanitation’s stakeholder in Durban. This assisted in the fair representation of the socio-hydrological water-trading configuration.

The Close Loop Diagram (CLD) clearly indicates how a complex web of socio-economic and environmental challenges confronted by a basin could be managed in a sustainable manner, while the stock and flow diagram relates the various sub-system feedbacks to the socio-hydrological mass balance of the basin. The SD mechanism allows effective evaluation linkage between water for livelihoods and water as a resource. This allows the integration of the three 'Es' ─ economic, efficiency and equity ─ to be employed.

4.11.1 Conceptual CLD and SFD development

The stock and flow mathematical models are created using feedback loops which link the various sub-systems based on the socio-hydrological mass balance. The Stock Flow Diagram (SFD) illustrates scenarios for a hypothetical water trading market in deriving efficient water allocation among the riparian users

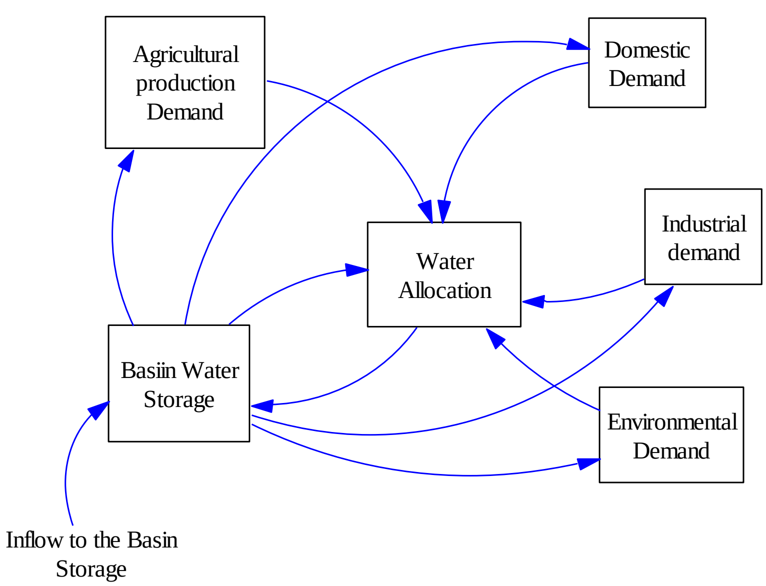

Figure 44: Causal loop diagram for the water system model

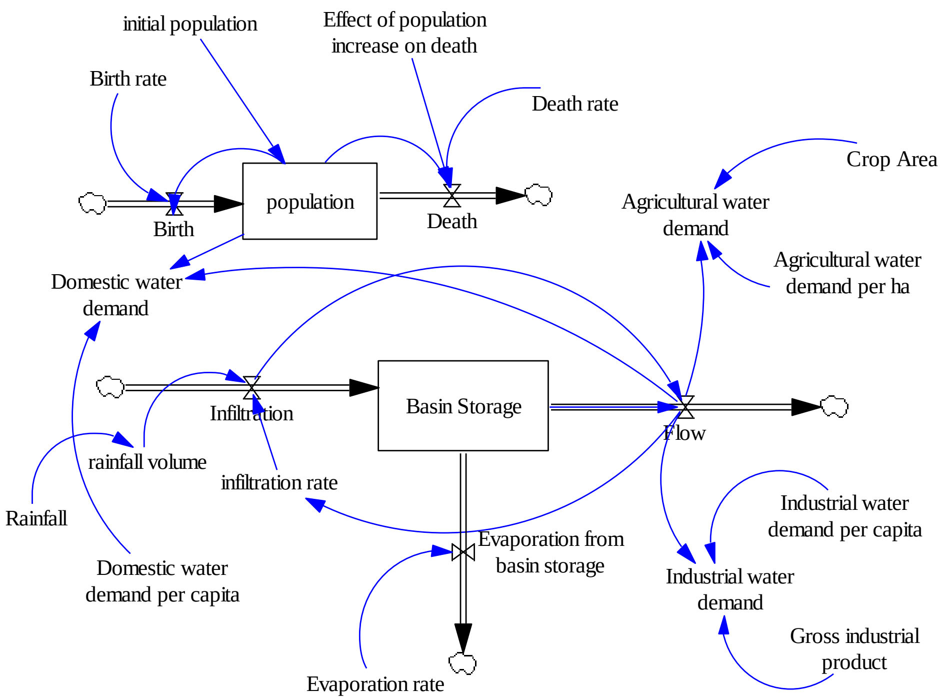

Figure 45: Stock-Flow Diagram of the population sub-sector

CHAPTER 5: RESULTS AND DISCUSSIONS

5.0 Introduction

This chapter presents the results in accordance with the study's four specific objectives and accordingly signpost the reader on the main research objectives. It provides an in-depth discussion on various results. The chapter commences with the discussion on multivariate statistical analysis of MRB surface water quality trade-off assessment among users by identify the basin ecosystem dependant, and analysis the surface water quality index rating into pollutant strength for their environmental and public values benefit preservation. It then discusses on Trend analysis of meteorological variables and their effect on rainfall patterns and distribution. The prediction of streamflow follows this with forecasting of rainfall; quantification of the Basin water balance; simulation of annual water yield for the basin; water demand assessment; while concluding with the watershed sustainability framework scenarios.

5.1 Results and discussion for specific objective 1

To examine the trade-offs among users through the identification of the basin ecosystem dependants' while analysing the surface water quality's index rating.

This sub-section discusses the usage of multivariate statistical analysis on MRB surface water quality datasets. The preservation of the aquatic environment and their public benefit values protection for societal use cannot be over-emphasized in integrated water quality and quantity management. They help to balance both the temporal and spatial scales of the hydrological cycle from the ecological perspective requirement.

5.1.1 Multivariate statistical analysis of MRB surface water quality

The Water Quality Index was used to aggregate diverse parameters and their dimensions into a single score, representing their historical water quality status. The PCA was useful for reducing and interpreting large multivariate data sets with underlying linear structures, and for discovering previously unsuspected relationships.

5.1.1.1 Principal Component Analysis

The result of the first principal component (PC1) in Figure 46 represents the direction of the highest variance of the data while the second principal component (PC2) accounts for most of the remaining variance under the constraint to be orthogonal to the preceding component PC1 (Lennox and Rosen 2002).

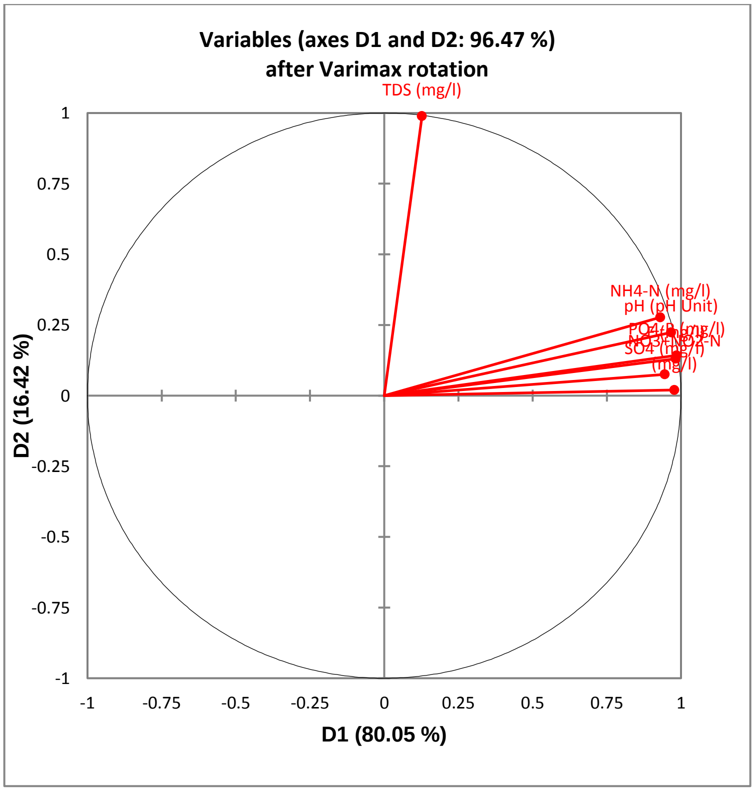

Figure 46: The observed PCA parameter analysis

The results of the MRB's PCA water quality analysis shows that most Variables falls within axes D1 and D2: 96.47 %) after Varimax rotation (Figure 46). Based on pre-screening using PCA, PC1 classified the measured data according to parameters that mostly affects streamflow. This reveals that the river has been subjected to a rapid decline in water quality status through increasing population while human activities will have directly affected the water quantity through incessant abstraction.

The factor variables analysis Figure 47 show that the cluster analysis factors, F1, F2, and F3 consist of varied variance in water quality i.e. 81.9, 3.14 and 0.858 (%) respectively, while Table 27 shows the samples factor variables squared cosine contribution.

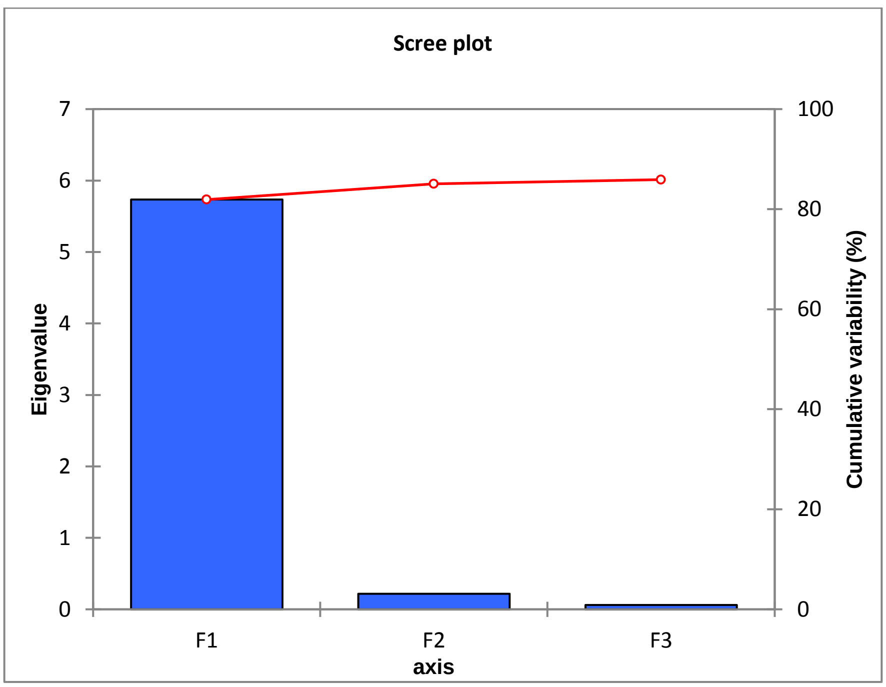

Figure 47: Latent factor variability of the cluster analysis

Table 27: Contribution of the factor variables squared cosine

	F1	F2	F3
pH (pH Unit)	**0.984**	0.001	0.010
NO3+NO2-N (mg/l)	**0.924**	0.032	0.003
NH4-N (mg/l)	**0.936**	0.007	0.046
F (mg/l)	**0.978**	0.005	0.016
PO4-P (mg/l)	**0.989**	0.004	0.006
SO4 (mg/l)	**0.885**	0.014	0.099
TDS (mg/l)	0.105	**0.890**	0.003

Values in bold correspond for each variable to the factor for which the squared cosine is the largest

The factor analysis effect was quite evident from the results of the grouped Agglomerative Hierarchical cluster classification of the 10 sub-basin sampling sites (Figure 48), that resulted in three clusters (Figure 49), classifying them into relatively highly polluted (HP), medium polluted (MP) and less polluted (LP) group basins.

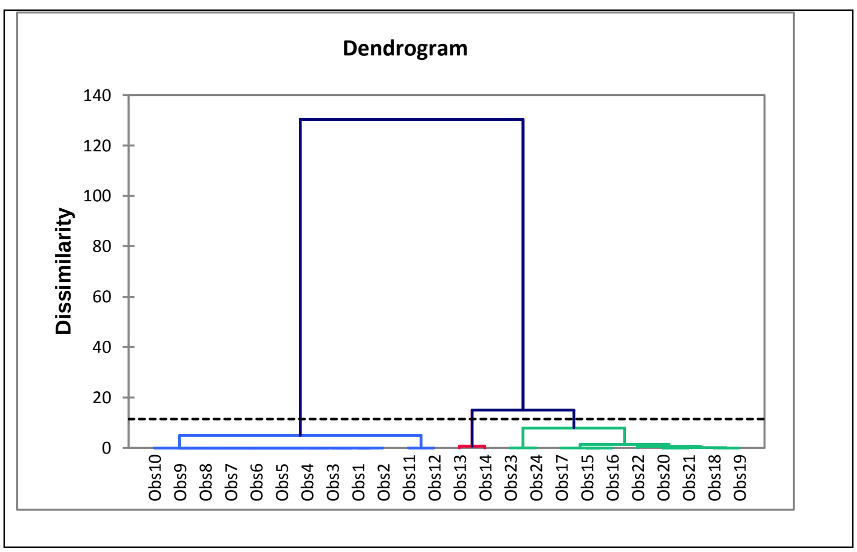

Figure 48: Classification of the dataset observations into HP, MP and LP basins

This number of clusters might have been influenced by the environment's water quality, which is mainly affected by land use and industrial structure

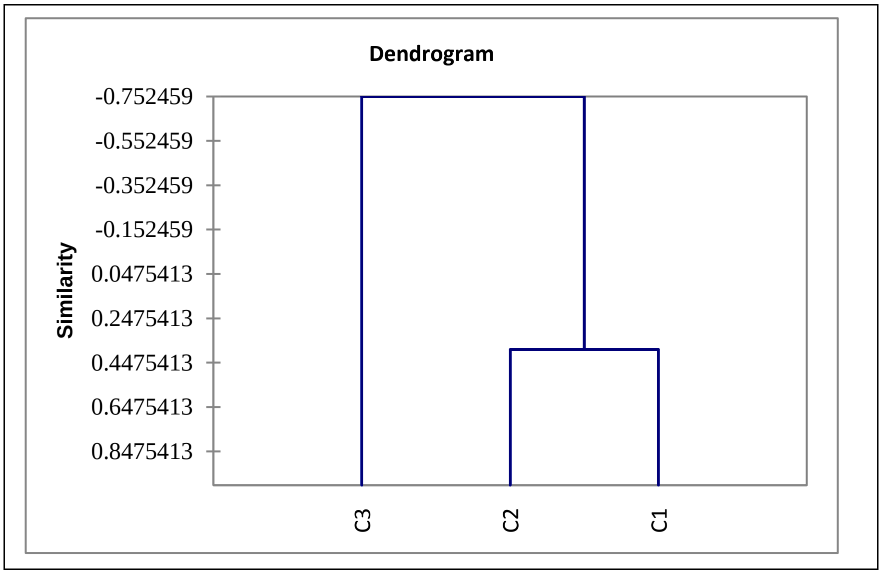

Figure 49: The Agglomerative Hierarchical Cluster HP, MP, and LP Classification

Table 28 shows the relative sub-basin cluster summary. The results by class (cluster) 1 represent HP, cluster 2 represent MP, while group cluster 3 represent LP sub-basin:

Table 28: Class centroids: Variance decomposition for the optimal classification

Class	pH (pH Unit)	NO3+NO2-N (mg/l)	NH4-N (mg/l)	F (mg/l)	PO4-P (mg/l)	SO4 (mg/l)	TDS (mg/l)
1	-0.977	-0.929	-0.972	-0.938	-0.971	-0.864	-0.317
2	0.977	0.743	1.047	0.813	0.894	0.665	2.800
3	0.977	0.966	0.957	0.963	0.987	0.904	-0.180

The procedural step described in Chapter Four section 4.3 was repeated for each of the sub-basin water quality index calculations using Equation 50 – Equation 54. Table 29 presents the results of the Mkomazi River Basin water quality index analysis, while Table 30 depicts the sub-basin water quality index rating for drinking, irrigation, and aquatic life utilisation.

Table 29: Mkomazi River Basin water quality index analysis

Parameters	**Water quality Standard**	**Assigned weight**	**Relative weight**	**Quality rating**	**Sub-Indices**
pH (pH Unit)	6.50	2.50	0.19	15.03	2.89
NO3+NO2-N (mg/l)	1.50	2.40	0.18	123.83	22.86
NH4-N (mg/l)	2.00	2.00	0.15	52.33	8.05
F (mg/l)	1.00	1.60	0.12	156.36	19.24
PO4-P (mg/l)	1.00	1.00	0.08	135.97	10.46
SO4 (mg/l)	1.50	1.50	0.12	123.94	14.30
TDS (mg/l)	3.00	2.00	0.15	112.61	17.32
Total		13.00		WQI=Sum(SI)	95.13

Table 30: The Mkomazi sub-basin water quality index rating

Sub Basin	**Drinking water**		**Irrigation**		**Aquatic life**	
U10A	88	Good	67	Good	56	Good
U10B	167	Poor	83	Good	78	Good
U10C	78	Good	126	Poor	98	Good
U10D	54	Good	63	Good	79	Good
U10E	168	Poor	67	Good	56	Good
U10F	164	Poor	63	Good	108	Poor
U10G	176	poor	63	Good	78	Good
U10H	57	Good	76	Good	79	Good
U10J	157	poor	74	Good	98	Good
U10K	178	poor	65	Good	90	Good
U10L	165	Poor	67	Good	65	Good
U10M	287	Very Poor	67	Good	89	Good

The results of the water quality index suggest irrigation and aquatic utilisation only have a mild effect when compared to WHO standards. The values of these parameters are not harmful to human health; however, if they occurred over and above the defined limits set by APHA 1998, 2005, DWAF 1996, and WHO 2005, then it would be cause for concern. However, the high value of the Water Quality Index at sub-basin (U10F) suggests an entropic environment for the ecosystem. Figure 50 shows the basin ombro-thermic diagram in relation to its sub-basins.

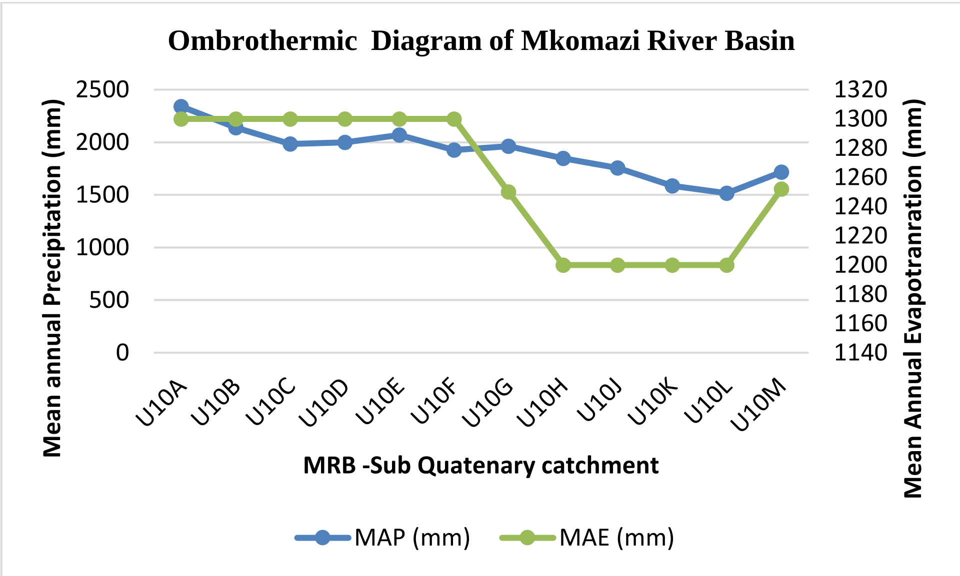

Figure 50: Ombrothermic diagram of the MRB in relation to sub-basins

The ombro-thermic diagram as depicted in Figure 50 shows conflict in water use across the catchment sub-basin. While the sub –basins (U10A-U10F) have surplus water, the subsequent sub-basins (U10G-U10M) where the MAP line graph crosses the MET line graph were in abject water deficit. The resultant wet and dry periods thus have adverse effect on the hydrologic trophic classification to place individual aquatic species into proper perspective towards preservation of their public benefit.

Table 31 shows the biodiversity classification for South African rivers and lakes. Generally, the basin falls within the mesotrophic region with high species diversity; moderate productivity; and some nuisance algae/ aquatic plants.

Table 31: The biodiversity classification for South African rivers and lakes

Trophic status	**Implication**	**Nitrogen (mg N/l)**	**Phosphorus (mg P/l)**
Oligotrophic	Moderate species diversity; Low productivity; No nuisance algae/ aquatic plants	<0.5	<0.005
Mesotrophic	High species diversity; Moderate productivity; Some nuisance algae/ aquatic plants	0.5-2.5	0.005-0.025
Eutrophic	Low species diversity; High productivity; Blooms of nuisance algae/ aquatic plants; Often toxic blue-green algae	2.5-10	0.025- 0.25
Hypertrophic	Very low species diversity; Very high productivity; Blooms of nuisance algae/ aquatic plants; Often toxic blue-green algae	>10	>0.25

5.1.2 Discussion on Mkomazi sub-basin water quality index rating

The mesotrophic status of the basin permeates a healthy, rich heterogeneous environment that supports a wide range of ecological species environments. Thus, the good condition of the Mkomazi River has limited the pest species from becoming problematic in this basin. The rich biodiversity of the study area allowed fishing and farming as the only economic empowerment for the region. Also, ecologists have used hydrologic trophic classification to place individual streams and rivers into a broader spatial context with the goal of preserving the river health for public benefit (Schulze and Pike 2004).

Furthermore, the effect of vegetation intruding, degraded grassland, encroaching bushland and thicket as well as the impact of alien invasive species has adversely impacted on the biodiversity of the study area. These adverse consequences are often the direct result of societal practices or activities. They have contributed to the financial burden of the stakeholders through incessant need to repair degraded land, control resultant flash floods and an accumulation of sediment. Thus, the removal of alien species, adequate landscape control among users; and rehabilitation of the eroded land is necessitated.

5.2 Results and discussion for specific objective 2

To propose water allocation mechanisms in achieving equitable water distribution and large benefits from water uses across the basin's communities and users.

This objective has been further broken down into sub-objectives (A and B) to connote a logical scientific step towards its accomplishment. The subsequent section provides results and discussion regarding the two sub-objectives (A and B) towards the fulfillment of the overall objective.

It commences with the provisional results for the Hydro-meteorological trend analysis, and their effect on the annual and seasonal variability of the Basin's hydrological phenomenon. This is followed by the results and discussion on the trend analysis of rainfall data; factor analysis results for the streamflow-rainfall relationship; the results of the ANN seasonal classification for streamflow prediction; and the results of the ANNs streamflow prediction, its calibration and validation.

This section further discusses seasonal flow variation and spatial rainfall relationship; the use of manual and SWAT hydrological models in assessing water balance. The performance evaluation, sensitivity, calibration and validation of the SWAT model follows. The section concludes with a water budget accounting systems summary and discussion depicting changes in the basin storage level.

5.2.1 Results and discussion for the hydro-metrological trend analysis

The various time series statistics methods, not limited to Linear Trend analysis, Mann-Kendall (MK) and Sen's Slope significant trend estimation were carried out in assessing the expected annual and seasonal variation pattern towards a rainfall-runoff relationship for the Basin's hydrological runoff quantification. A cursory run of the non-parametric and parametric approach (Mann–Kendall and Sen's Slope methods) across the months (Jan-Dec) for the duration (2008-2015) shows an increasing trend and variability changes among the climatic variables. The results of the Sen's slope are given in Table 32 column 7. The closer its value was to 0, the less its trend signifies, while the sign of the Sen's Slope buttress trend is characteristic of either an increasing or decreasing rate. The Mann-Kendall test with a very high positive value of S [column 4) is an indication of an increasing trend whereas a very low negative value indicates a decreasing trend.

Table 32: The results of the Seasonal Sen's slope and Mann-Kendall Test

	Unit [2]	Kendall's tau [3]	S [4]	Var(S) [5]	p-value (Two-tailed) [6]	Sen's slope [7]	Trend [8]
MaxT	°C	0.009	34	0.824	0.05	-0.026	Increasing
MinT	°C	-0.053	-191	0.2	0.05	-0.037	Decreasing
Solar	MJ/m^2	-0.083	-296	0.046	0.05	-0.026	Decreasing
windsp	[m/s]	-0.032	-115	0.442	0.05	-0.004	Decreasing
MaxRH	%	-0.205	-737	< 0.0001	0.05	-0.546	Decreasing
MinRH	%	-0.168	-604	< 0.0001	0.05	-0.475	Decreasing
R Evap	Mm	0.067	242	0.104	0.05	0.318	Increasing
Rain	Mm	-0.166	-596	< 0.0001	0.05	-0.408	Decreasing
Runoff	m^3/s	-0.039	-136	0.36	0.05	0	Decreasing

The non-seasonal Mann-Kendal and Sen's Slope trend test for all the months in the years of consideration (2008-2015) is presented in Table 33.

Table 33: The non-seasonal Sen's Slope and Mann-Kendall Two-tailed variables test

Variables [1]	Kendall's tau [2]	S [3]	Var(S) [4]	p-value (Two-tailed) [5]	Sen's slope [6]	Confidence interval [7]		Trend [8]
MaxT	0.018	802.000	3014798.667	0.645	0.001	] -0.002 ,	0.004 [	Increasing
MinT	-0.053	-2381.000	3014823.000	0.170	-0.004	] -0.008 ,	-0.000 [	Decreasing
Solar	-0.043	-1921.000	3014787.000	0.269	-0.003	] -0.005 ,	0.000 [	Decreasing
windsp	-0.012	-528.000	3014594.000	0.761	-9.524E-5	] -0.001 ,	0.000 [	Decreasing
MaxRH	-0.184	-8246.000	3014828.000	< 0.0001	-0.045	] -0.061 ,	-0.032 [	Decreasing
MinRH	-0.141	-6325.000	3014893.000	0.000	-0.038	] -0.052 ,	-0.024 [	Decreasing
Revap	0.000	-21.000	3014905.000	0.991	-1.047E-4	] -0.026 ,	0.026 [	Decreasing
Rain	-0.118	-5296.000	3014470.000	0.002	-0.408	] -0.135 ,	-0.047 [	Decreasing
Runoff	-0.025	-1136.000	3014688.667	0.513	-0.004	] -0.014 ,	0.004 [	Decreasing

Decreasing trends are found generally among the variables across the months except for maximum temperature and solar radiation. This is understandable, as increased solar radiation brings about an increase in temperature. Increases in temperature and radiation forcing variables do alter the hydrological cycle. The resultant effect determines the amount of precipitation, its frequency, intensity duration and the type of rainfall.

The level of their significant positive and negative trends at 5% and 10% for each of the seasonal trend is presented in Table 34. In all, the hydro-meteorological variable shows a decreasing trend except for maximum temperature and evapotranspiration in the seasonal distribution pattern while non-seasonal distribution shows maximum temperatures as the increasing trend variable in the summer season. The annual and seasonal trend for the entire basin series (2008-2015) behaves differently. The streamflows in winter (wetter months} have increased slightly over the period, whereas the streamflows in summer (drier months) have decreased slightly

Table 34: Significant positive and negative Sen slope trends at 5% and 10%

Seasons	5% significant		10% significant	
Winter	1+	2-	0+	3-
Spring	3+	1-	1+	2-
Summer	4+	2-	2+	1-
Autumn	0+	3-	2+	1-

5.2.2 Discussion on trend analysis of rainfall data

In order to established sustainable water allocation rules, trajectory projection of rainfall trend was carried out in the basin to reveal latent pattern. A detailed analysis can be found in reference thereto (Amoo and Dzwairo 2016) in which extracted results were presented in Figure 51 which shows the plotted annual rainfall data analysis trend at two stations: Shaleburn and Giants Castle.

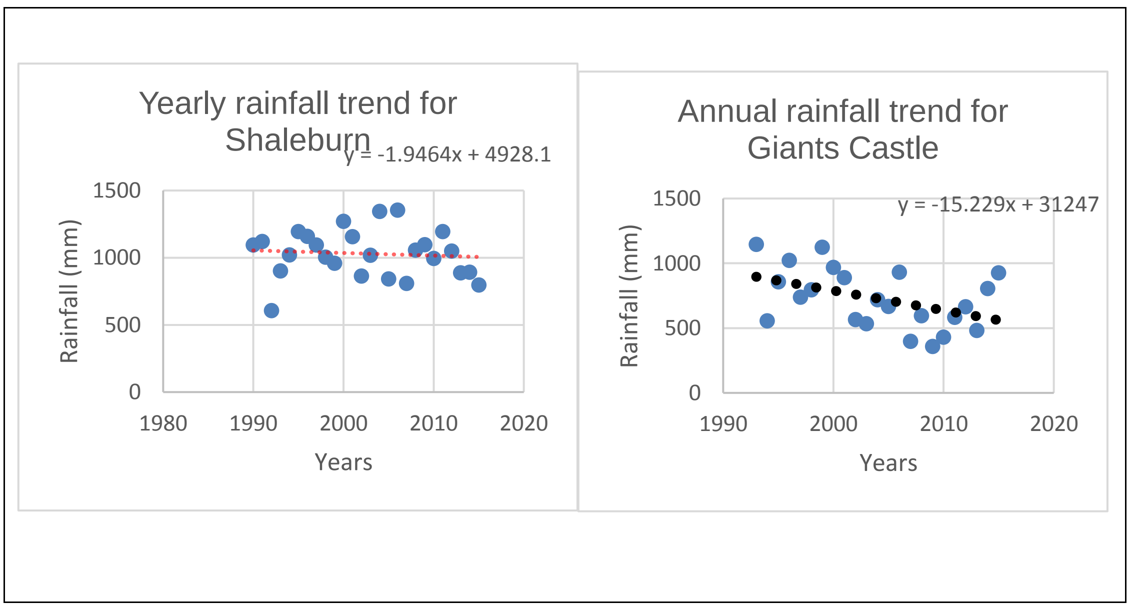

Figure 51: Plotted annual rainfall trend for Mkomazi basin

Trend analysis of the long period of rainfall was constructed for rainfall data between two different stations (Shaleburn and Giants Castle) covering the years 1990-2015 for the basin. The result shows that a sharp and decreasing trend was noticed over time. The mean annual rainfall was less than 500 mm which is far less than the required mean average 865 mm (Taylor, Schulze and Jewitt 2003). This shows there has been an increasing trend of drier climatic conditions at both stations (Giants Castle, and Shaleburn.) respectively, when relating this to literature on global scale (Dai, 2013). The rainfall trend line is showing a significant declining trend but at a non-significant 5% level. Furthermore, an insight into the monthly variability of the study rainfall area shows a replication of a larger South Africa environment.

There has been more pronounced dryness for the months from May to July as depicted in Figure 52 during the years (1990-2015) under consideration. This was further confirmed by the ombro-thermic diagram for other stations as explained in Chapter Four, section 4.6.

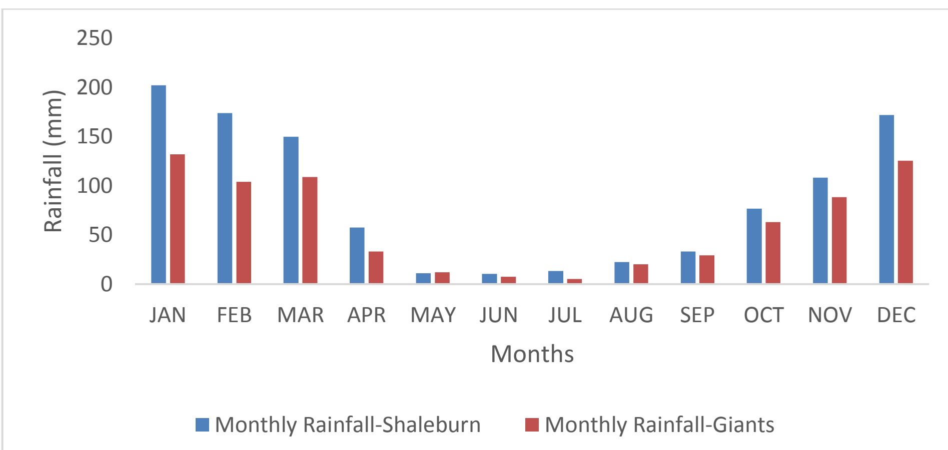

Figure 52: Plotted monthly rainfall data analysis trend

Figure 53 depicts the plotted monthly rainfall data used for this investigation. There was a decreasing trend, which reaches a climax in July before the gradual increase in the following months. The other monthly meteorological data followed the same rainfall monthly trend. Figure 54 and Figure 55 show the plotted monthly averages of humidity and temperature for the period under study. It can be observed from both stations that they all follow the same monthly pattern. This was because of the strong influence of rainfall occurrence.

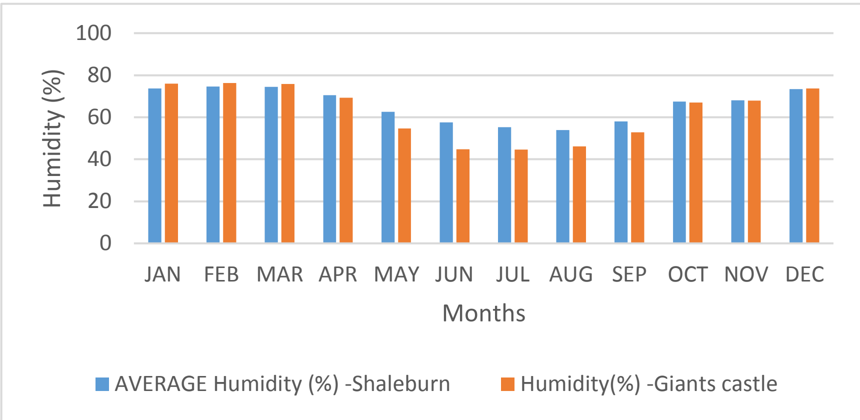

Figure 53: Plot of average monthly humidity at the two weather stations

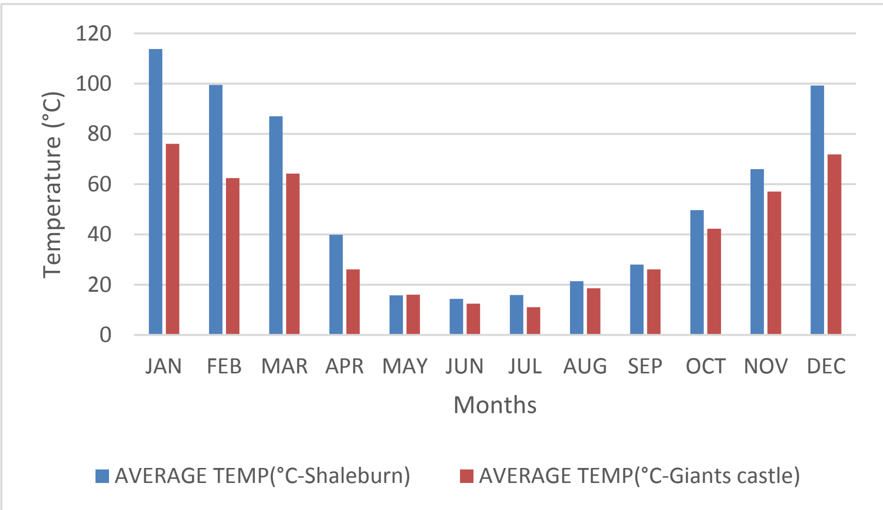

Figure 54: Plot of average monthly temperature at the two weather stations

An increase in temperature occurs between the months of October and February, after which it follows a downward trend until it reaches its minimum between the months of June and July. Figure 55 is the plot for average monthly wind speed observed for the stations under investigation.

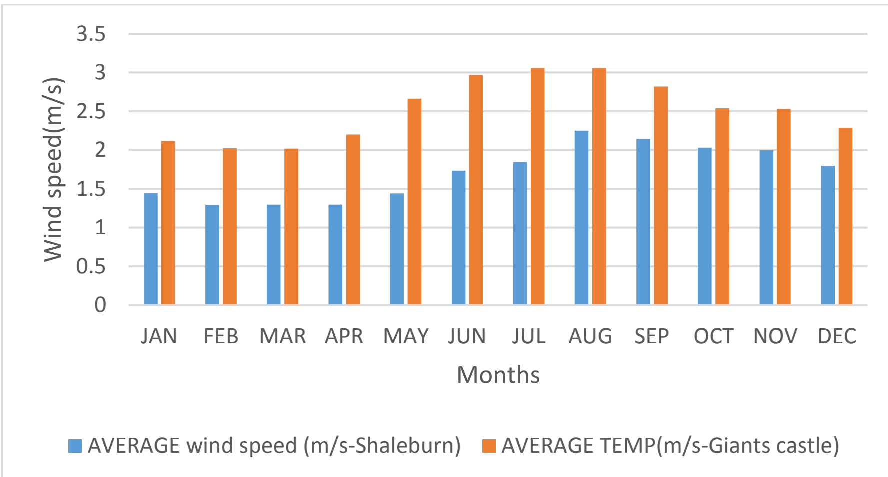

Figure 55: Plot of average monthly wind speed at the two weather stations

It can be inferred from Figure 55 that wind speed and rainfall graphs are both mutually exclusive. An upward trend in one resulted in a downward trend for the other. The magnitude of temperature inversely resulted in low humidity and wind speed, which adversely affected the magnitude of rainfall over the catchment area.

Furthermore, an insight into the monthly variability of the study area rainfall shows a replication of a larger South Africa environment. There has been more pronounced dryness for the months from May to July as depicts in Figure 56 during the years (1990-2015) under consideration.

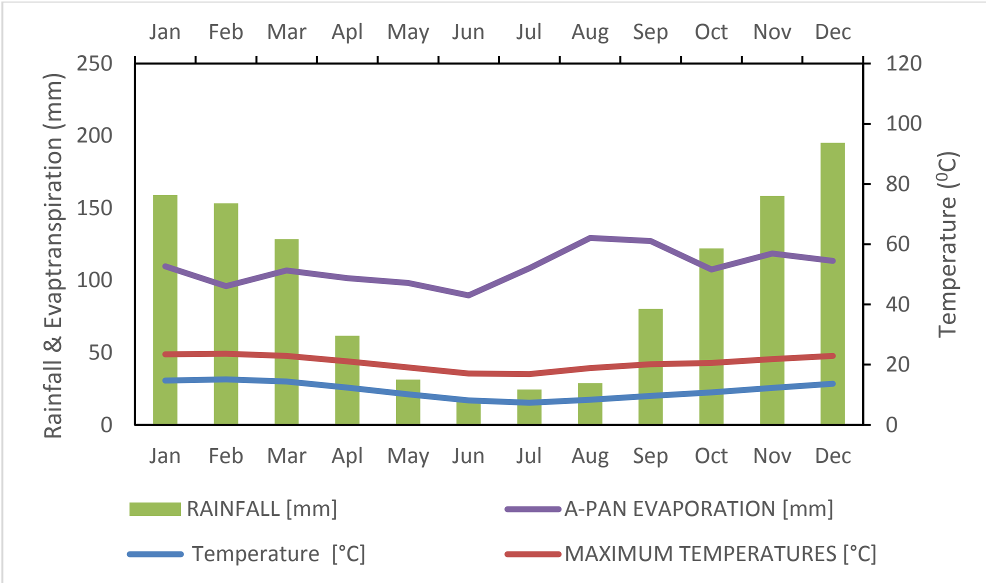

Figure 56: Mean monthly meteorological data variation for the Basin

Figure 58 and Figure 59 depict the rainfall-runoff annual flow variability over the river as analysed from the mean monthly rainfall data using Microsoft Statistical software XLSTAT by Addinsoft.

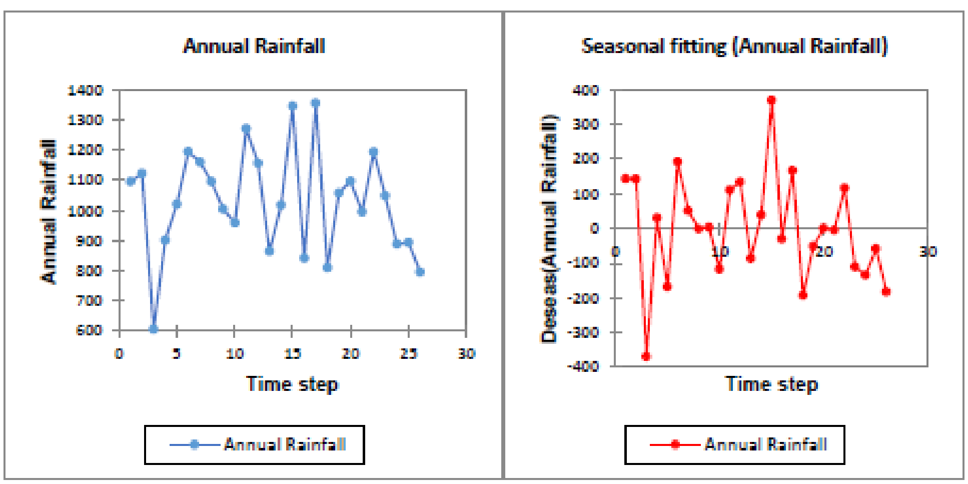

Figure 57: Mean annual variability and seasonal distribution of rainfall

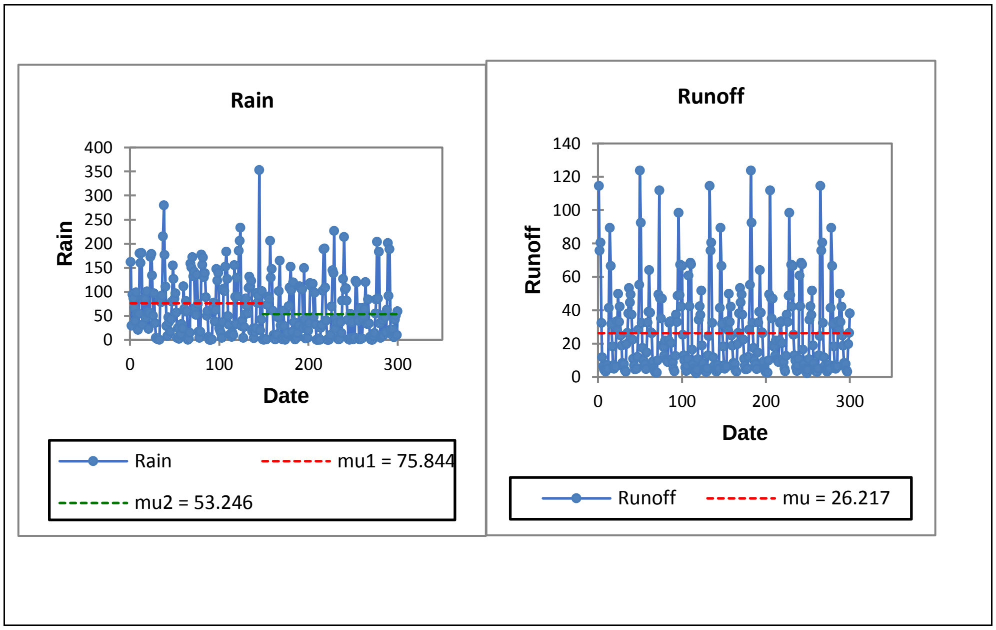

Figure 58: Rainfall-runoff annual variability and seasonal distribution

The seasonal fitting (Figure 57 and Figure 58) trend shows an unequal distribution of the precipitation pattern over the years. Recent climatic variability has made the rainfall to be unevenly distributed across the basin leading to periodic droughts, which are both severe and prolonged in the sub-catchment. This tends to make some sub-basins experience a water deficit. This assertion is further supported by the analysed mean annual discharge data collected for the period 2005─2015 as depicted in Figure 59. These results further collaborate studies by Herrfahrdt-Pähle (2010) and Quesne *et al.* (2010a) that a strict restriction in respect of water users is required to maintain and ensure continuous availability of water in the environs.

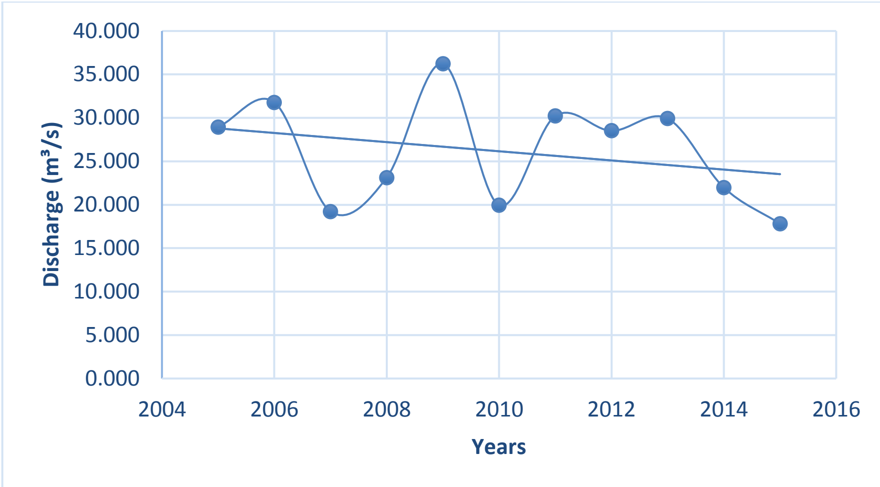

Figure 59: Mean annual flow in the Mkomazi River Basin

5.2.3 Factor analysis results for streamflow-rainfall relationship

The Factor analysis helps in understanding what constructs underlie the data (latent class) as shown in Table 35.

Table 35: Factor loading of the variables

	Factor Loadings								
Variables	**F1**	**F2**	**F3**	**F4**	**F5**	**F6**	**F7**	**F8**	**F9**
MaxT	**0.629**	0.004	0.235	0.038	0.008	0.046	0.022	0.006	0.013
MinT	**0.869**	0.006	0.000	0.036	0.016	0.011	0.026	0.016	0.020
Solar rad	**0.606**	0.186	0.009	0.003	0.037	0.033	0.122	0.004	0.000
Windsp	0.027	**0.372**	0.369	0.142	0.061	0.019	0.000	0.010	0.000
MaxRH	0.419	**0.441**	0.013	0.036	0.018	0.003	0.011	0.057	0.002
MinRH	**0.552**	0.169	0.150	0.045	0.009	0.035	0.004	0.026	0.010
Revo	0.230	**0.498**	0.028	0.041	0.049	0.147	0.005	0.002	0.000
Rain	**0.377**	0.014	0.236	0.204	0.122	0.011	0.034	0.001	0.001
Runoff	**0.440**	0.027	0.000	0.247	0.257	0.020	0.003	0.006	0.000
Values in bold correspond to each variable, the factor for which the squared cosine is the largest									

The bold squared cosine values depict the most significant variables that affect discharge flow. The PCA is used to reduce the data into a smaller number of components. Based on the pre-screening of the data using PCA, the data were classified into two main components, namely PC1 and PC2. PC1 is a more significant component than PC2. Using the corresponding factors loading value, the scores on PC1 can be computed as in Equation 57, while the scores on PC2 can also be estimated as in Equation 58.

$$PC1 = \mathbf{0.629} \times Temp_{Max} + \mathbf{0.869} \times Temp_{Min} + \mathbf{0.606} \times Solar + \mathbf{0.027} \times Windsp + \mathbf{0.419} \times RH_{Max} + \mathbf{0.552} \times RH_{Min} + \mathbf{0.23} \times ET_o + \mathbf{0.377} \times Rainfall$$

Equation 57

$$PC2 = 0.004 \times Temp_{min} + 0.006 \times Temp_{max} + 0.186 \times Solar + 0.372 \times wind\ speed + 0.441 \times R.\ Humiditymax + 0.169 \times R.\ Humiditymin + 0.498 \times ET_o + 0.014 \times Rainfall$$

Equation 58

It can be observed from Table 36, that factor loading explains most of the variability associated with the variables. Figure 60 and Figure 61 show that F1 accounts for the highest variance of 46.10%, while F2 explains about 19.07% of the total variance. The F1 variables are strongly correlated with streamflow prediction. Factor 1 has the highest loading for temperature, and solar radiation followed by relative humidity. This shows that the evaporation process is the dominating factor for water availability in this arid region.

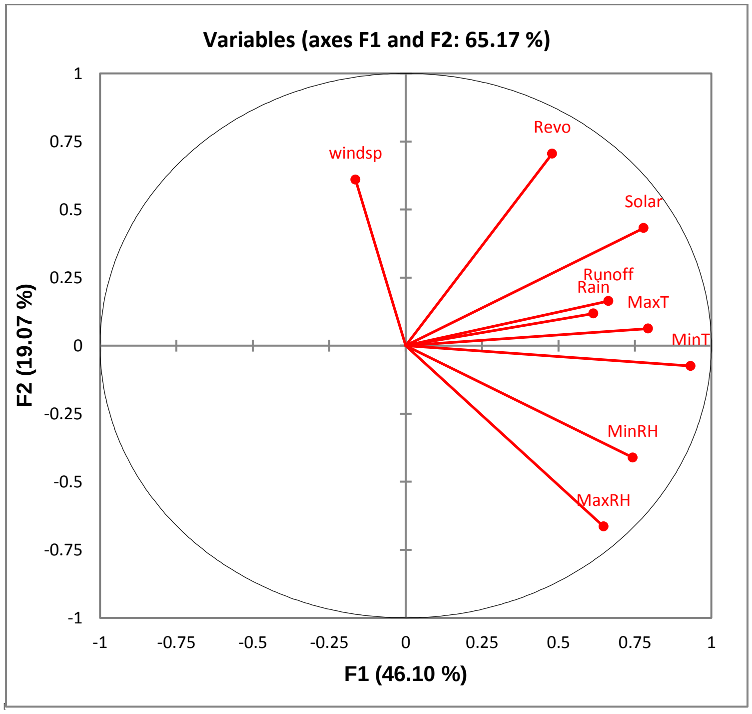

Figure 60: PCA loading plot of the dataset

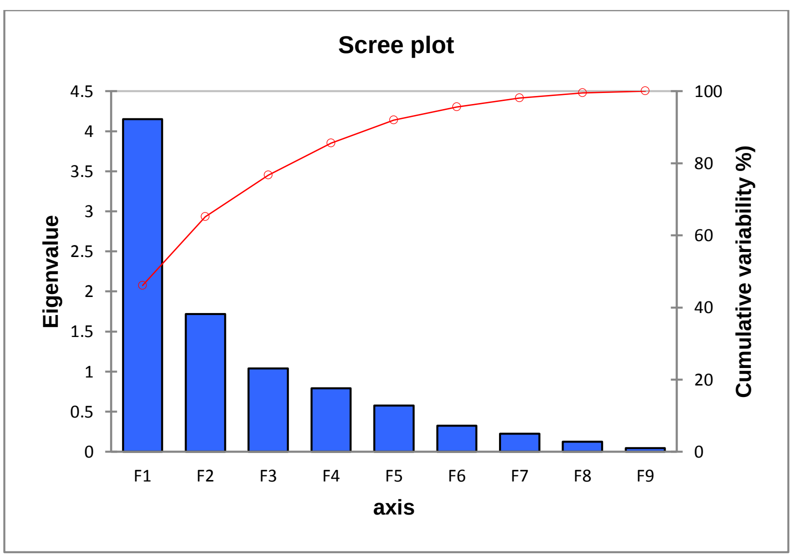

Figure 61: Factor analysis of the dataset

Factor Analysis in Table 36 shows the Eigenvalue and cumulative variability that is used to reduce the data into a smaller number of components. It shows the meteorological proportionate percentage significant towards the streamflow.

Table 36: Factor analysis of the Eigenvalue

Variables (%)	F1	F2	F3	F4	F5	F6	F7	F8	F9
Eigenvalue	4.15	1.72	1.04	0.79	0.58	0.33	0.23	0.13	0.05
Variability	46.10	19.07	11.56	8.81	6.42	3.62	2.52	1.39	0.51
Cumulative	46.10	65.18	76.73	85.55	91.99	95.58	98.10	99.49	100.00

Diagrammatical representation of the Factor Analysis indicates for each variable level of significance how they contribute to the total streamflow volume (latent class). The variability contribution of each meteorological variable was as shown in Figure 62. All the meteorological data influence the streamflow except the wind speed presented in the statistical factor analysis biplot, which stands alone. This shows it has the least effect.

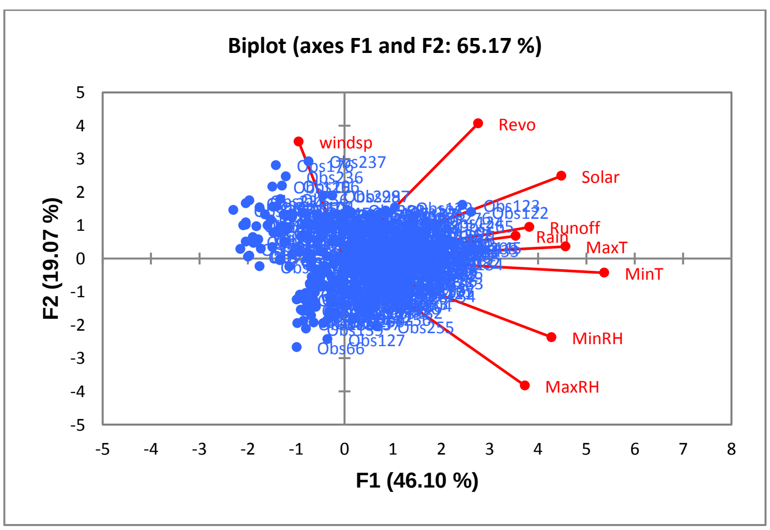

Figure 62: Contributing meteorological variable factor analysis

Factor analysis (FA) explores the dimensionality of a measurement instrument by finding the smallest number of interpretable factors needed to explain the correlations among a set of variables (Hu *et al.* 2014). This has been used in the analysis of the meteorological parameters input for the ANN model for predicting streamflow.

5.2.4 The results of ANN seasonal classifier for streamflow prediction

Modelling of streamflow data has been a vital tool that has been employed in forecasting both the long-term and short-term hydrological variability that occurs in a basin. Both modelling and simulation have assisted towards efficient management and planning of water resources. Detailed insight into modelling the four seasons and its Neural Network classification is given in Figure 63.

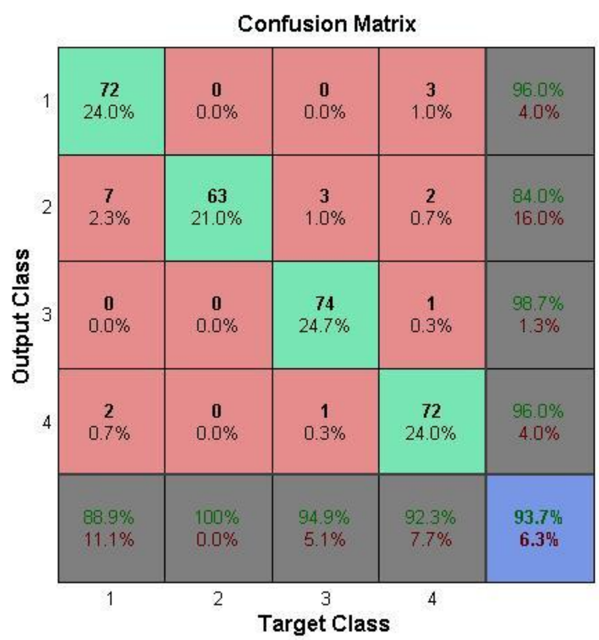

Figure 63: Seasonal classification by ANN model

The ANNs internal algorithm (i.e. the hidden layer gradient descent method) could classify them into the four-prominent seasons based on collected data which were sorted on a monthly basis and labelled as 1 - Summer, 2 - Autumn, 3 - Winter and 4 - Spring respectively. The developed ANN model in the present study consisted of eight input layers and four output layers. The different monthly hydro-meteorological data for each of the six catchments serve as input data. The confusion matrix shows 93.7% classification accuracy and was achieved by the classifier in cataloguing the labelled data into the appropriate season. Given any unknown data set for the test, the developed model could distinguish it and classify it into the appropriate season.

Based on the seasonal classifier, the monthly meteorological dataset was combined (Dec-Nov) and run as input for ANNs best-projected hydrologic flow regime forecast. The result of the optimal seasonal discharge forecast model is as presented in Figure 64.

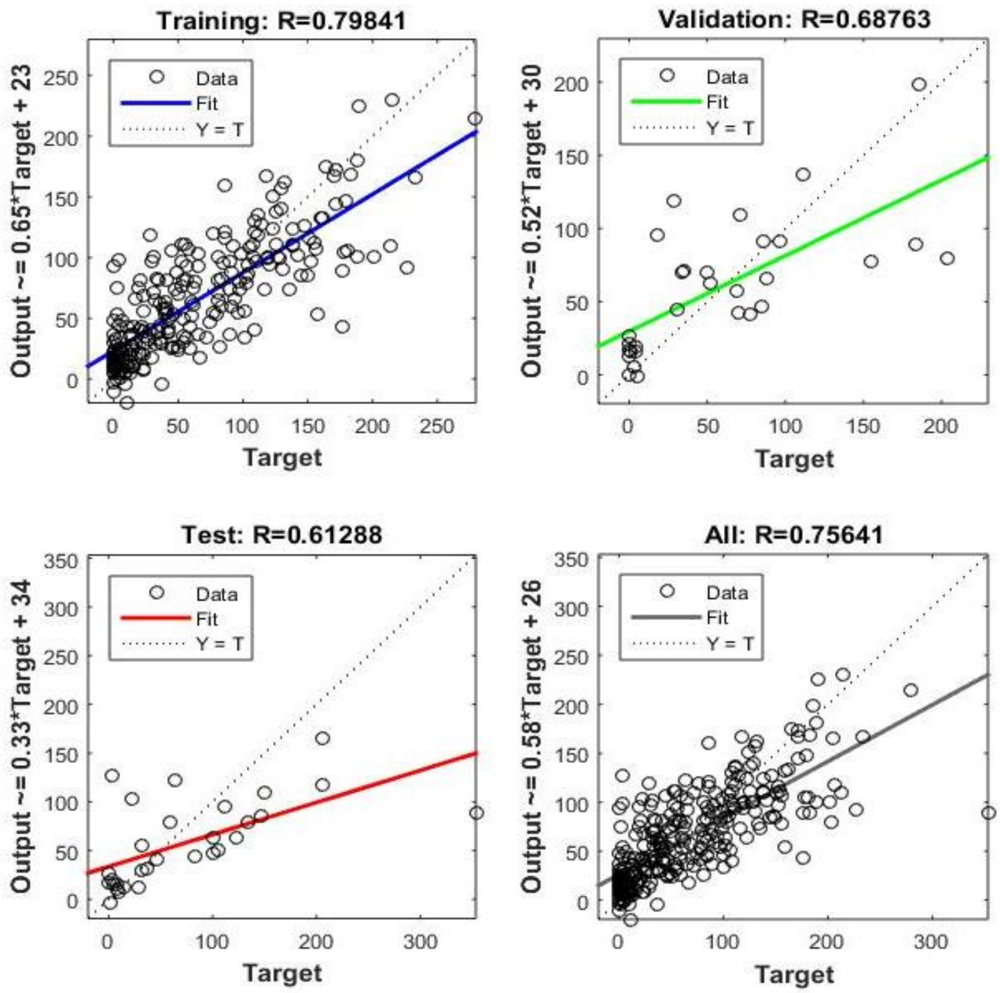

Figure 64: Output values for the optimal seasonal discharge (MATLAB R2015a)

The ANN model was calibrated for 2008 to 2011 and validated for 2012 to 2015. The performance measures of RMSE and CC values are 79% and 61% respectively during the calibration period. During the verification period, the RMSE and CC values are slightly improved and the values of 68% and 75% were achieved, respectively. The ANNs forecasted results provide the likelihood of high, near median or low streamflow. Figure 65 shows the results of the training test as well as the optimum prediction performance of the network architecture.

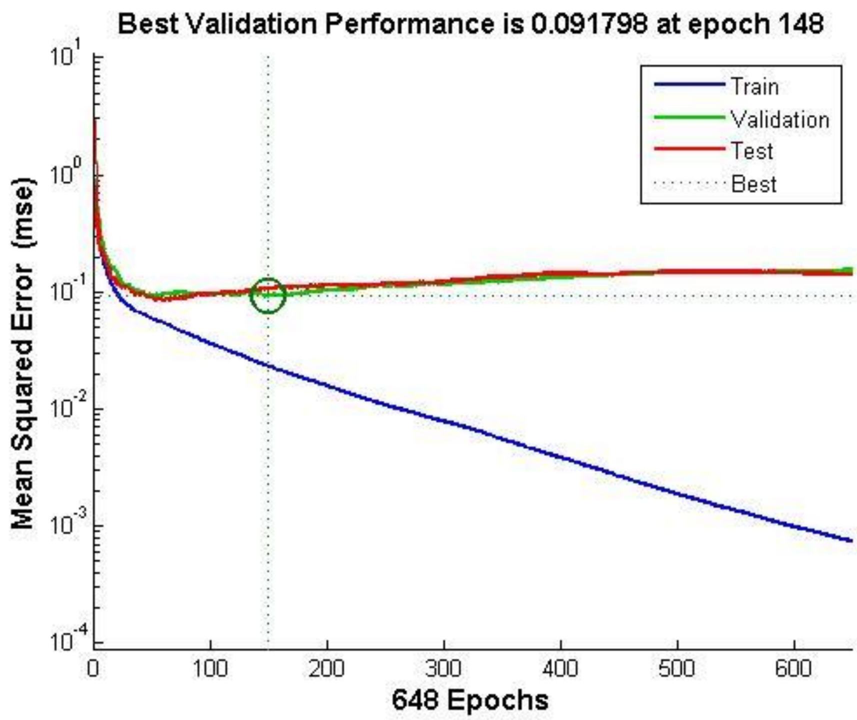

Figure 65: Performance evaluation measures

5.2.5 Discussion on ANNs streamflow prediction, calibration, and validation

The result from the four seasons was detrended and deseasonalised using the right ANNs configuration (Figure 66). The ANNs forecasted discharge data were a test against observed runoff data collected at a U1H009 station along the River. Comparing the ANNs simulated value and the observed runoff variables show a satisfactory ANNs forecasting model for the seasonal run. The MATLAB toolbox was used in modelling the hydro-meteorological variables in forecasting rainfall. The result showed that ANNs is a better forecasting tool since values of R are > 0.5 when compared to other data-driven modelling tools (regression and probability distribution).

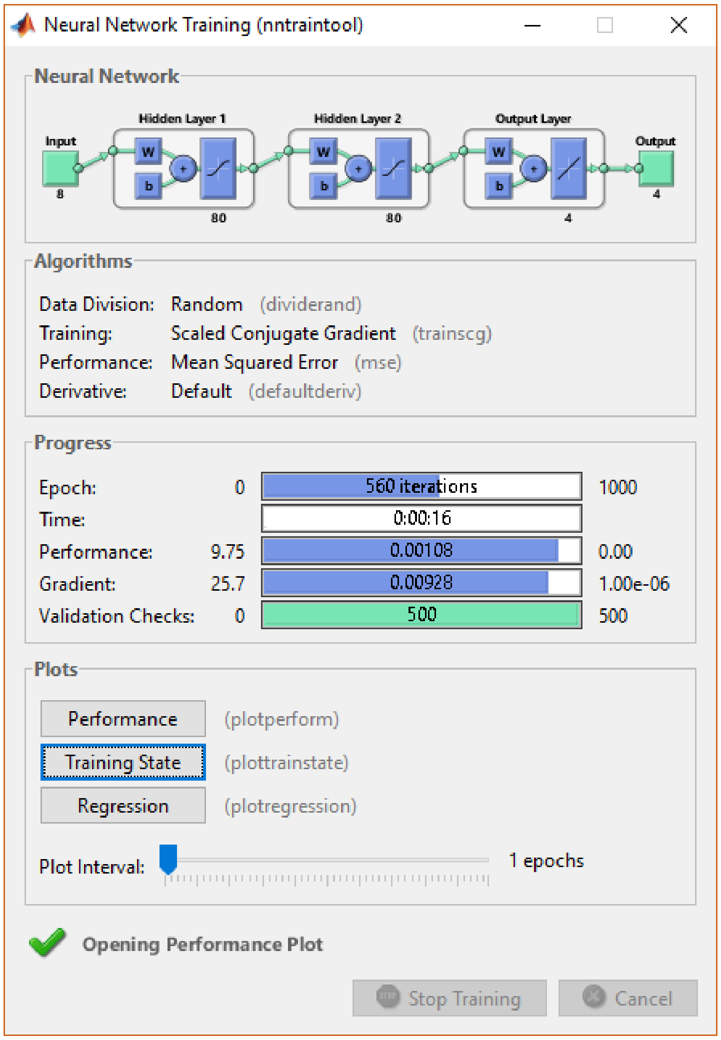

Figure 66: ANN seasonal configuration model

The seasonal streamflow in the Mkomazi Basin was observed to follow regression pattern trends during training, testing and validation as shown by the MATLAB gradient plot (Figure 67) for optimal seasonal prediction of datasets. The initial wavy line before the linear epoch time to completion period indicates the presence of noise in the data despite its statistic correction.

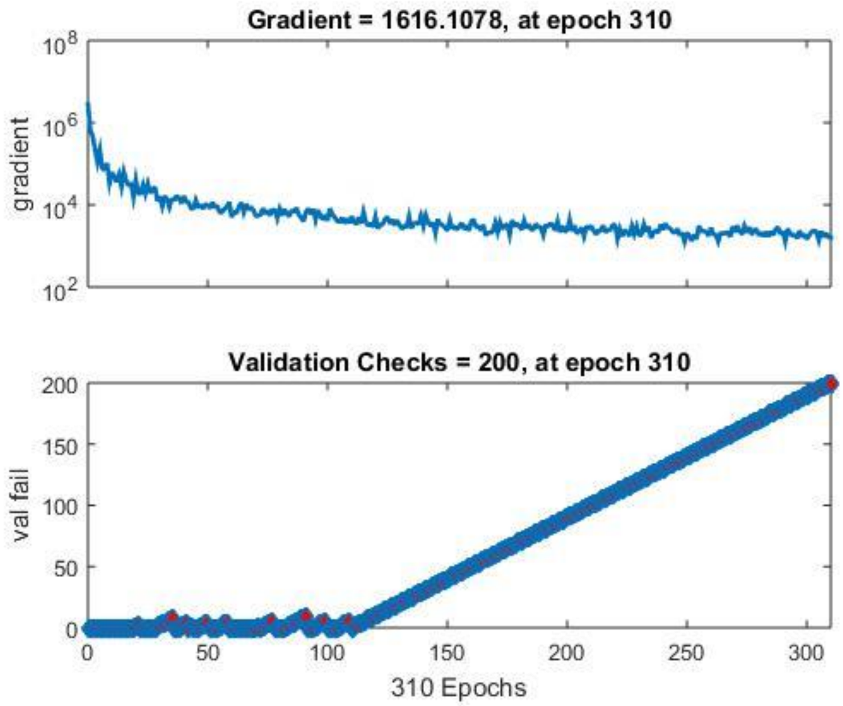

Figure 67: Sample data gradient and epoch time for seasonal flow prediction

To validate the observed streamflow with the predicted ANNs regression model for each season summer sample data was used as a case study. The observed MRB runoff at (Mkomazi drift UIH009) station was used to compare with the ANNs model simulated output in Shrestha (2016) Calibration Helper v1.0 Microsoft Excel Worksheet.

The model performance was evaluated using statistical parameters. The result of the calibration was presented in Figure 68 , while Figure 69 is for the validation period.

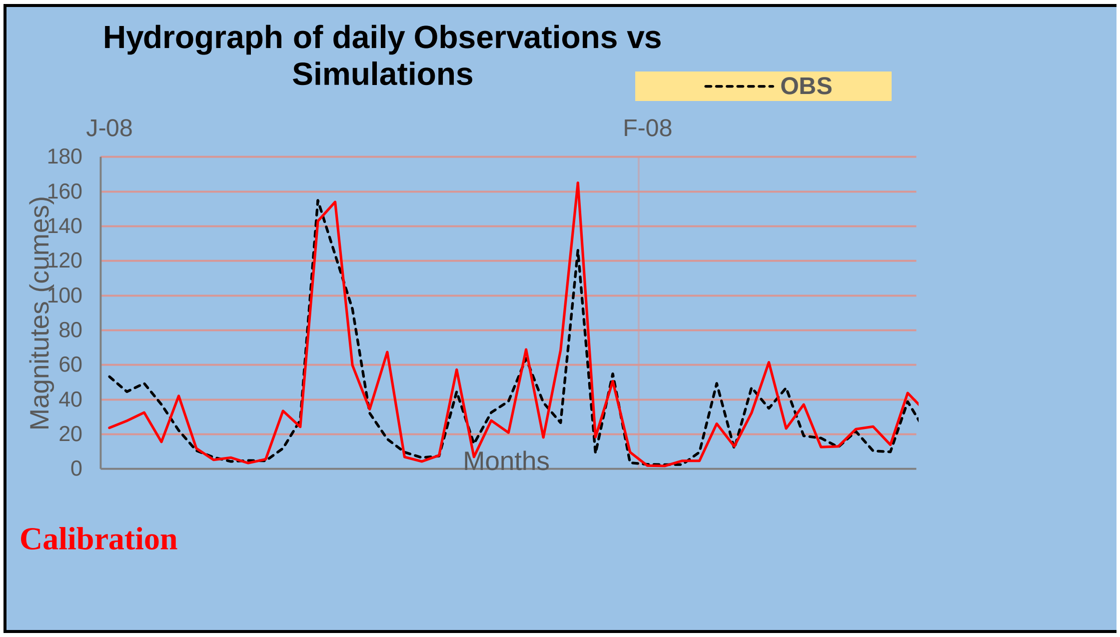

Figure 68: Observed and simulated discharge during the calibration period

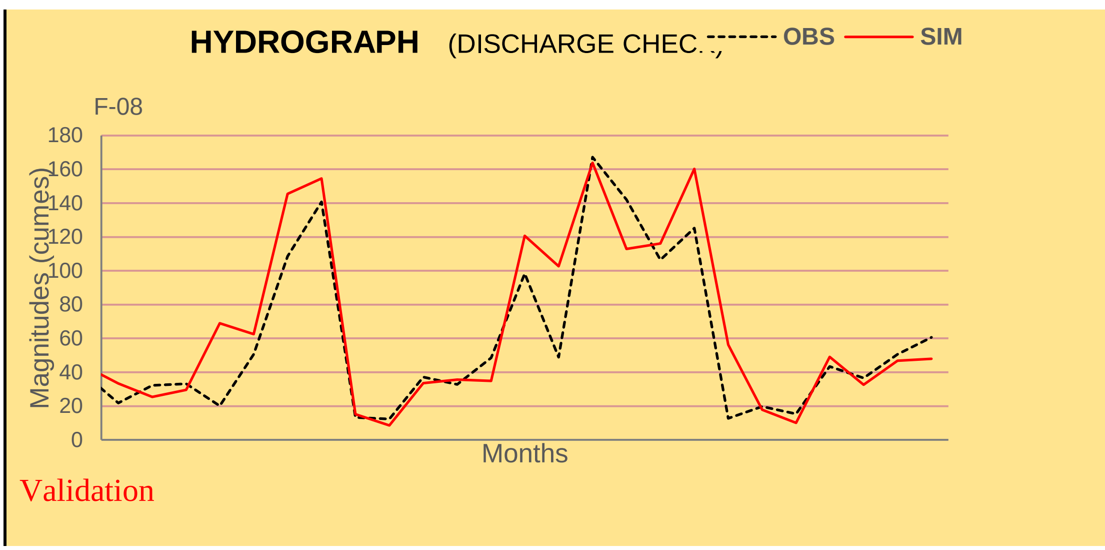

Figure 69: Observed and simulated discharge during the validation period

As it can be seen from the Figures, there is a good correlation between the observed flow and the simulated flow, indicated by NSE and R^2 of 0.76 and 0.72, respectively, for calibration period, and NSE and R^2 of 0.70 and 0.78, respectively, for the validation period. In addition, the correlation coefficient of 0.85 for calibration data and correlation coefficient of 0.88 for the validation data indicate that the experimental data are reliable. Table 37 depicts the calibration and validation statistical performance summary Furthermore, the data for the calibration and the validation exercises are within the confidence interval of 95%.

Table 37: The calibration and validation statistical performance summary

Output statistics	**Calibration**	**Validation**
NSE	0.62	0.77
NSE_{rel}	0.47	-0.32
R^2	0.77	0.83
wR^2	0.62	0.69
RSR	0.53	0.48
PBIAS	3.10%	13.90%

The ANNs model result shows that the calibration and validation stage is satisfactory. The graphical result of both has more peaks, and is flatter at base flow. This depicts that the river discharge and elevation vary over time at any section of the river, and this may have accounted for the varying magnitude of flow estimated over the period. Figure 70 represents the estimated seasonal catchment yield of higher surface flow in winter with decreasing lower base flow across the seasons. Streamflow is at its lowest in the winter period. In order to carry out the Seasonal flow variation (2008-2015) the average mean flow for each season was sum up and classified into the four prominent season. Figure 70 presents the decreasing trend from 1-summer; 2-Spring; 3-Autum; and 4-Wimter.

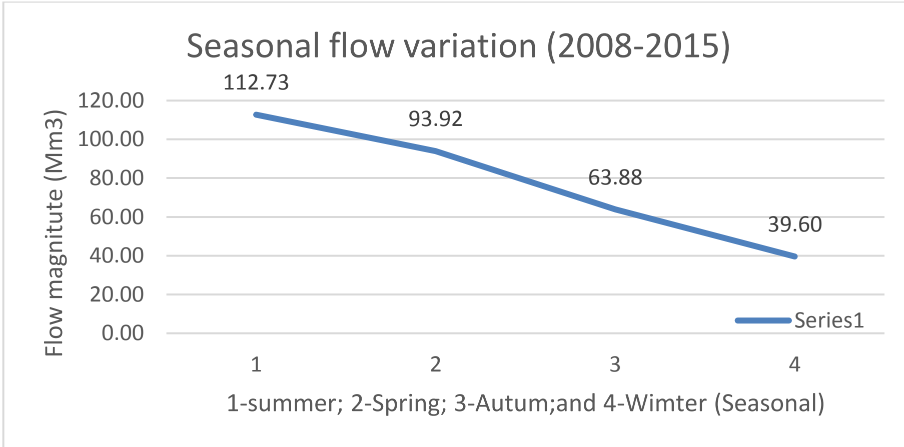

Figure 70: Seasonal variability flow dynamic across the river

5.2.6 Discussion on seasonal flow variation and spatial rainfall relationship

From the analysis carried out above, heavy rainfall characterizes the summer season. The summer rainfall variations are related more closely to average temperature, with higher temperatures associated with lower rainfall. Lower rainfall in winter tends to be linked to higher temperatures, whereas streamflow is at its lowest in the winter period. This can be linked due to little or no rainfall during the season, which is also known as the dry season of the year. Spatial distribution of rainfall is the major factor controlling the streamflow patterns of the river studied. Therefore, the highest impact of the basin hydro-meteorological variables on streamflow generation was felt during the summer period.

In addition, as depicted in Figure 71, the relationship between runoff and Mkomazi rainfall has been high and stable over the period of study (2008-2015). Summary, a spatially distributed correlation was plotted between rainfall and runoff. The fit runoff predictions model was similar to the observed rainfall measurement. The observed similarity shows that both the rainfall calibration and runoff validation stage for the locations lies in similar hydrological basins.

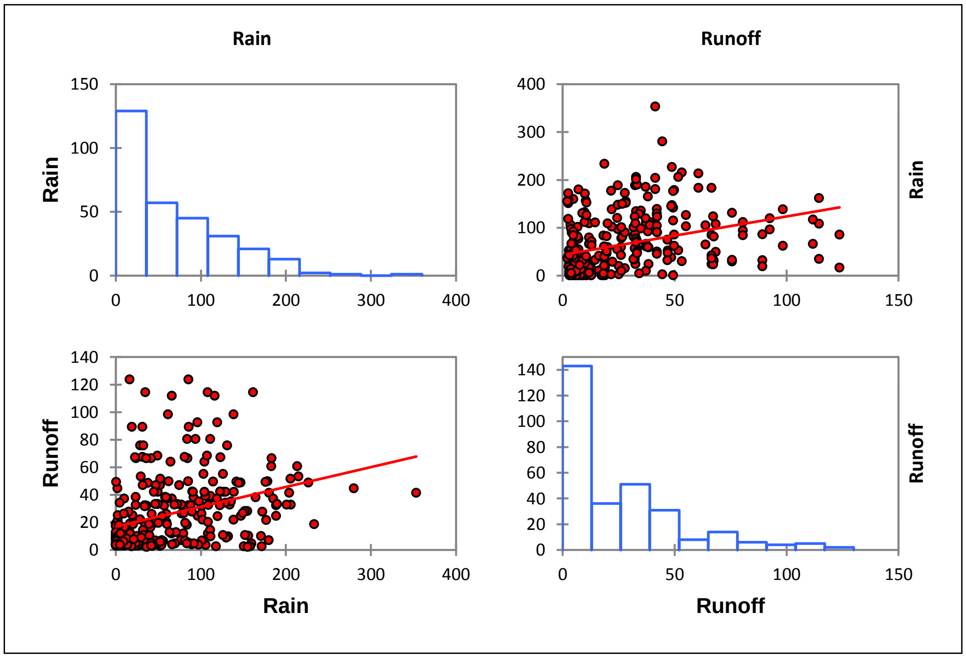

Figure 71: Correlation plot between rainfall and runoff

5.3 Seasonal hydrological flow regime summary

Seasonal hydrological flow regime is of the utmost importance in understanding potential water allocation schemes and subsequent environmental standard flow regulation. In this study, a combination of statistical techniques and ANN was used to evaluate the hydro-meteorological trend, and a seasonal pattern classifier and forecast of streamflow has been conducted.

For this purpose, a nonparametric approach consisting of the Mann–Kendall test and Sen's method, and a parametric approach (ANN) based on factor and principal component analysis of extremes statistical theory has been applied. Owing to the seasonal character of the variables, the result concludes that all the variables considered except wind speed are the most important parameters, which influence the estimation of streamflow.

Furthermore, there is a strong relationship between runoff and the basin rainfall over the period of study (2008-2015).

The results show the potential function of ANN in characterising the individual seasons and projected maximum likelihood trend for the surface water patterns. The methods applied further confirm our assertion that these patterns are indeed unique across each season's months. When water authorities and stakeholders have a reliable streamflow forecast, it becomes easy to optimally allocate water resources for competing water uses such as domestic, hydropower generation, agricultural and environmental flows.

5.4 Discussion of results on water balance assessment

The result of the mean annual and monthly water balance between the relative periods 2008-2015 for Mkomazi River is presented in Table 38 along with the change in storage (ΔS) based on Equation 59:

$$P - (ET + RO) = \pm \Delta S \qquad \textbf{Equation 59}$$

Where: P = precipitation, ET = evapotranspiration, RO = surface runoff, and ΔS = change in storage

Table 38: Mean annual hydrological budget based on climatic variables (2008-2015)

	U10A	U10B	U10C	U10D	U10E	U10F	U10G	U10H	U10J	U10K	U10L	U10M
MAP (mm)	1170	1069	992	999	1034	963	981	924	878	793	758	858
MAE (mm)	1300	1300	1300	1300	1300	1300	1250	1200	1200	1200	1200	1252
MAR(mm)	501	420	362	291	309	177	199	180	154	111	96	143
Change in storage	-631	-651	-670	-592	-575	-514	-468	-456	-476	-518	-538	-537

The annual hydrologic budget indicates a negative budget, suggesting a water deficit of value ranging from -670 mm to -456 mm. The water deficit of an equal amount of water (-670 mm to -456 mm) of water must enter the system from other sources to maintain hydrological water balance.

In order to deal with water management issues, it is ideal to analyse and quantify the different elements of hydrological processes occurring within the area of interest as the understanding of the spatial and temporal variation and interaction of these hydrologic components assist in the formulation of strategies for water conservation. Figure 72 presents the general behavioural trend of observed mean annual representation of runoff, precipitation and evaporation at the Basin while Table 39 shows the results of the monthly water budget for each of the sub-basins' contribution to the total water yield of the watershed.

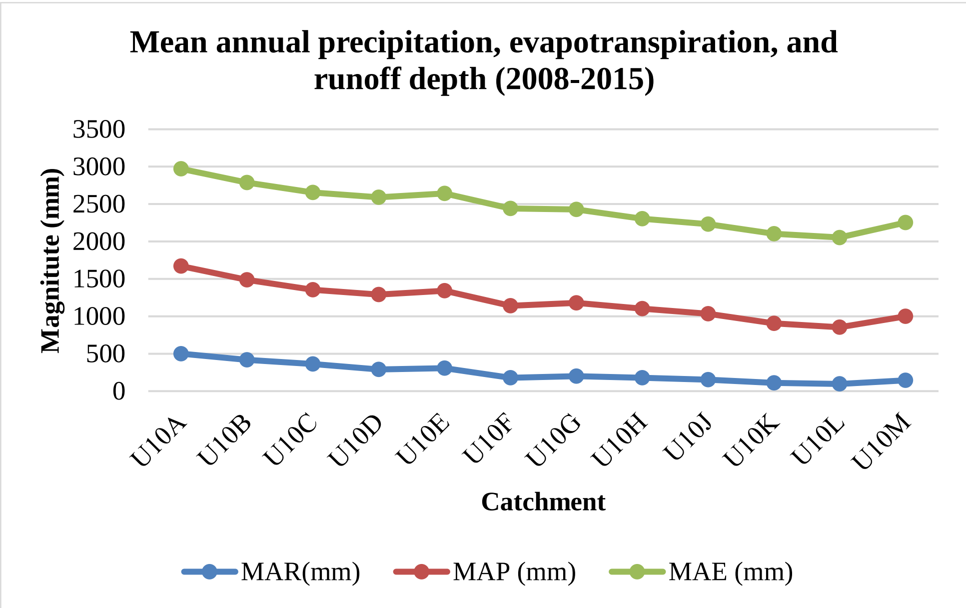

Figure 72: Mean annual precipitation, evapotranspiration, and runoff depth

Table 39 shows the results of the monthly water budget for each of the sub-basins' contribution to the total water yield of the watershed.

Table 39: Mean monthly water balance of Mkomazi in mm (period 2008-2015)

	Jan	Feb	Mar	Apl	May	Jun	Jul	Aug	Sep	Oct	Nov	Dec	Annual
Pl	106.13	65.48	81.34	46.03	13.41	11.34	16.54	22.47	33.93	72.7	81.98	95.42	646.77
ET	112.52	112.64	97.57	84.62	74.59	65.07	70.42	84.95	99.21	99.13	103.18	104.21	1108.1
Rout-Rin	57.986	60.579	50.584	30.615	14.07	8.062	6.068	6.719	7.244	12.423	18.775	40.77	313.9
ΔW	-64.379	-107.732	-66.808	-69.202	-75.25	-61.789	-59.951	-69.199	-72.524	-38.853	-39.978	-49.567	-775.23

The analysis shows an annual deficit of 775.23 mm water balance with a varied range of between 39.9-72.5 mm across the months. This indicates a semi-arid region. Thus, the need for the efficient and judicious use of water cannot be over-emphasised. Therefore, there is a need for a groundwater inflow of an equal amount in mm annually to balance the deficit

.

5.5 Results and discussion of SWAT model water accounting budget

The use of the SWAT model in a GIS environment to simulate the basin water budget was carried out to give an estimate of available water to be shared among the different end users and the environment. The model visualisation output allows standardised water accounting procedures that quantify the watershed processes and assess a safe level of exploitable water volumes. This assists the decision makers to synthesise and fix the maximum amount of water that can be withdrawn and consumed by the allocable sector.

5.5.1 Model pre-calibration

The values of the pre-calibrated runoff hydrograph are useful in calibrating and validating the SWAT model. It gives insight into assessing the model performance by comparing the mean annual runoff generated by the model to the mean actual runoff measured on site.

Thus, a graphic representation of the pre-calibration period is as shown in Figure 73. SWAT was used to quantify each of the hydrological processes taking place within the basin watershed. The pre-calibration stage implies that the implication of water yielding potential of the deep aquifer is at minimum when related to the lateral flow.

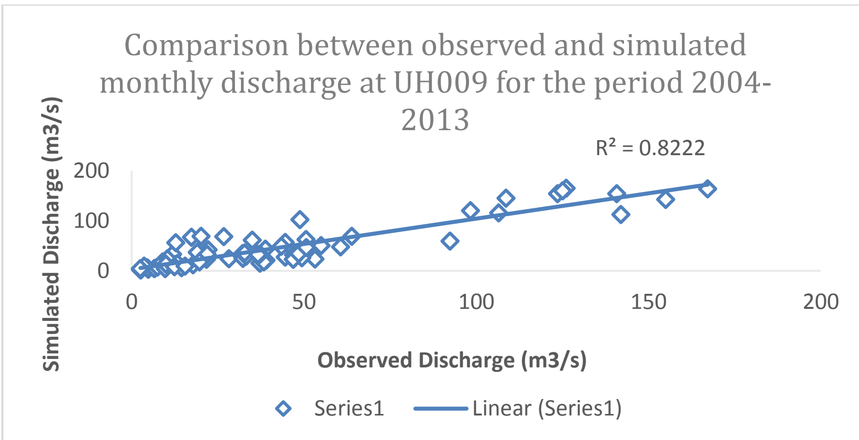

Figure 73: The pre-calibration period discharge comparison

5.5.2 SWAT -Cup sensitivity analysis and calibration result

Prior to calibration and validation of the SWAT model, a sensitivity analysis was examined as part of the modelling process to determine which parameters influence the model structure and output most. It is helpful to understand the influence of input on model structure and model parameters on the model outputs. Generalised sensitivity analysis tools in SWAT-CUP were used to assess the parameters that have a strong influence on model outputs. SUFI2 is a sequential procedure where all sources of uncertainties are mapped to a 95PPU set of parameter ranges that envelop most of the observations. The sensitivity analysis for 9 model parameters was carried out via the SWAT-CUP SUFI2 auto calibration optimisation method. The results are as shown in Figure 74 and Table 40.

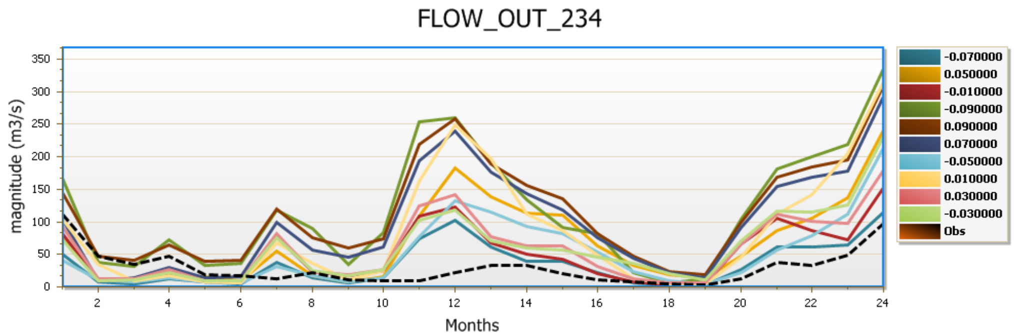

Figure 74: The relative fitted rank SUFI2-SWAT-CUP sensitivity output

Table 40: The relative fitted rank sensitivity output

S/N	Parameter_ Name	t-Stat	P_ value
1	R__CN2.mgt	-3.0700	0.0100
2	V__ALPHA_BF.gw	-2.2500	0.1453
3	A__GW_DELAY.gw	-2.5000	0.2450
4	A__GWQMN.gw	-1.6540	0.6000
5	A__RCHRG_DP. gw	-0.0150	0.7050
6	A__REVAPMN.gw	0.0435	0.5000
7	V__GW_REVAP.gw	0.0200	0.0200
8	V__SOL_AWC(..).sol	3.1000	0.2000
9	V_ESCO.hru	4.6200	0.4000

Where: CN2-SCS is the runoff curve number; GW_DELAY-Groundwater delay (days); ALPHA_BF-Baseflow alpha factor (days); RCHRG_DP-Deep aquifer percolation fraction; REVAPMN- Threshold depth of water in the shallow aquifer for ‘revamp’ to occur (mm). GWQMN - Threshold depth of water in the shallow aquifer required for return flow to occur (mm); GW_REVAP-Groundwater ‘revamp’ coefficient; and GWHT-Initial groundwater height (m); The rest ESCO and SOL_AWC are soil permeability parameter.

Figure 75 result gives the graphs of the SWAT-CUP SUFI2 auto calibration optimization parameter sensitivity output. In absolute value category, the bigger the value of t-stat, and the smaller the p-value, the more sensitive the parameter, while Table 40 shows that the most sensitive parameters for hydrological modelling of MRB watershed are: CN2.mgt; ALPHA_BF.gw; GW_DELAY.gw; A__RCHRG_DP. gw.

This result is in agreement with those found in similar studies: Loveland *et al.* (2000); Schuol and Abbaspour, (2007); Stehr et al., (2008); and Fadil et al., (2011) confirming that these four parameters are the crucial sensitive parameters for water balance and stream flow.

Figure 75 shows the SWAT-Cup sensitivity plot. The CN2.mgt parameter is the most sensitive parameter with best fitting values of less than -0.01 at relative change (r__).

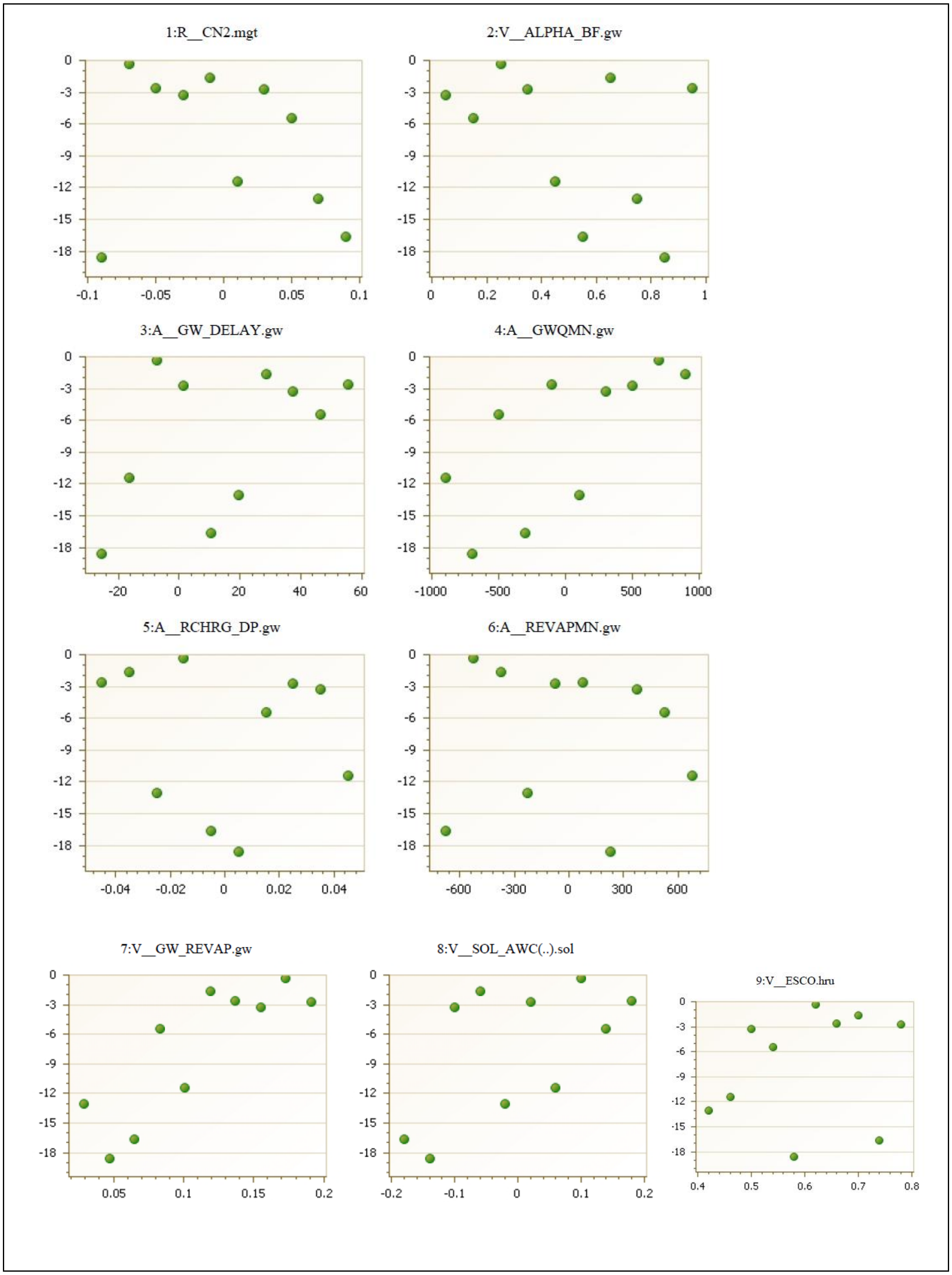

Figure 75: SWAP CUP sensitivity for 9 model parameters

5.5.3 Performance evaluation, calibration and validation of SWAT model

The successful application of a hydrological model depends on how well the model is calibrated (Gupta, Sorooshian and Yapo.P.O 1999). This is necessary to evaluate the capability of the hydrologic model prediction. All parameters are assumed to be uniformly distributed. Krause, Boyle and Bäse (2005) suggested the SWAT-CUP method for different efficiency criteria for hydrological model assessment. The calibration defines the minimum and maximum ranges for the parameters in SUFI2. Figure 76 and Table 41 depict the calibration simulated (Sim.) monthly runoff values (calibration 2004-2008) result.

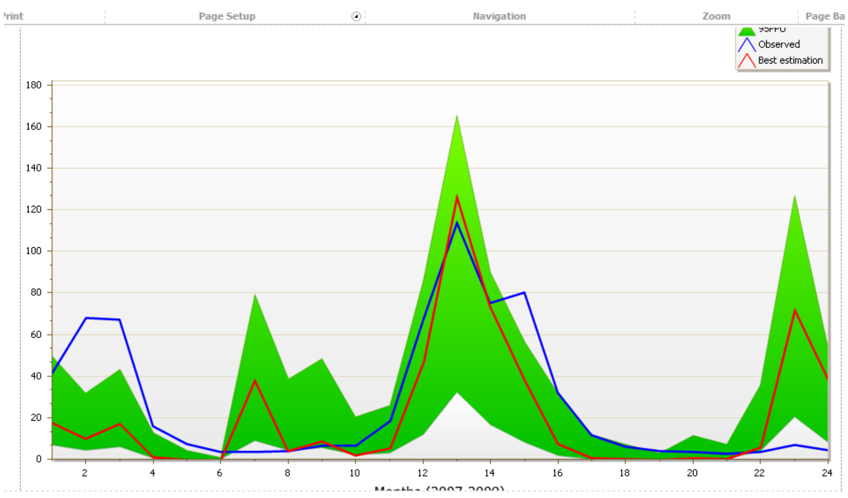

Figure 76: 95PPU observed and Sim monthly runoff values (calibration 2004-2008)

Table 41: Calibration output statistic

R^2	0.65
NSE	0.54
PBIAS	21.30
RSR	0.82

The results of the calibration are presented in Figure 78 and Table 41, while Figures 79 and table 42 are for the validation period. As it can be seen from the Figures, there is a good correlation between the observed flow and the simulated flow, indicated by NSE and R^2 of 0.54 and 0.72, respectively, for calibration period and NSE and R^2 of 0.58 and 0.89 respectively, for the validation period. The performed analysis at validation provides a better insight into the model fit, Figure 77 and Table 42 depict the result at validation stage (2009-2013).

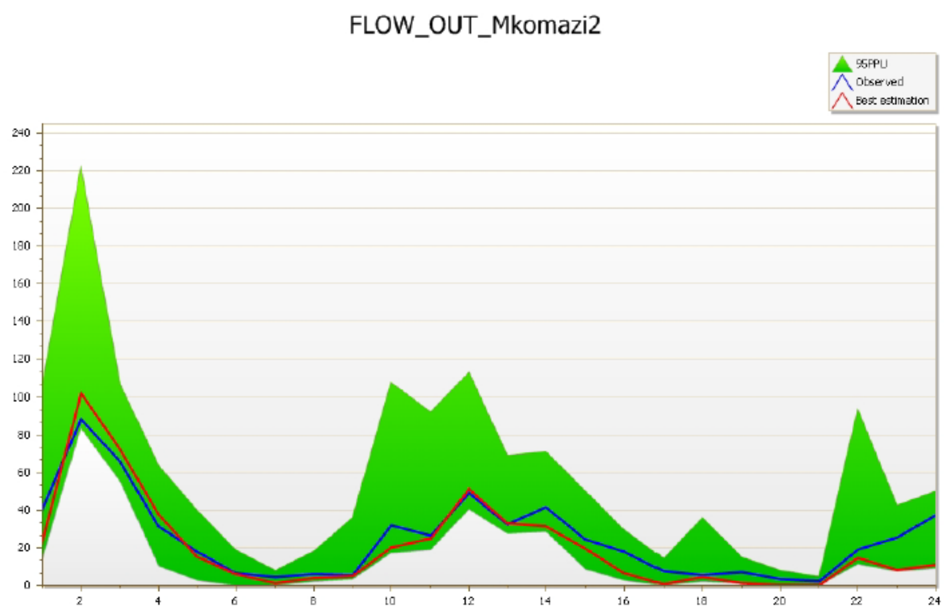

Figure 77: 95PPU observed and Sim. Monthly runoff values (validation 2009-2013)

Table 42: Validation output statistic

R^2	0.89
PBIAS	17.00
NSE	0.80
RSR	0.44

The calibration and validation values for goodness-of-fit (RSR, PBIAS, NSE, and R^2), obtained during the calibration and validation period, are all acceptable. For instance, the R^2 and NSE are about 0.89 and 0.80, respectively at validation for daily discharge simulation with a slight over-estimation of the low flow during this stage.

5.5.4 Statistical assessment of discharge (post calibration)

The statistical indicators of the validation period (2009–2013) at UI009 (Mkomazi drift) were also acceptable for predicted monthly streamflow simulation (Figure 80).

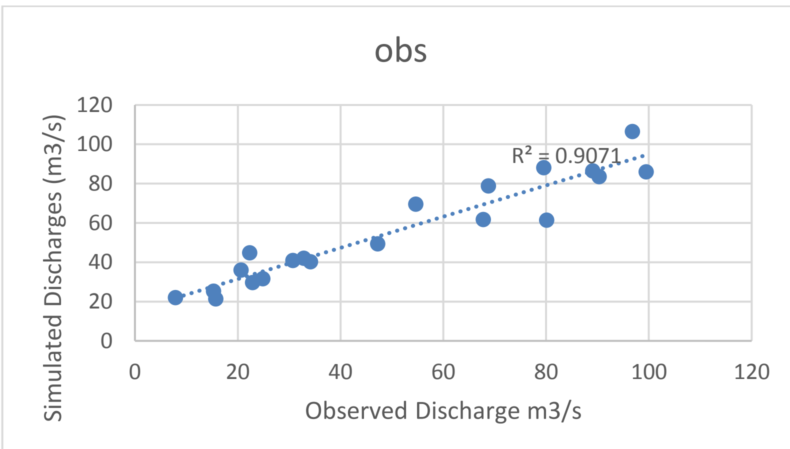

Figure 80: Observed and simulated monthly discharge (validated) at UI009

Figure 78 is the regression plot of the simulated and predicted simulated monthly discharge (validated) at MRB for the period 2009-2013.

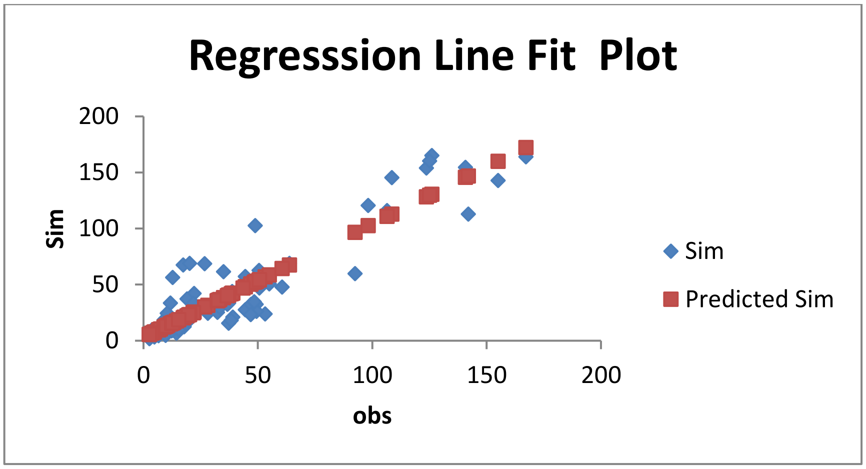

Figure 78: Predicted and simulated monthly discharge (validated) at UI009

Both the simulated and predicted simulated monthly discharge (validated) at MRB for the period 2009-2013 provided a satisfactory model calibrated to predict the stream flow.

5.6 Results and discussion of SWAT water yield

SWAT quantification of groundwater and the surface monthly mean water yield over the HRUs chronologically sequential is presented in Figure 79 and Figure 80. The simulated result reveals a mean monthly water yield range of 2.7-34.8 m^3/s for groundwater and 28.6-36.0 m^3/s for surface water over the study years (2004-2013).

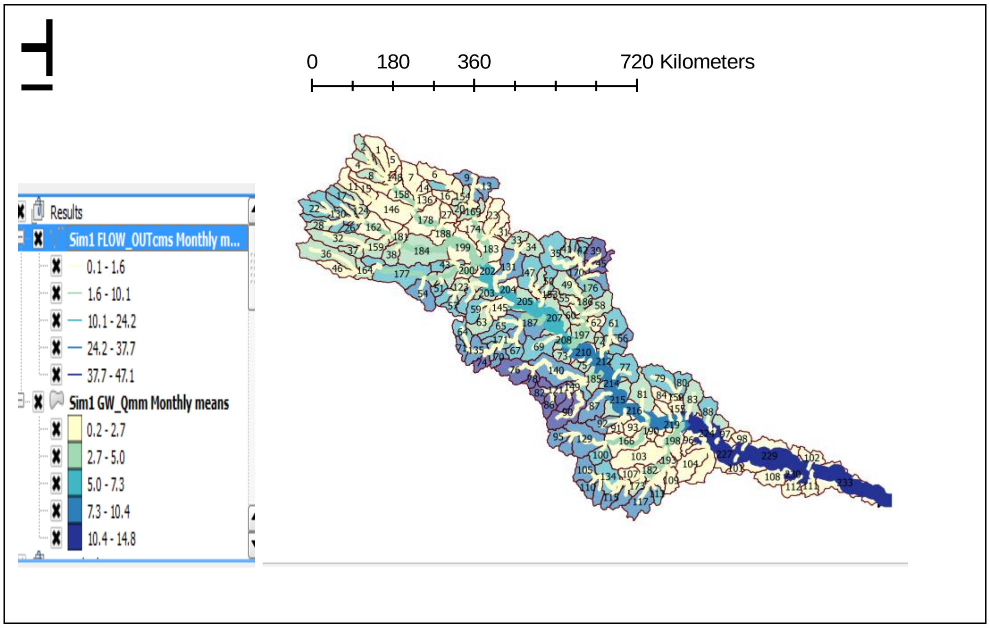

Figure 79: Groundwater monthly mean water yield for the basin (2004-2013)

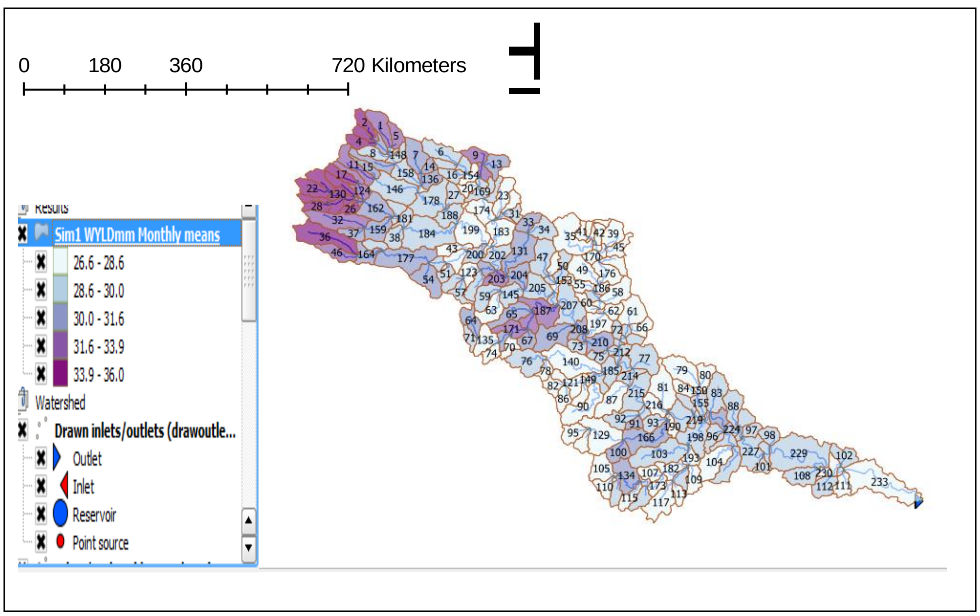

Figure 80: Surface water monthly mean water yield for the basin (2004-2013)

The model performance evaluation results with Nash-Sutcliffe efficiency and coefficient of determination (R^2) values of 0.89 and 0.80 at validation stage indicates a strong model efficiency to observed values. The model performance shows a convincing rationale for greater rainfall variability and water yield evaluation. There is a gradual increase in both the surface water (SW) and groundwater (GW) yields across the river downstream.

5.6.1 Discussion of water budget accounts and changes in storage basin.

More details on the predicted values of surface runoff, average curve number, precipitation, base flow and PET can be found in Figure 81.

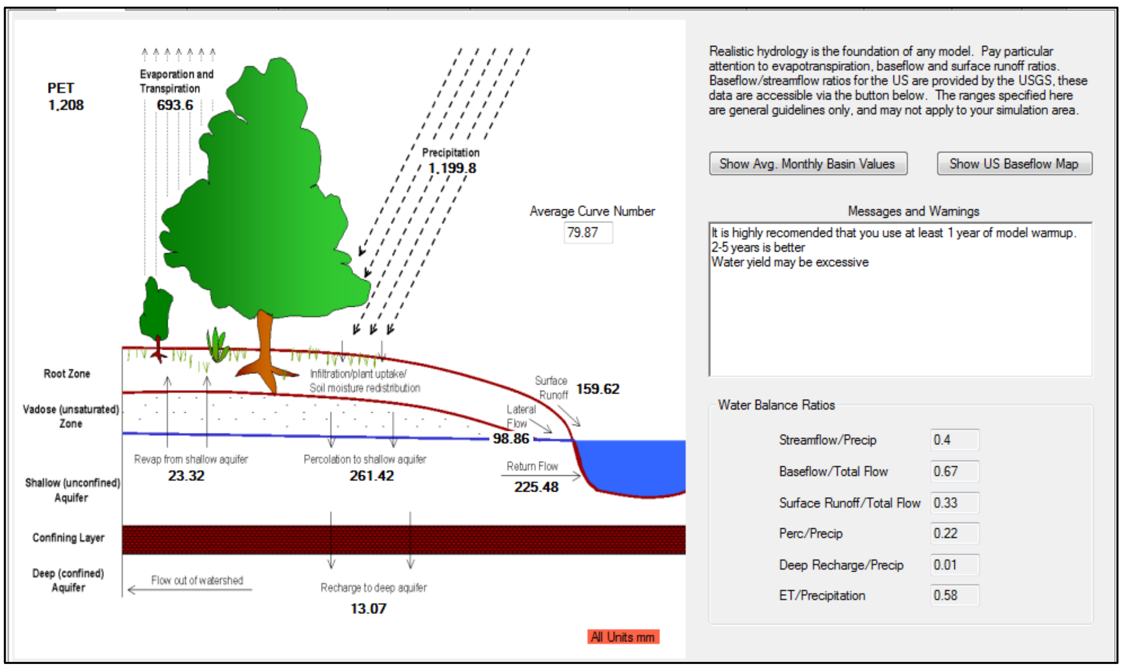

Figure 81: QSWAT annual summary for the basin water budget
Source: SWAT Error Checker simulation interface for QSWAT version 1.2.0.9

The diagrammatical illustration of the basin hydrological process and component shows higher PET. The SWAT-QGIS visualisation layout shows the annual summary of the daily outputs for the basin water budget. Figure 82 shows the basin other water balance simulation ratios of Streamflow/precipitation (0.4 mm); Baseflow/Total flow (0.67 mm);

Surface Runoff/Total flow (0.33 mm); Percolation/precipitation (0.20 mm); Deep recharge/precipitation (0.01 mm) with an Evapotranspiration/precipitation ratio of 0.58 mm respectively.

Analysing the hydrological characterisation of the basin, shows that approximately 76.94% of the total annual rainfall turns into green water (evapotranspiration 65.67% and interception 22.27%), while 18.45% of the annual rainfall constitutes the blue water flow. This percentage represents the fractional annual rainfall, which does not return to the atmosphere. Of the surface water flows, 67% of this amount is used for beneficial consumption, while, a 33% recoverable fraction represents non-consumed water that was used for the primary production of natural vegetation and agricultural ecosystems.

Beneficial water consumption constitutes water consumption that was used for beneficial purposes such as agriculture, energy, tourism economy or the environment while the non-beneficial water use denotes the water that was consumed but was lost into the system (leakages). The SWAT computed water balance configuration distinguishes between the different hydrological components.

The model validation confirms the reliability of SWAT to generate green and blue water flow in the Mkomazi River basin. This was with respect to various guidelines set for hydrological model assessment studies (Legates and McCabe 1999; Krause, Boyle and Bäse 2005; Moriasi *et al.* 2007). Table 43 depicts the comparison of monthly-observed data and simulated monthly discharge flow in the calibration and validation periods. The predicted output confirmed SWAT as an accurate tool in output uncertainty error minimisation. The unexpected high values error witness in January monthly discharge validation period might be because of influx of erosion. Flood-producing high rainfalls are a major problem confronted in the basin.

Table 43: Monthly mean flow comparison (observed and simulated)

	Calibration (2004-2009)			Validation (2010-2013)		
	(Monthly Discharge (m3/s))			(Monthly Discharge (m3/s))		
Months	Q abs	Q pred	**Error %**	Q obs	Q pred	**Error %**
Jan	42.12	17.90	**15.07**	41.31	24.92	**66.68**
Feb	68.34	10.21	**36.17**	89.23	103.20	**-13.54**
Mar	67.47	17.57	**31.05**	66.48	72.88	**-65.08**
Apr	16.24	1.42	**9.22**	31.63	38.17	**-66.51**
May	7.44	0.04	**4.61**	18.17	15.75	**24.56**
Jun	3.72	0.02	**2.30**	6.81	6.53	**2.86**
Jul	3.87	38.61	**-21.62**	4.85	1.83	**30.68**
Aug	4.15	4.28	**-0.08**	6.33	4.17	**21.95**
Sep	6.58	8.88	**-1.43**	5.73	5.22	**5.28**
Oct	6.92	1.92	**3.11**	32.49	20.24	**24.57**
Nov	18.84	5.42	**8.35**	27.16	25.41	**17.79**
Dec	68.28	47.01	**13.23**	49.57	51.60	**-20.67**
Average			**8.33**			**19.05**

The water quality components (nitrogen and phosphorous) transport in the watershed is represented in Figure 82 QGIS interface for SWAT version 1.7

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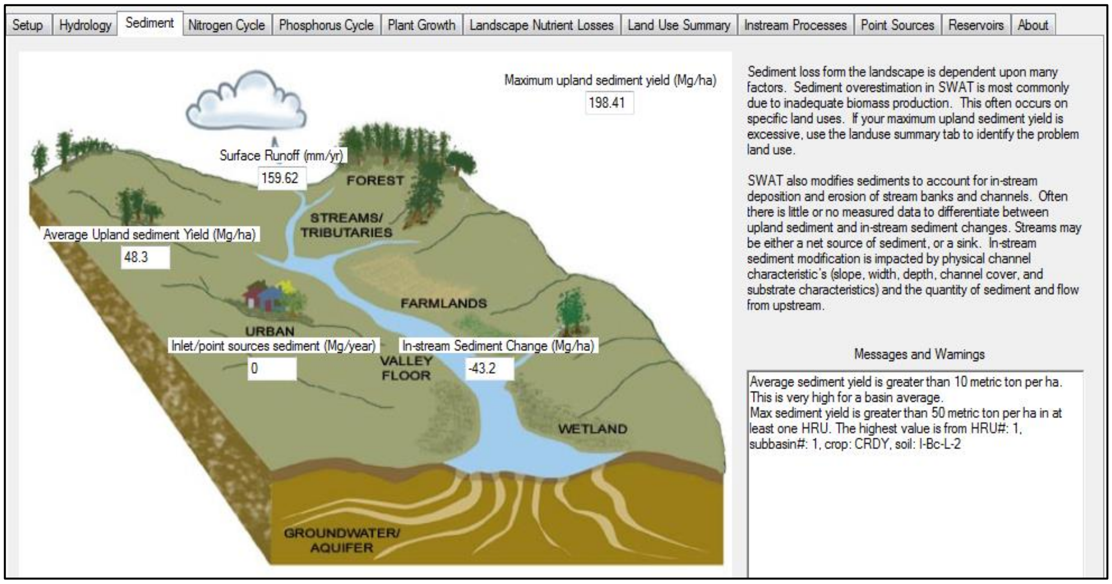

Figure 82: QSWAT Nitrogen and phosphorous water quality's component transport
Source: SWAT Error Checker simulation interface for QSWAT version 1.2.0.9

The model's behaviour in transporting inorganic materials (nitrogen and phosphorous) shows the extent of erosion abstraction on the soil texture and land cover. Largely, this has had a substantial influence on the land usage changes and process that has occurred in the basin. The average upland sediment yield of (48.3 Mg/ha) and in-stream sediment change value of -43.2 Mg/ha reveals farmlands, and valley floor vegetation pattern influences on the hydrological abstraction process which in turn affect the water quality.

The following section summarises the results of the SWAT model simulation for the basin's annual water balance component (Table 44).

Table 44: Annual values of the water balance components

Water balance components		Rainfall	Total ET ET	Actual	Surface Runoff	Groundwater	Water Yield	Stock
Calibrations	mm year	923.34	261.40	693.60	123.40	13.07	195.80	-8.54
	Rainfall partition (%)	100.00	24.60	59.90	8.70	5.80	20.20	-4.76
Validations	mm year	1100.00	305.04	855.00	321.00	260.70	308.00	206.21
	Partition (%)	100.00	26.40	18.23	12.54	9.56	21.75	-9.31
Average	mm year	1300.00	224.00	1100.00	855.00	80.67	306.00	-564.0
	Rainfall partition (%)	100.00	29.30	60.34	11.32	8.45	22.21	-7.40

5.6.2 Summary water budget quantification

The SWAT integration approach that combines 13 years of daily meteorological variable with spatial topography data gives a better water balance composition routing. Total annual water balance varies from the SWAT hydrologic model of 775 mm to 1,350 mm. The study concludes that, given the painstaking model set up, the SWAT model promises to be a good tool in estimating the basin's water balance parameters. Its visualisation technique and calibration of the simulated flow with observed data provides a reliable tool to establish sustainable water resources management for the Basin. The model was calibrated with the observed monthly inflow of data from 2004-2009, and cross validated with another set of independent data set from 2010 -2013.

5.7 Results and discussion for specific objective 3

To synthesise rules for sharing limited water resources towards operational analysis for environmental flows estimation.

The third objective was meant to synthesise rules for sharing limited water resources while maintaining the minimum environmental flow requirement and setting priorities during water scarcity. Although study related to environmental flow estimation poses a tedious task for further research work consideration. However, an attempt was made in this study for the e- flow estimation because it is very much required in ensuring proper management the river basin sustainability and maintaining environmental water quality.

In this section, the adapted synthesis rules which was done through review of records in Chapter Two was applied in the sharing of limited water resources by considering seasonal variable flow fluctuation and ensuring an agreeable equitable water ratio distribution among the water recipient users prior to the allocation. The synthesis rules was drawn from similar world experiences, modified and adapted to the case study area. This has help to assist in setting priorities during water scarcity.

An operational analysis for the estimation of environmental flows was approached through a synthesis flow-duration curves (FDC) best- fitting model for future stochastic in-streamflow prediction. An FDC provides a simple, but yet comprehensive, graphical view of the overall historical variability associated with streamflow in a river basin. It is a useful graph that shows that the climate and geomorphological descriptors strongly influence the hydrology of a place (Fennessey and Vogel 1990).

The graphical plot of discharge vs. percentage of the time that a particular discharge was equalled or exceeded under the flow duration curve (with arithmetic scales) gives the average daily flow, with the 50% of this value which represent the median daily flow (Johnson, Whiteaker and Maidment 2009).

The monthly environmental flow requirement was worked out to maintain and sustain the preservation of aquatic benefit and public future use. In achieving this, future monthly flows of the river have been forecast from developed stochastic streamflow models. The developed stochastic probability distribution model provides large similar sequences of streamflow data that can be used to estimate projected future quantities of water (Fennessey and Vogel 1990; Acreman and Dunbar 2004; Aqil *et al.* 2007). Using Equation 2 to Equation 5 as described in Chapter Two, section 2:10

The Flow-duration curves for each month's best-fit model (discharge) were made to provide insight as to how well the models fit the observed data. The developed best-fitted probability distribution models are as presented in Table 45. This can be used for projected estimation of water yield for the basins. The best-fitted model for each month was based on the minimum values of calculated Mean Relative Deviation.

Table 45 result reveals Log-Pearson type III as the best statistical parameters of the historical inflows (Feb-Nov) while the natural logarithmic transformation of Gumbel best fits flows of Jan and Dec.

Table 45: Best-fit model for each month of January to December

Month	Best fit Model	Model Equation	MRD
Jan	Log-Gumbel	Qp = Antilog (0.63 + 0.55YT)	26.4724
Feb	Log-Pearson III	Qp = Antilog (0.96 + 0.89K")	43.8097
Mar	Log-Pearson III	Qp = Antilog (0.86 + 0.87K")	36.6784
Apr	Log-Pearson III	Qp = Antilog (0.72 + 0.91K")	51.4296
May	Log-Pearson III	Qp = Antilog (0.53 + 0.77K")	23.1989
Jun	Log-Pearson III	Qp = Antilog (0.51 + 0.98K")	66.6701
Jul	Log-Pearson III	Qp = Antilog (0.42 + 0.78K")	19.5408
Aug	Log-Pearson III	Qp = Antilog (0.34 + 0.74K")	25.5913
Sep	Log-Pearson III	Qp = Antilog (0.36 + 0.75K")	39.8180
Oct	Log-Pearson III	Qp = Antilog (0.49 + 0.72K")	36.6573
Nov	Log-Pearson III	Qp = Antilog (0.67 + 0.69K")	25.3741
Dec	Log-Gumbel	Qp = Antilog (0.60 + 0.58YT)	24.1917

The Flow Duration Curve for the months January-June and July-December is shown in Figure 83 and Figure 84. A flow duration curve is a plot of discharge vs. percentage of the time that a particular discharge was equalled or exceeded. The area under the flow duration curve (with arithmetic scales) gives the average daily flow, and the median daily flow is the 50% value (Johnson, Whiteaker and Maidment 2009).

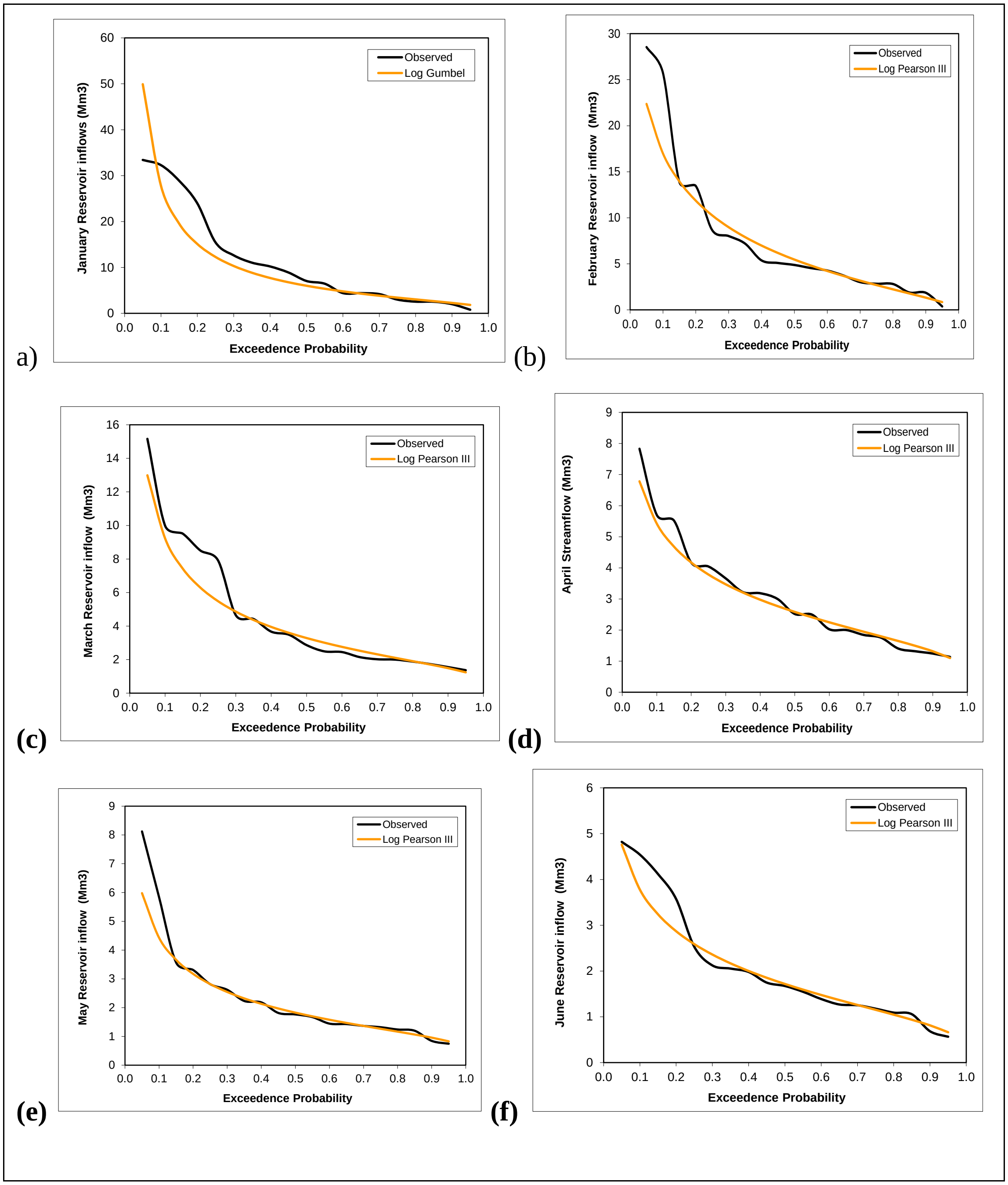

Figure 83: Flow duration curves between January and June at the Mkomazi Basin

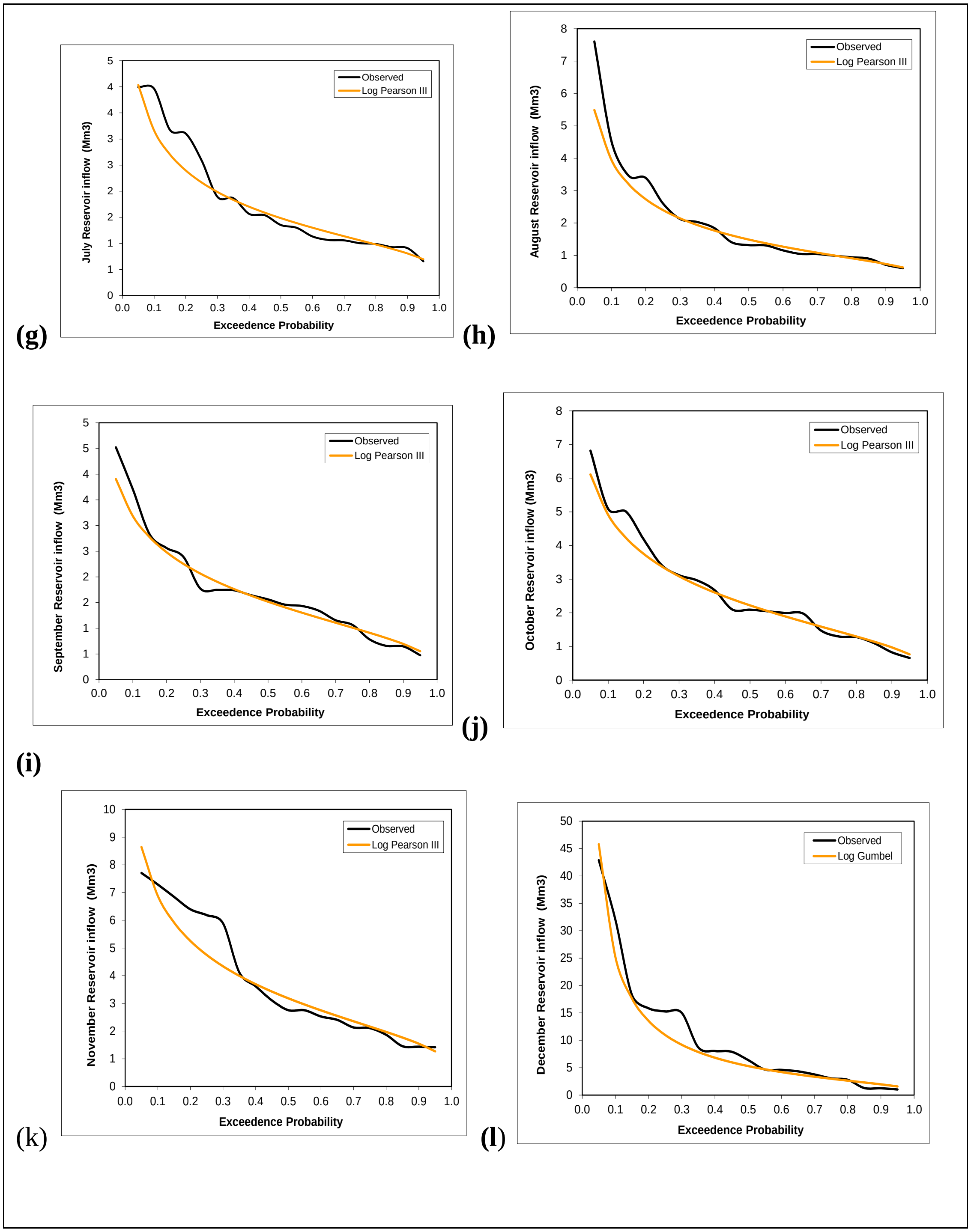

Figure 84: Flow duration curves between July and December at the Mkomazi Basin

The result shows an extreme value of flow magnitude (0.89Mm^3) and a fair seasonality annual fitting for rainfall distribution resulting in streamflow (Figure 85)

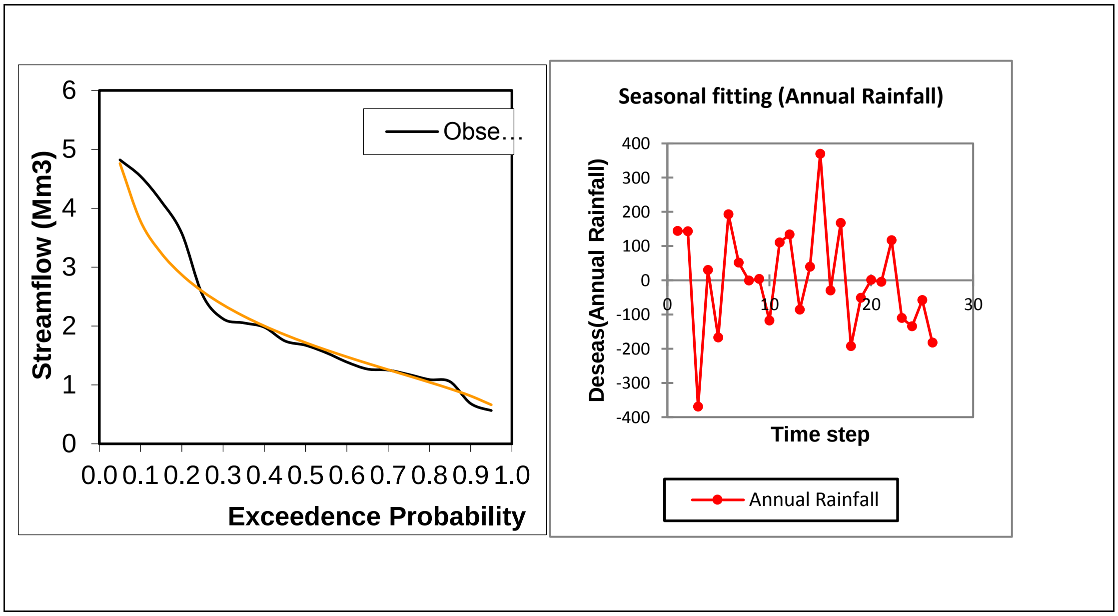

Figure 85: The FDC and Seasonal annual rainfall distribution plot

The constructed flow duration curve at UIH009 discharge location and time has helped to answer the question of different magnitude of flow expected at the different months for the study period.

5.7.1 Environmental water requirement

Generally, Instream Flow Requirement (IFR) is defined as the minimum flow, which must flow in a stream. The IFR is the maximum value of either low flow or environmental control flow. Environmental Flow refers to 'the minimum river flow required for maintaining the biodiversity of the riverain ecosystem including endangered fish species and the riparian corridor' (Adams, Cowie and Van Niekerk 2016). The operational analysis for the estimation of environmental flow in the basin was evaluated as follows: SWAT daily-simulated outflow has been aggregated to a monthly basis, thereafter to an annual time step for each month. The annual runoff series was then arranged in descending order, and ranked for there probability of exceedance using Weilbul's formulae (Equation 60). The value of one represents the highest rank value while the lowest value is the number of data in the series.

$$P_i = \frac{m}{n+1}$$ **Equation 60**

Where M is the rank, and n is the number of data points in the series, Table 46 gives the computed values of different Weibul ranking for different dependable flows at U1H009, while Table 47 depicts dependable flows (m^3/s) at Mkomazi U1H009 discharge station.

Table 46: Computed Weilbul ranking for different dependable flows

Year/ Month	**2008**	**2009**	**2010**	**2011**	**2012**	**2013**
June	352.006	209.098	1422.011	112.248	466.476	552.573
July	189.573	164.208	317.930	100.261	287.104	327.056
August	224.744	268.170	2.897	707.359	3534.308	1383.116
September	672.261	1590.366	73.383	411.408	116.395	911.351
October	187.183	213.782	147.835	1187.455	951.530	1285.462
November	925.168	775.928	698.551	901.356	572.173	1294.327
December	2252.905	577.683	724.110	93.304	697.405	2754.340
January	40.683	3838.547	521.758	66.374	800.982	4384.080
February	751.579	4128.536	500.917	1653.272	1854.475	3059.669
March	884.982	1617.623	1852.063	3.701	1691.778	3113.075
April	433.814	2255.383	4429.006	1024.100	3899.427	4284.967
May	1153.144	1826.235	7555.745	112.509	4156.812	1553.320
Grand total	**8068.043**	**17465.560**	**18246.205**	**6373.348**	**19028.865**	**24903.336**
Weibull Ranking	5.000	4.000	3.000	6.000	2.000	1.000
Probability of exceedance flow	**71.4286**	**57.1429**	**42.8571**	**85.7143**	**28.5714**	**14.2857**

Table 47: Dependable flows (m^3/s) at Mkomazi U1H009 Discharge station

Name of Project	Dependable Flow (Cumes)		
	60%	70%	85%
U1H009	17465.560	8068.043	6373.35

The water allocation results in the different dependable flow rates of 60%, 70%, and 85% reliability revealed it to be 17465.56, 8068.04 and 6373.35 (m^3/s) at U1H009 discharge station respectively. The allocable water (Table 47) was subsequently shared considering the prevailing condition at the time.

Environmental flows have been calculated using a hypothetical method suggested by (United Nations 2000), which uses 20% of the 70% dependable flows in each wet month and 15% of the average monthly flows in the different months that had been worked out. These values are reserved for environmental and ecological requirement purposes. Computed summary of monthly environmental flow requirements for the basin is as shown in Table 48.

Table 48: Summary of monthly environmental flow requirements

Months	Jan	Feb	Mar	Apl	May	Jun	Jul	Aug	Sep	Oct	Nov	Dec
EFR (CMS)	16.102	112.737	132.747	165.072	172.972	152.801	148.436	133.712	100.839	78.077	38.775	37.936

The results indicate a decline in EFR from October month until January month (78-16 m^3/s). This amount is required for the satisfaction of the ecosystem flow requirement in ensuring longitudinal connectivity in the movement of nutrient and biota. The quantified value implies a safe level of exploitable water volume to satisfy the ecosystem requirement.

5.7.2 Discussion on dependable water allocation assessment

The allocation was considered at 60%, 70% and 85% dependability of the total surface water availability. The previous allocations were either set at their maximum level at the beginning of the season or set at a lower level and subsequently increased as the season advanced. This has often resulted in not meeting the growing water demand. Usable water is usually less due to spatiotemporal variation in the water's availability. Thus, water resources allocation can be spatiotemporal distribution among the different users based on 70% dependable flow as formulated in Table 49.

Table 49: Water allocation for Gross annual yield at 70% dependability

S/N	Details	Sub-Total	Total
	Gross annual yield at 70% dependability		8068.04
	Surface water requirement at UIH009		
	IRRIGATION (60%)	4,840.826	
	DOMESTIC (20%)	1,613.609	
	INDUSTRIAL (10%)	806.804	
	ENVIRONMENTAL & ECOLOGY (10%)	726.124	
	Regeneration (+)	8.070	
	Sub-total of water balance at 70% dependability	8,068.040	

5.8 Results and discussion for specific objective 4

To establish a framework for water trading that encourages water use efficiency and allows the movement of water to new users.

Figure **45** in Chapter Four illustrates how the established system dynamic stock and flow diagram offers a solution to water shortage from both the demand and supply sides of the system. It allows trade-off evaluation among the contending users. The understanding of how this proposed water trading occurs clearly indicates how a complex web of socio-economic and environmental change affects the hydrological system. Table 50 presents the source value and parameters required for water demand calculation.

The riparian water demand includes data analysis for livestock, domestic, industrial, and environmental/ecological water demand. Each of the sectorial water demands has been calculated based on the Hussain, Thrikawala and Barker (2002) method, while the livestock water demand has been formulated after Wu *et al.* (2013).

Table 50: Parameters value use for each of the riparian water demands

Variables	Parameters	Source
eThekwini medium variant population (2001-2010)	3,609,259	(Statistics SA 2010)
Gross industrial product per annum	101.86	(DWAF 2004)
Domestic water demand per capita	135m^3	(DWA 2009)
Industrial water demand per capita	44Mm^3/annum	(Moseki, Tlou and Ruiters 2010)
Irrigation water demand per crop per hectare	475m^3	(DWAF 2014)
Water demand per cold blooded animal (WDCDA)	10 L/(capita*day)	(DWAF 1996)
Water demand per warm-blooded animal (WDWDA)	45 L/(capita*day)	(DWAF 1996)
Seasonal difference in demand (Ss, and Si)	5%	

Water Demand for Domestic can be calculated as in Equation 61

$$Q = (Wc \times N \times S_d) \times 365$$ **Equation 61**

Where: $Wc = water\ consumed\ per\ person\ \left(taken\ as\ 135\,\frac{m^3}{d}\right)$; $N = Population$ and an adjusted seasonal difference in demand S_d (%). This fractional percentage representing seasonal difference is the monthly annual resident demand.

The agricultural water demand is taken as irrigation water used. The mathematical equation for minimum total irrigation water required is as presented in Equation 62

Minimise

$$TIRWU_{vol} = \sum_{i=1}^{n}(\left(CWR_i \times S_i\right)/ e_i \times A_i) \qquad \textbf{Equation 62}$$

where $TIRWU_{vol}$ is the total irrigation water use in m^3 and CWR_i is the total annual estimated gross crop water requirement under irrigation, in m^3, for crop i. Si is the monthly fraction of the annual demand for crop i (%) and e_i -efficiency of water use by crop i (%). The CWR can be estimated broadly using the inductive method based on standard crop deltas, Table 51(Grové 2011).

Table 51: Crop water requirement and planting areas for the crops

S/N	Crop	Crop water requirement (mm)
1	Maize	620
2	Sugarcane	810
3	Lucerne	1800
4	Pecan nuts	1920

It has a farmland with an area of 6 373.9 hectares with four different major crops namely maize, sugar cane, lucerne and pecan nuts planted on 361 fields (DWA 2009). Commercial afforestation planting is also significant in the area.

Livestock daily water requirement varies among animal species. SA Water Quality Guideline volume 8 classifies animals as warm blooded and cold blooded (DWAF 1996). Thus, Livestock Water Demand is calculated as in Equation 63

$$TCWD = (WB * WDPWB + CB * WDPCB) * 365 * 10^{-3}$$ **Equation 63**

Where WB and CB represent warm-blooded livestock and cold-blooded livestock, respectively, in m^3/day units, WDPWB and WDPCB signify Water Demand per warm-blooded livestock and cold-blooded livestock, respectively, in m^3/day.

The industrial water demand can be estimated as the Gross Industrial Product multiplied by the average water demand per unit Industrial Product/ per capita ($\left(\frac{m3}{year}\right)$. Equation 64 connotes its calculation.

Equation 64

$$TIWD = WDIP * GIP * 365$$

Where: WDIP is the Water Demand per Industrial Product and GIP is the Gross Industrial Product (m^3). SAPPI-SAICCOR's industry, which exists at the mouth of the Mkomazi River and irrigation farming, are the largest water users in the area.

Using the necessary values from Table 50 and using necessary GIS shapefile from DWS (2016). Table 52 is the summarised basin water beneficiaries' demand. The Table showed domestic, livestock and industrial water abstraction has the highest beneficiaries of the Mkomazi River uses. Streamflow reduction plant and irrigation users followed this. The storage in dams represents the lowest MRB water beneficiaries.

Table 52: The Beneficiaries of the Mkomazi River

Mkomazi average water Uses per annum	**Column1**	**Column2**
		Volume(m^3/ha)
Irrigation (ha)	6373.87	2,526,652
Streamflow reduction plant	50,108.89	29,617,666
		32,144,318
Abstractions		
Water Supply Service $\frac{m^3}{yr}$	15,300,513	
Livestock $\frac{m^3}{yr}$	1,158,027	
Industrial Urban $\frac{m^3}{yr}$	35,719,308	
Industrial Non-Urban $\frac{m^3}{yr}$	4,455,815	56,733,663
Storage in Dams		in 281 Dams
Min (M^3)		40
Ave (M^3)		127,569
Max (M^3)		9,800,000

5.8.1 Total annual net benefits of water use

A substitute for priority-based allocation is the use of economic optimization indices based on cost (Equation 65); when privilege is given to those users that return the highest net benefits to the community.

$$MaximiseTNB_i = \sum_{j-Ag} NB_{Ag,j} + \sum_{j-M\&I} NB_{NB\&I,j} \qquad \textbf{Equation 65}$$

The simulated total net benefit to be derived from water use is denoted as TNB_i. Where i = domestic, irrigation and industrial water demand respectively.

The decision variables for maximising total net benefits for domestic and industrial water use has been derived from an inverse demand function from water use (Rosegrant *et al.* 2000). Figure 89 shows the users that return the highest net benefits to the community**.**

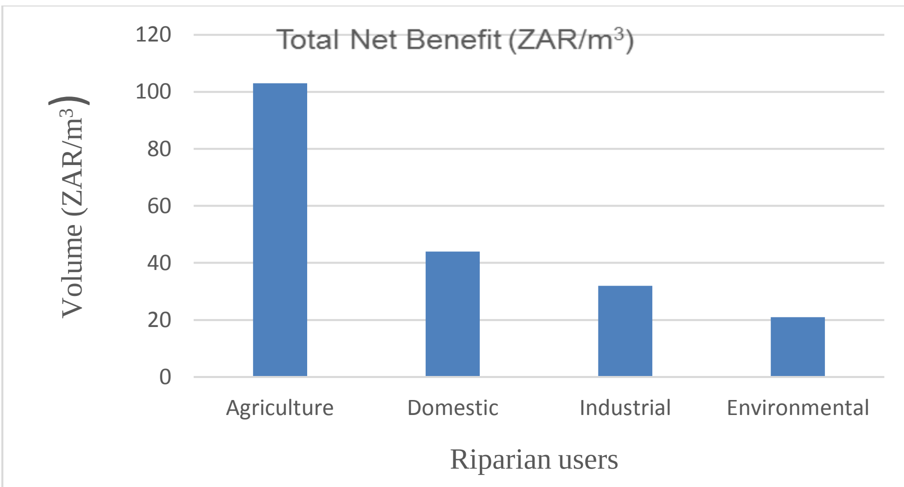

Figure 89: Optimal net benefit of water users

The net benefit (profit) from agricultural water is derived thus: maximised planting area (A), in m^2, is to increase food production and employment on the farm. This has relative importance in terms of job creation and ensuring food security. Moreover, abundant food supply will invariably result in cheaper food prices for South Africans.

The mathematical model for maximising crop revenue from the total planting area is presented in Equation 66:

Maximise

Equation 66

$$CR = \sum_{i=1}^{n} (Y_i * P_i * A_i) - \sum_{i=1}^{n} \left(IW_i * A_i * I_c \right) + \sum_{i=1}^{n} (V_c * A_i)$$

Where: Y_i is the crop yield of the ith crop in (ton/m^2); P_i is the selling price of the ith crop in (ZAR/ton); A_i is the planting area of the ith crop in m^2. IW_i is the irrigation water need for the ith crop in (ML/m^{2}); Ic is the irrigation water cost (ZAR/ML); V_c is the variable cost per m^2 for the ith crop (fertilizers, herbicides and sowing) (ZAR/ m^2).

Figure 90 depicts the non-dominated solutions for the crop-planning model when maximising total planting area in Excel solver.

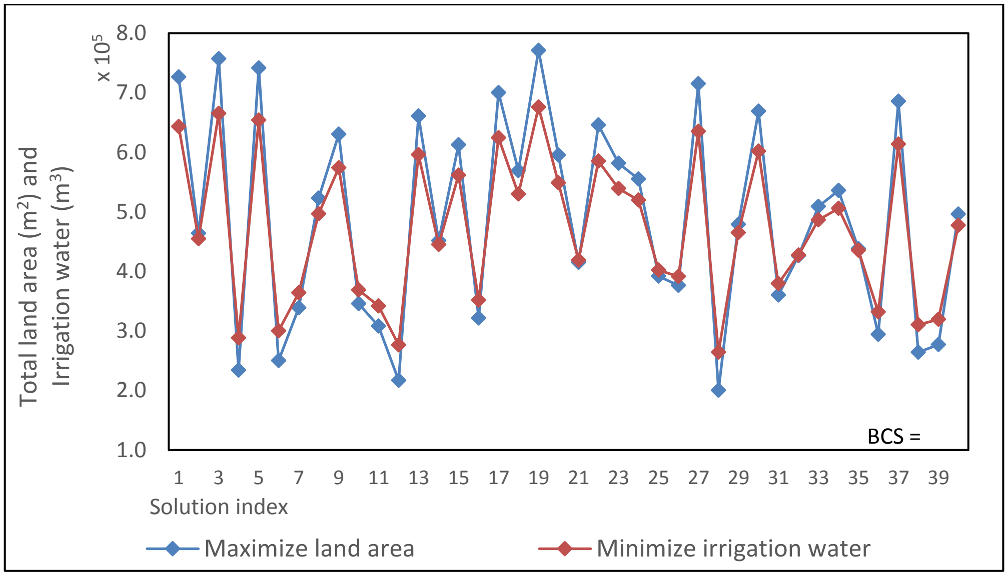

Figure 90: Excel coded solution for max. Total planting area and min. planting area

At depicted in figure 90, the plot shows how much of a watershed area that could be managed in an integrated manner to guard against water scarcity. The excel solver optimization solution indicates the total land area (m^2) and irrigation water (m^3) that was required to grow the prominent crop (maize, sugarcane, Lucerne and pecan nuts). Session 5.8.2 further discussed the use of multi-objective optimization for net benefit analysis of water uses

5.8.2 Discussion on optimal net benefit of water uses

The use of multi-objective optimization in planning the type of cropping pattern and applied technology reveals the minimum irrigation water requirement towards maximising the land planting area (Figure 90). The result reveals irrigation/ agriculture demand as the major water use. Therefore, minimising irrigation demand must be given priority.

The results indicate 7×10^6 m^2 of land planting area will require a minimum amount of 6.5 $x10^6$ m^3 of irrigation water to optimise the four-cropping pattern cultivation. The application of multi-objective optimization algorithms with the aid of quantitative tools provides an analytical user-friendly model that determines both crop plantation and yield endogenously with an efficient water use.

Among the existing agricultural water management methods in the area is the contour bank farming. The contour bank farming method is usually used in an area that is easily prone to excessive rainfall erosion. Ridges are constructed across the overflow, thereby reducing the risk of land degradation and soil erosion effect (Nkondo *et al.* 2012). By their structure, the ridges impact negatively the surface runoff pattern both temporally and spatially. Therefore, efficient planning and management strategies are essential for optimum utilization of this scare resource for continuous improvement and sustainable development in the study area.

5.8.3 SDM framework sustainability results and discussion

In this study, indices of sustainability index (SI) as defined by Xu *et al.* (2002) in Equation 67 was used in measuring the SDM vulnerability.

$$SI = \begin{cases} \frac{(S-D)}{S} & S>D \\ 0 & S \leq D \end{cases}$$ **Equation 67**

Where S is the available water supply and D is the water demand. The SI combines the ratio of aggregated possible water demand relative to the corresponding supply at the same time in validating the medium and long-term water fulfillment from both sides (supply and demand) at varied dependability flow conditions (Table 53).

Table 53: The sustainability index for varied dependable flow conditions

Variables	**Scenarios**	**Variables**	**60%**	**70%**	**85%**
A	BaU	SI	1.0	0.25	0.36
B	Climate change (Precipitation varies in 10%)	SI	0.75	0.24	0.30
C	Irrigation improvement	SI	0.50	0.23	0.26
D	Integrated scenario	SI	0.25	0.20	0.22

SI values smaller than 0.25 correspond to low or no stress on water supply, which implies that water demand is less than or equal to 80% of the potential water supply, whereas those greater than 0.25 reflect vulnerable conditions, i.e., water demand is greater than 80% of the potential water supply. Values of zero indicate an unsustainable water supply, i.e., water demand already equals or exceeds all available local water resources.

The result of the integrated scenarios (B+C) (Figure 86.) of the SD sustainability index at varied dependability conditions in relation to the basin storage basin (Figure 87) do not only predict the likely hydrological dynamics variation at a given time but also reveal the need for increased storage capability to cater for the growing population.

The integrated scenario (D) combines rainfall variation (B) with improved irrigation water use efficiency (C) and gives optimal sustainability performance (0.25) of the system at 70% dependable flow over long time. This implies that water demand is less than or equal to 80% of the potential water supply. Figure 90 discuss the exponential curve of the integrated scenario sustainability.

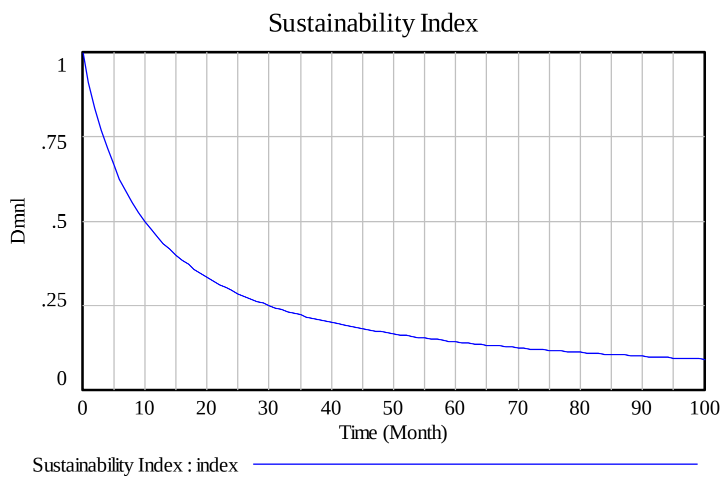

Figure 86: The integrated scenarios sustainability index

Using the necessary parameters from Table 50 and its utilization in the theoretical conceptualized SDM framework as depicted in figure 47, Figure 91 shows a pictorial plot of the hydrological components sustainability, and the need for increase storage basin with time area. The various water demand sub-sectors will continue to be of high increased compared to the available water in the storage basin. Thus, necessitating measures for regulating water use to includes creating awareness to avoid water use wastage in its various uses; crop diversification and precision water use in farming, the use of metering and pricing for water auditing.

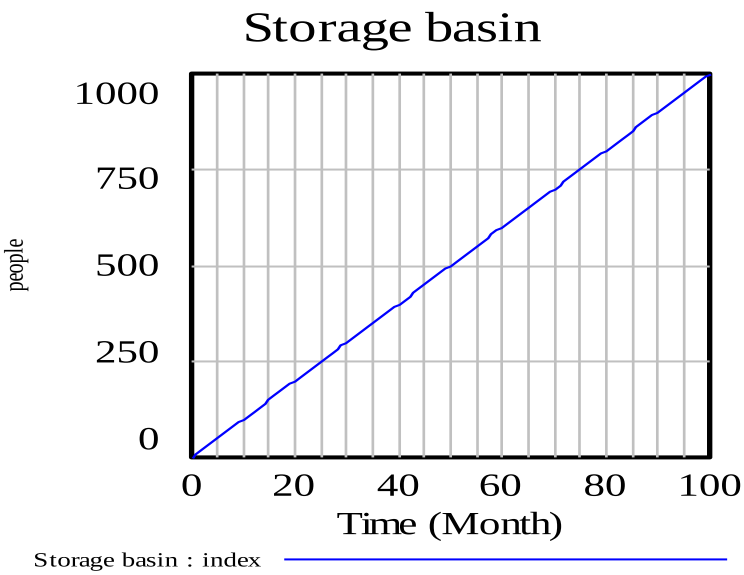

Figure 87: Population verse storage basin dynamics variation

5.8.4 Key findings discussion in relation to the research objectives

DWA (1999b) states, among others, that the potential influence of human activities on water quantity and quality includes variability in the natural flow of the river. The current changes witnessed in the basin include intensified agricultural activity and cattle rearing and unprecedented urbanisation at the catchment site. These changes have both a direct (water diversions, withdrawals and discharges) and an indirect (land-use, vegetation cover) impact on the basin flow regime. The indirect impacts are the most significant impacts occurring in the basin. They have affected the hydrologic cycle, runoff generation mechanisms and the water balance configuration as supported by Loveland *et al.* (2000).

The main research themes covered in this study are:

A review of the purposeful hydrological model that can be used for sustainable water allocation planning, investigation of data treatment, bias correction and minimization of uncertainty was done. Investigation of seasonal variability based on available meteorological data and rainfall anomaly; computation and quantification of the basin water budget and the different water components; interpretation and analysis of simulated results followed this from the various modelling processes. The sustainability of the established framework for water trading formed the last discussed objectives.

Among the main implications of the key results for sustainable development is whether there are sufficient and reliable data. This problem was exacerbated by deteriorating gauging networks, reduced budgets, and the lack of adequate monitoring capacity within the national hydrological agencies. All these issues were resolved using statistical tools not limited to correlation, regression, PCA, FA, trend frequency of Mann–Kendall and Sen's method.

The exploration of these data mining techniques and information into hydrological approach models has helped improve minimisation of prediction error at a time when technological advances in measurement and computation are becoming available. Another major aim achieved in this study was the development of a database of climatic variables and physiographic and hydrological characteristics of the basin. The several local, regional and global sources of data were explored (Chapter Three). The results of the climatic variables (temperature, and precipitation) can serve as baseline information for water resources management in the province.

The challenge confronting preservation of ecosystems that depend on Mkomazi River for their environmental and public benefit values was addressed by the outcomes of the employed WQI and PCA analyses. The results as depicted in Chapter 5, Section 5.1.1 reveal hydrological connectivity at different spatial and temporal scales interruption with the hydrological cycle. The obtained principal component (PCs) from factor analysis indicates wide variations in the basin-meteorological parameters. This reveals that the river has been subjected to a rapid decline in water quality status, which may possibly be due to increasing population and human activities.

In addition, the challenges confronting water regulation among the contending different uses and users reveal societal activities of commercial forestry, irrigation, dryland and subsistence agriculture as it interrupts the basin hydrological runoff and seasonal variability in streamflow.

The Mkomazi Basin hydrological processes in general terms show complexity in the different combinations of physiographic characteristics. This complexity is partly because of the different response features of the sub-basins that make up the Mkomazi River system. The study reveals a bimodal pattern of rainfall distribution in the basin seasonal cycle. This variability anomaly contributes to risks in the availability of sustainable water resources as supported by(Bank 2006). Flood-producing high rainfalls are a major problem confronted in the basin. This finding is also collaborated by a study carried out by Katjavivi (2009).

The use of ANN and another data-driven machine language (regression) offered an attractive option for hydrologists for the forecasting of streamflows in the Mkomazi Basin. The study elucidated the efficacy of ANN as a forecasting model, PCA, CA, and FA as inference statistical descriptive tools, while the use of the SWAT model as an integrated hydrological model suggests the use of technology and conservation measures for facilitating efficient improvement in bridging multi-disciplinary areas towards complex problem-solving.

The long-held practice of intensive farming has been observed in the lower region of the catchment. This lower region is far more viable than the middle and upper catchments; thus, the majority of the high yielding crops are stationed in the lower catchment. While commercial forestry is often dominant within the middle region of the basin, the socio-political and economic structures in the upper region of Mkomazi mainly supports low input products. On the other hand, the downstream of this catchment is more competitive due to the relatively low amounts of rainfall (850-500mm). These will continue to hinder commercialised forestation, and as well as subsistence farming practices needed in support peasant farmer livelihood. Most farmers in this area often store excessive amounts of rainfall in dams, whilst irrigating from these dams as at when required. The adverse consequences of water use in the upper region of the basin have impacted on the cessation/ low yield in the tributary's lower region. Ironically, agricultural practices are less dominant within these regions as less amounts of rainfall dominate this region.

The output results of the system dynamic model have shown it to be a veritable tool for cause and effect evaluation for a decision support system. It can help explore a top-bottom-top management approach to give more insight into the successful implementation of integrated watershed management

CHAPTER 6: CONCLUSIONS AND RECOMMENDATIONS

6.1 Introduction

Water allocation planning is a continuous set of rules required for sustainable use of water resources. They are derived from the ever-changing human-hydrologic interaction**.** The study investigated the application of an integrated hydrological model in a GIS environment as a means to proposing a sustainable water allocation plan and management. The study also examined the trade-offs among users through the identification of the basin ecosystem dependants' while analysing the surface water quality index rating. It has proposed water allocation mechanisms in order to achieve equitable water distribution and large benefits from water uses across the basin's communities and users. Synthesise rules for sharing limited water resources towards operational analysis for environmental flows estimation; and to establish a framework for water trading in order to promote water use efficiency while facilitating movement of water to new users.

6.2 Summary of findings

The grouped Agglomerative Hierarchical cluster analysis of the 10 sub-basin sampling sites resulted into three clusters classification namely: relative less polluted (LP), medium polluted (MP) and highly polluted (HP) group basins, The factor analysis showed F1, F2, and F3 consist of varied variance in water quality of 81.9, 3.14 and 0.858 (%), respectively.

The SWAT simulated result reveal monthly mean water yield range 28.6-36.0 m^3/s over the years with Nash-Sutcliffe efficiency and coefficient of determination (R^2) values of 0.77 and 0.83 at validation stage.

The SWAT-CUP applied model's performance is satisfactory with strong model efficiency (0.54 and 0.80) to observed values both at calibration and validation stage. In addition, the study showed that 2.8 $x10^8$ (m^3) of water was predicted by the model as the water yield potential in the watershed; with curve number (CN) as the most sensitive parameter for estimation of both streamflow and water balance calculation within the catchment.

The various apply statistics models offer robust opportunities for data correctness, improves monthly streamflow simulation, rainfall-runoff forecasting, water balance evaluation, dependable flow allocation and a pointer to scenario evaluation in the medium and long-term run. The applied model's performance is satisfactory with strong model efficiency when compared to documented observed values.

This chapter summarises the main findings that came from the model application in the Mkomazi Basin and makes recommendations for further improving the use of integrated hydrological modelling systems for sustaining water allocation planning.

6.3 Recommendations

The grouped agglomerative hierarchical cluster classification of the basin water quality index into HP. MP and LP suggest prompt action be taken to redress the deteriorate sub-basin.

The likelihood of this study ANN seasonal streamflow outcome and the reliability of the models can be increased with more data using real-time data instead of long-term average data use.

The results from the Mkomazi water use beneficiaries for the human inhabitants, animal production and irrigation farming revealed that less than 5% surface water of the total basin's annual stream flow was utilised in the locality. Despite this figure, the water allocation has often been unfavourable to their immediate community. Their neighbouring urban communities are using the water within their domain.

The rural-urban development must allow physical water infrastructure changes to progress in accordance with the catchment water requirement, without any detrimental impact on the immediate environment.

In addition, the proposed rules that guide SD simulation negotiation used in Chapter Five can be improved with a more realistic one after the actual communication platform has been created with the local water users' associations and water managers' stakeholder.

6.4 Direction for further study

While the current study focused on water allocation based on priority, future studies could focus on environmental flow requirement at ecological sensitive areas within the Mkomazi quaternary basin. More research will still be required to address water quality pollution and its impact.

Another imperative issue discovered in the SWAT calibration process was the effect of curve number (CN)-on streamflow and water balance evaluation. Future examination effect of curve number (CN) should be made with respect to land use and land management practices and their impact on runoff.

Although sustainable water use is in search of a harmonious balance between the ecosystem and human water uses, there is the need for further research into the trade-off between environmental flow and agricultural flow based on the water allocation framework.

6.5 Conclusions

Considering the extent of the drought, and the paucity of the uneven allocation of the water resources at the study area. The needfulness of integrated hydrological models such as SWAT and ANNs cannot be overemphasised in ensuring the sustainability of Mkomazi Basin, while unlocking the untapped potential of water resources for the development of the agricultural and industrial sectors, and still meeting the requirements of the ecosystem.

Furthermore, given the painstaking in manual calculation of the optimal estimation of hydrologic balance variables, SWAT visualization method of the hydrologic budget is a useful tool in order to establish sustainable water resources management in each of the basin hydrological response unit (HRU).

Water resources managers and the agricultural water management sector would find optimal use in the developed ANNs - seasonal classifier to link hydrologic flow variability with meteorological trend characterisation on different temporal scales based on available past data and rainfall variability to be very useful. This could also be an avenue for further researchers in water allocation planning to explore.

In conclusion, decision makers and policy management would find the employed tools and methods to identify opportunities towards enhancing water allocation planning and maintaining the sustainability of the ecosystem.

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