HYDROLOGICAL MODELLING UNDER LIMITED DATA AVAILABILITY – A CASE STUDY OF UMDLOTI RIVER, SOUTH AFRICA.

Submitted in fulfilment of the requirements for the degree of

Master of Engineering

In the Department of Civil Engineering and Surveying,

Faculty of Engineering and the Built Environment

At the Durban University of Technology

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FEBRUARY 2016

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ABSTRACT

Due to the water scarcity in South Africa, new strategies in management planning are needed in order to sustain water resources. The increase of population and economic growth in South Africa has a negative effect on the water resources. Therefore, it should be well managed. The main concerns of the sustainability of water resources are hydropower, irrigation for agriculture, domestic and industries. Hence, the use of integrated water resources management in a single system which is built up by a river basin will help in water resources. This study was focused on water management issues: some of the principal causes of water shortages in UMdloti River are discussed. The current situation of water supply and demand at present is discussed. It also addressed some essential elements of reasonable, cooperative and sustainable water resources management solutions. Many developing countries are characterized as there is limited data availability, water scarcity and decrease of water levels in the dams. The eThekwini municipality is also having similar problems. Water resources have been modelled under this limited data using the hydrological modelling techniques by assessing the streamflow and observed data. The aim of the study was to address the issue of water management how water supply sources can be sustained to be manageable to meet the population growth demand considering the capacity of Hazelmere Dam demand downstream of the dam. Hydrological models, simulation, and decision making support systems were used to achieve all the research objectives. Hazelmere Dam has been modelled so that it can be used efficiently for the benefit of all users downstream of the dam for their economic and ecological benefits. Monthly reservoir inflow data for Hazelmere Dam was obtained from the Department of Water Affairs, South Africa. The nature of data is streamflow volume in mega liter (Ml) recorded for every month of the year. This was converted to mega cubic meter (Mm^3) for use in the analysis herein. A period spanning 19 years of data (1994 – 2013) was used for the analysis. Six parametric probability distribution models were developed for estimating the monthly streamflow at Hazelmere Dam. These probability distribution functions include; Normal, Log-Normal (LN), Pearson III, Log-Pearson type III (LP3), Gumbel extreme value type1 (EVI) and Log-Gumbel (LG). It was observed that UMdloti River is smaller when compared with other rivers within the KwaZulu-Natal Province which could make it difficult to implement integrated water resources management. The hydro-meteorological data collected also has some limitations. The meteorological stations are far away to one another and this would make it difficult to attach their readings with the corresponding water basin. The comparison between the observed and simulated streamflow indicated that there was a good agreement between the observed and simulated discharge. Even though, the performance of the model was satisfactory, yet, it should not be generalized equally for all purposes. The erosion on the study area must be addressed by the stakeholders. It must be minimized in order to sustain the water resources of the UMdloti River. Erosion has a bad impact on the environment because it causes environmental degradation as well. Further investigations are recommended that account for the geological characteristics and the source of the base flow to make sure the rate of groundwater is sufficient for any future developments.

Harnessing more energy from existing water sources within the frontier of the country is important in capacitating the South African Government's commitment to reduction of the country's greenhouse gas emissions and transition to a low-carbon economy while meeting a national target of 3,725 megawatts by 2030. This study also aimed to determine the amount of energy that can be generated from Hazelmere Dam on the uMdloti River, South Africa. Behavioral analyses of the Hazelmere reservoir were performed using plausible scenarios. Feasible alternative reservoir operation models were formulated and investigated to determine the best operating policy and power system configuration. This study determines the amounts of monthly and total annual energy that can be generated from Hazelmere reservoir based on turbines efficiencies of 75%, 85% and 90%. Optimization models were formulated to maximize hydropower generation within the constraints of existing abstractions, hydrological and system constraints. Differential evolution (DE) optimization method was adopted to resolve the optimization models. The methodology was applied for an operating season.

The optimization models were formulated to maximize hydropower generation while keeping within the limits of existing irrigation demands. Differential evolution algorithm was employed to search feasible solution space for the best policy. Reservoir behavioural analysis was conducted to inspect the feasibility of generating hydropower from the Hazelmere reservoir under normal flow conditions. Optimization models were formulated to maximize hydropower generation from the dam. DE was employed to resolve the formulated models within the confines of the system constraints. It was found that 527.51 MWH of annual energy may be generated from the dam without system failure. Storage was maintained above critical levels while the reservoir supplied the full demands on the dam throughout the operating period indicating that the system yield is sufficient and there is no immediate need to augment the system.

DECLARATION

I hereby declare that the work reported in this thesis "**Hydrological modelling under limited data availability – a case study of uMdloti River, South Africa**" 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 parts for a degree in this or any other university. This thesis presents a compilation of manuscripts that were prepared, compiled or published during the course of the research work.

Thulasizwe Innocent Mashiyane

DEDICATION

I dedicate this work to Almighty God and the saviour who kept me thus far.

You deserve the Glory and you are worthy to be praised

You are source of life

Your word is power its creates

You are true source of Inspiration

You are my everlasting Father God of Peace, Omnipresent.

I worship you.

ACKNOWLEDGEMENTS

I would like to thank Almighty God and His son Jesus Christ who gave me strength and guidance towards the successful completion of my Masters of Engineering Degree in Civil Engineering. Without you in my life GOD, I am just nothing and you deserve my glory.

I would like to thank and appreciate to the following individuals and institutions that assisted me and driving me to the successful completion of research.

I am very grateful to have Professor Josiah Adeyemo as my supervisor. You were sent by God to lift my life. I really appreciate your constructive criticism, guidance, patience, steady support, encouragements and guidance towards the successful completion of my masters. May God bless you and your family.

Sibonisile Nokuthula Mashiyane, thank you so much for being my friend and companion throughout my study. You are the best woman ever. I appreciate you and untiring commitment to my success. I am truly favoured to have you in my life. I love you. May God Bless you.

My great parents; James Mashiyane and Clementia Mashiyane (Late) for giving me a chance to live in this world. Thank you so much. I am forever grateful to you. I also appreciate my fantastic siblings, Mbali, Nkululeko and Sphumlile, for their unflinching support. You stand out among real brother and sisters!

Bongumenzi and Bathozile Mpungose, thank you for daily motivations which gave me strength to finish my Master’s degree. You are a father and mother indeed. May God bless you.

My Grandparents; F.A Msweli and V.W Nzimande, thank you for everything you have done in my life. May the Almighty Father bless and reward you with many more years.

I am delighted to be one of the students at Durban University of Technology doing my Master of Engineering. The assistance that I received was much appreciated. May God move the faculty forward.

My sincere thanks go to Mr Cameroon of the Department of Water Affairs, South Africa, for his assistance in obtaining data and other information necessary for the completion of this research work. Also thanking South African Weather Services and Umgeni Water for their information to achieve Master’s degree. May the Almighty reward your labour of love.

Lethokuhle, Sinokuhle and Aphiwokuhle, thank you for understanding that your daddy needs to study. I appreciate you and thank the LORD for giving you to us.

May God bless you all, Amen.

Thulasizwe Innocent Mashiyane

LIST OF ABBREVIATIONS

ANFIS	Adaptive Neuro-Fuzzy Inference System
ANN	Artificial Neural Network
BCS	Best Compromise Solution
CPA	Compromise Programming Approach
CPMDE	Combined Pareto Multi-objective Differential Evolution
DAFF	Department of Agriculture, Forestry and Fisheries
DE	Differential Evolution
DSS	Decision Support System
DUT	Durban University of Technology
DWA	Department of Water Affairs
EA	Evolutionary Algorithm
EFR	Environmental Flow Requirement
EKF	Extended Kalman Filter
EGA	Enhanced GA

EMOA	Evolutionary Multi-Objective Algorithms
ESKOM	Electrical Company of South Africa
ESV	Existing Storage Volume
FCC	Flood Control Curve
GA	Genetic Algorithm
GAO	Genetic Algorithm Optimisation
GHG	Green House Gases
GP	Genetic Programming
IDNP	Inexact De Novo Programming
IFBDP	Inexact Fuzzy De Novo Programming
IWM	Integrated Watershed Management
IWRM	Integrated Water Resources Management
LUC	Land Use Change Model (LUC)
mASL	meters Above Sea Level
MDEA	Multi-objective Differential Evolution Algorithm

MOP	Multi-objective Programming
MOPSO	Multi-Objective Particle Swarm Optimisation
MCDA	Multi Criteria Decision
MRD	Mean Relative Deviation
MSRD	Mean Square Relative Deviation
MULINO-DSS	Multi-Sectorial, Integrated and Operational Decision Support System
NCSS	North Coast Supply System
NF	Neuro Fuzzy
RRM	Rainfall-Runoff Model
RRMCAL	Rainfall-Runoff Model Automatic Calibration Tool
SAWS	South African Weather Services
UHM	Urban Hydrological Models
UW	Umgeni Water
WAMIS	Water Management Information System

WFD	Water Framework Directive
WHO	World Health Organization
WRAM	Water Resource Allocation Model
WRM	Water Resources Model
WRC	South African Water Research Commission
WRPM	Water Resource Planning Model

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CHAPTER 1

INTRODUCTION

1.1 BACKGROUND

Water is a scarce resource around the world especially in South Africa (Harmancioglu, Freda and Barbaros 2008). The scarcity of water is becoming a global problem especially in the arid and semi-arid regions of the world hence, it must therefore be sustained. South Africa is a country that experiences low average annual rainfall and the water demand is far above the supply (Karlberg *et al.* 2007). Increase in population, rapid economic development, urbanization, industrialization, tourism, and inefficient irrigation activities, have made river basins in many parts of South Africa suffer from water scarcity. This calls for sustainable approach in water management around many areas in South Africa.

Most of the catchment areas within South Africa receive high records of water demand which is far greater than the amount of water available for supply (Oyebode and Adeyemo 2014). Therefore, water researchers, managers and stakeholders are making great stakes in order to manage the scarce resources within the country for sustainable and beneficial use among competing users. Water is a renewable resource however, misuse of water may cause shortages especially with the growing population in the eThekwini Municipality of South Africa (Harmancioglu, Freda and Barbaros 2008).

Global warming and greenhouse gases effects have a great impact on the availability of freshwater resources. Previous studies on climate change (Fischer *et al.* 2007; Walker and Schulze 2008; Sun *et al.* 2013) reveal that variabilities in climate affect the water cycle and the natural ecosystems. Streamflow is a fundamental component of the water cycle and a vital source of freshwater for various uses such as agricultural, domestic, industrial and flood control (Kisi 2007). In the hydrology of river basins, variation in streamflow remains a major effect of the complex, non-linear nature of hydrological and meteorological variables within such a basin (Leonard, Metcalfe and Lambert 2008). Hence, it is therefore expedient to predict or model streamflow both on short and long term basis as this will ensure effective planning, management and rightful allocation of the ever important, but scarce water resources. Short term predictions provide signals and information about an impending danger of flood or drought (Mishra *et al.* 2013). In contrast, long term predictions provide information about useful long-term water supply strategies and in making judicious decisions in the optimization of reservoir operations such as hydropower generation and irrigation scheduling operations (Kisi 2007; Popova and Pereira 2011).

Since 2004, the utilization of water has been doubled in South Africa especially in eThekwini Municipality where there is emphasis on future water shortages (Oyebode and Adeyemo 2014). Most of the main rivers that are within eThekwini Municipality are drying up (Kjeldsen, Smithers and Schulze 2002). It has been estimated that when population doubles, suitable water of our planet will not meet the demand of water supply, irrigation, industrial needs and other needs (Minciardi, Robba and Sacile 2007).

South Africa is blessed with many water resources which include rivers, lakes, ground water and sea water. Some of these water resources supply the demand of eThekwini area and its surroundings (Kjeldsen, Smithers and Schulze 2002). EThekwini Municipality is located in the East Coast of South Africa in the Province of KwaZulu-Natal (KZN). It has four regions which are North Coast, South Coast, West Coast and Central. The Municipality spans an area of approximately 2 297 km² and is home to some 3.5 million people (Statistics South Africa 2011). It consists of a diverse society, which faces various social, economic, environmental, and governance challenges. As a result, it strives to address these challenges, which means meeting the needs of an ever-increasing population. The population of the municipality, with reference to Census 2011 is 3 442 361(eThekwini Municipality 2011). The population has grown by 1.08 % from 2001 to 2011 as against 2.34% from 1996 to 2001(Statistics South Africa 2011).

This study focusses mainly on UMdloti River, which is located in the North Coast of eThekwini. Besides,UMdloti river, eThekwini has other rivers which supply the area and its surroundings (Nkondo *et al.* 2012). Due to the scarcity of water in South Africa, new strategies such as better management planning is needed in order to sustain water resources. The eThekwini population is expected to rise continuously and also the gap between water supply and demand will be widened significantly as a residual effect of this population growth. It is therefore imperative to adopt modelling strategies like hydrological modelling in order to manage the available water resources in a way to meet the demand of irrigation, drinking water, industrial and other needs.

1.1.1 Hydrological modelling approaches

Hydrological modelling is an important aspect of water management of river basins and catchments. Forecast of future events are very important for adequate planning and management of water resource systems. Both short term daily streamflow forecast and long term monthly or yearly streamflow forecasts are needed for adequate optimization of variables in order to plan for future expansion or reduction of river basins (Kisi 2007). When water authorities and stakeholders have reliable streamflow forecast, it becomes easy to optimally allocate water resources for competing water users such as domestic, hydropower generation, agricultural and also environmental flows

Streamflow forecast is also very important in the case of multi-purpose reservoirs because it provides adequate information about the amount of sediment deposited and subsequent water flow from the river into such reservoir (Elferchichi *et al.* 2009). There are several hydrological modelling techniques adopted for the prediction and forecast of streamflow variables such as sediment deposits and seasonal changes within a catchment. These hydrological modelling techniques are majorly characterized into two namely; process-based techniques and data-driven models (DDMs) (Oyebode and Adeyemo 2014).

The process – based technique has the ability of providing detailed representation and interpretation of hydrological processes. They incorporate the laws of physics in river catchments to make a detailed representation of the hydrological processes within a river catchment (Shen and Phanikumar 2010). Process-based techniques have been a useful tool for understanding the impact of natural and anthropogenic influences on water resources. The limitation of this technique includes mis-calibration, over-parameterization, and parameter insensitivity (Yilmaz, Gupta and Wagener 2008). All these factors have limited its use to small catchments and short time frame predictions.

On the other hand, data-driven models are more popularly used in hydrological modelling than the process-based techniques. DDMs are easier to use and their overall development time is relatively smaller when compared to process – based models (Kisi 2008). DDMs define the input and output relationships between variables, and also solves the sensitivity challenges associated with process – based models (Gong 2014). Common examples of DDMs are statistical frequency distribution models, artificial neural networks (Komma, Blöschl and Reszler 2008; Kumar, Raghuwanshi and Singh 2009; Li *et al.* 2010; Kisi 2011; Komakech *et al.* 2011; Kloss *et al.* 2012; Kurek and Ostfeld 2013; Kling, Stanzel and Preishuber 2014; Koech, Smith and Gillies 2014; Lehmann and Finger 2014; Li and Guo 2014; Li *et al.* 2015), fuzzy rule – based systems (Lu, Huang and He 2011; Shi *et al.* 2014) and evolutionary algorithm techniques (EAs) such as differential evolution (Cheung *et al.* 2003; Azamathulla *et al.* 2008; Chang and Chang 2009; Chen and Chang 2009; Adeyemo and Otieno 2010a; Chang *et al.* 2010; Adeyemo 2011; Baños *et al.* 2011; Afshar 2012; Bieupoude, Azoumah and Neveu 2012; Arunkumar and Jothiprakash 2013; Belaqziz *et al.* 2013; Chang and Wang 2013; Chang *et al.* 2013; Belaqziz *et al.* 2014; Carrillo Cobo *et al.* 2014).

1.2 STATEMENT OF THE PROBLEM

Water resources in South Africa have been threatened due to the low annual rainfall being experienced in the country (Calzadilla *et al.* 2014). South Africa has also been classified as a water – stressed country because it was rated the 30th driest country in the world (Crowley and van Vuuren 2013).

Also, one major factor that enhances the accuracy and reliability of hydrological modelling forecast is availability of data (Yu *et al.* 2013). Large amounts of datasets are required for calibration and validation of hydrological models, but these are only obtainable in developed countries of the world. Developing countries like South Africa are characterised with limited data availability, as a results of many ungauged catchments. EThekwini municipality is also having similar problems. Therefore, water resources variables at UMdloti River will be modelled under this limited data by discovering and adopting suitable hydrological modelling techniques. Since potential use of UMdloti River for hydropower generation is also important, the evaluation of the river for sustainable hydropower generation was done without affecting other uses of the river.

1.3 STUDY OBJECTIVES

The aim of the study was to address the issue of water management, how water supply sources can be sustained to be manageable to meet the population growth demand considering the capacity of Hazelmere Dam demand downstream of the dam:

1. Performance of statistical analysis on hydrological and meteorological data of UMdloti River.
2. Estimation of monthly streamflow using probability distribution models, which is a family of statistical procedures.
3. Suggestion of new management strategies that can be implemented to sustain water resources management under limited data.
4. Identification of the potential of Hazelmere dam for hydropower generation.

1.4 PROJECT JUSTIFICATION

South Africa is a water stressed country with rainfall of less than 500 mm in about two-third of its area (Nkondo *et al.* 2012). Sustainable planning and management of existing infrastructure is therefore essential. Water resources management will ensure that existing structures are used optimally, while future predictions and forecast are done. Due to population explosion and economic development in South Africa, different methods need to be explored to manage the country’s water resources for sustainability. This study used hydrological modelling to model water resources using limited available data.

The outcome of this study will help stakeholders in developing relevant approaches to adequate management of water resources within the region. It will also aid operators of reservoirs and other water systems in the country to plan for future operations of the systems. Finally, outputs from this research may be useful to water management departments like Department of Water Affairs (DWA), Water Research Commission (WRC), Umgeni Water (UW), Water Institute of Southern Africa (WISA) and eThekwini Municipality in managing the catchment.

1.5 SCOPE OF THE STUDY

The scope of this study mainly focuses on the sustainable management of water resources within the UMdloti River in eThekwini municipality of South Africa. The water variables were optimized using hydrological modelling techniques such as probability distribution frequency analysis and optimization. This is to determine the amount of inflow into the river and also to allocate the appropriate water quantities to each of the competing users. The models developed in this study were applied to UMdloti River. The potential of Hazelmere Dam of hydropower generation was carried out using evolutionary algorithm technique. The study did not cover the public participations and survey on how to sustain water resources management. Also, the water quality assessment and the effect on the ecosystem due to depletion in the UMdloti River were not covered.

1.6 LIMITATIONS OF THE STUDY

The available air temperature data was collected at a point a bit far from the case study area. The nearest point for air temperature is Mount Edgecombe which is about 12 km to the study area. However, this does not have too much effect on the results.

1.7 DESCRIPTION OF THE STUDY AREA

UMdloti River is managed by Department of Water Affairs (DWA) in South Africa but operated under licence by Umgeni Waters (Turton 2004). UMdloti river catchment is the chosen area for this study. It is a coastal river situated in the North Coast of Durban, South Africa. The word UMdloti according to Govender (1999) means the following; the plough share, the violent river and the river of the world tobacco plant.

UMdloti river rises at an altitude of 823 m in the Noodsberg area and passes through Verulam until it enter the Indian ocean (Umgeni Water 2014). At about 5 km north-west of Verulam, a concrete gravity dam named Hazelmere was erected along the river in the year 1976 (DWA 2013). The river is located on Latitude 29°35'54.2"S and Longitude 31°02'34.3"E with a relief of about 93 m above sea level. The elevation is 85.98mASL, area of the river is 597 km^2 while the evaporation is 1200 mm. Rainfall volume is 977 mm while natural runoff is 100 m^3 per year (Umgeni Water 2014). The average wind speed in the study area is 10 m/s. Average temperature is 29°C, relative humidity is 87% and climatic zone is sub-tropical (Turton 2004). The UMdloti River runs 433km to the sea.

Hazelmere Dam is built across the UMdloti river basin. According to Umgeni Water (2014), the UMdloti region obtains its raw water primarily from Hazelmere Dam on the UMdloti river. Raw water is abstracted from the dam for treatment at Umgeni Water's Hazelmere water treatment plant and supplied into the North Coast Supply System (NCSS). Hazelmere Dam was constructed in 1975 and situated on the UMdloti River approximately 5 kilometres North of Verulam (Umgeni Water 2014). The capacity of Hazelmere Dam is 17.86 mega litres (ML), while the depth of the dam is 24.94 ms. Hazelmere Dam also supplies water for irrigation, sanitation, domestic, industrial and recreation. The catchment area is 376.00 km^2 and the dam is 800 m above sea level. An analysis of the base flow-derived stream run-off values per quaternary catchment suggests that groundwater recharge from rainfall varies in the range 3% to 7% of the mean annual precipitation (Umgeni Water 2014).

Figure 1: Map showing the position of Hazelmere Dam, South Africa. (Adapted from DWA (2015)

1.8 THESIS OVERVIEW

This thesis is organized into six chapters. The general structure of the thesis and the focal point of each chapter can be described as follows:

Chapter 1: Introduction

This chapter gives a general background to this study, introduces current issues with respect to sustainable water resources management in South Africa. It spells out the nature of water resources within South Africa and also identifies research problems. It provides a brief review of modelling techniques employed in water resources management. This chapter also outlines the scope, objectives, significance of the study and limitation to the study. Finally, a description of the study area, the rationale for its study, structure of the thesis and publications from the study are presented.

Chapter 2: Literature Review

This chapter provides a comprehensive review of popular hydrological modelling techniques and modern trends with respect to their applications in hydrological modelling. It describes the use of statistical methods in modelling of hydrologic variables. Decision support systems and frequency analysis, which were used in the study, were also given elaborate description. Finally, hydropower generation was also reviewed as an alternative source of renewable energy.

Chapter 3: Methodology

This chapter begins with the collection of necessary hydro-climatic datasets obtained for the study area. Thereafter, the methods adopted for data analysis were discussed in full. The techniques used in data analysis, input variable selection, data and model development are discussed in details. Six probability distribution models were adopted and ranked using the Weibull's plotting position and their corresponding return periods were estimated. Mean Relative Deviation (MRD) and Mean Square Relative Deviation (MSRD) statistics were used to measure the goodness – of – fit of all the developed models in order to select the best fit model out of the six.

Finally, the toolkit used for the implementation of differential evolutionary algorithm, the objective function and the model structure as well as the constraints used to model hydropower generation potentials in Hazelmere Dam are fully explained.

Chapter 4: Estimation of monthly streamflow in Hazelmere Dam using probability distribution models

This chapter presents the results obtained from the estimation of monthly streamflow using parametric probability distribution models and hydro–meteorological statistical analysis of the study area. The relevant literature reviews are discussed in Chapter 2 of this thesis while various methodologies adopted have been adequately discussed in Chapter 3 of this thesis. The results of the various methodologies with regards to all the objectives of this study as stated in Section 1.3 of this thesis are hereby presented. Six different probability distribution models were developed and fitted into a flow duration curve. The chapter ends with the discussion of the results from the comparative study.

Chapter 5: Maximization of Hydropower Generation from Hazelmere Dam in South Africa

This chapter contains a full study which aimed to determine the amount of energy that can be generated from Hazelmere Dam on the UMdloti River, South Africa. Behavioral analyses of the Hazelmere reservoir were performed using plausible scenarios. Feasible alternative reservoir operation models were formulated and investigated to determine the best operating policy and power system configuration. The optimization models were formulated to maximize hydropower generation while keeping within the limits of existing irrigation demands. Differential evolution algorithm was employed to search feasible solution space for the best policy. Findings suggest that if the water resource in the dam is properly managed, about 558.54 MWH of annual energy may be generated from the reservoir under medium flow condition without system failure.

Chapter 6: Conclusion and Recommendation

This chapter presents a general summary based on the results of the previous chapters. It also provides suggestions and recommendations for future research. Each chapter is concluded by the details of research output(s) from the chapter. The data sets used in this study and their implications are presented in this chapter as well. Recommendations were made on adequate ways of sustaining the water resources at uMdloti River catchment.

This thesis represents a compilation of manuscripts where each chapter is an individual entity and therefore, some repetitions between chapters are unavoidable.

1.9 PUBLICATIONS

Mashiyane, T., Olofintoye, O. and Adeyemo, J. 2015. Maximization of hydropower generation from Hazelmere Dam in South Africa. Environmental Economics, 6 (1).

Mashiyane, T. and Adeyemo, J. 2015. Hydrological modelling of Hazelmere Dam in South Africa under limited data availability. 4th Regional South Africa YWP Conference, Pretoria, South Africa. Accepted.

Mashiyane, T and Adeyemo, J. 2015. Streamflow modelling under limited data availability - A case study of Umdloti River in South Africa. Prepared for submission to Water SA.

CHAPTER 2

LITERATURE REVIEW

2.1 SUSTAINABLE WATER RESOURCES STRATEGIES

South Africa is a country that experiences low average annual rainfall and the water demand is far above the supply (Karlberg *et al.* 2007). Increase in population, rapid economic development, urbanization, industrialization, tourism, and inefficient irrigation activities, which is often the highest user of water has made river basins in many Eastern and Southern Mediterranean countries suffer from water scarcity (Harmancioglu, Fedra and Barbaros 2008). It is important to manage water resources effectively due to the increase in water demand as a result of industrial, agricultural and economic development. It is therefore necessary to conduct studies on the sustainability of river basins within these regions and river uMdloti in South Africa has been selected for this study.

Several studies have been conducted which suggest diverse ways of mitigating the negative impacts of water scarcity around the world. Among these studies are Coutts (2006), who conducted a study on the efficient use of water in order to meet the social, economic development and the environmental needs of urban communities. The study was conducted in the urban communities in Australia where recycling of water was used as a strategy for water sustenance. A recycled water framework, based on sustainability of water demands was developed. This strategy was developed based on the triple bottom line principles so as to balance the developmental demand for water.

This principle involves stakeholder’s assessments and decision making processes to improve the use of treated waste water and its management. The key outcome of recycled water strategy is to improve the understanding of the community and the management required. Through the recycled water strategy, diverse guidelines and criteria were developed to effectively measure and evaluate the sustainability of recycled waste water treatment processes; thereby making sure that the objectives of government is achieved (Coutts 2006).

According to a study by Minciardi, Robba and Sacile (2007), a decision models for sustainable groundwater planning and control was developed. The authors iterated that world population is closely tied to a sustainable exploitation of groundwater, surface water and coastal water resources in order to prevent their depletion and contamination. The study considered two kinds of decision problems namely; controlled problems and planning problems. Controlled problem is based on real time information and also based on predictive (or receding horizon) scheme. This approach considers an optimization problem over a suitable time horizon (Minciardi, Robba and Sacile 2007). In the planning problems, they are formulated based on constraints corresponding to equal conditions for the dynamic systems considered.

The multi-cell approach was adopted in the model formulation. Two sets of state equations were generated for the model: water balance and mass balance equations. The decision model optimized water extraction from a set of wells. The model constraints were water flows, physical and chemical behaviour of the pollutants. The results of the study showed that the issues impacting on groundwater quality, namely the effects of agriculture practices and the over-exploitation of aquifers have been represented in order to use in the models for the planning and management of ground water resources (Minciardi, Robba and Sacile 2007). It also shows that further problems that are solved by decision models can utilize real – time information of the water system. Cost effective sustainability models are hereby recommended as well since there is a growing demand for the real-time control of the variables, which can affect water systems (Minciardi, Robba and Sacile 2007).

In Northern Greece, the sustainable development of natural resources with special focus on water supply reliability and public health protection was the core of a study carried out by Papadakis, Veranis and Arvanitidis (2007). The exponential and uncontrolled population growth in Northern Greece has resulted in a very high increase in water demand for agricultural, industrial, domestic and hydropower uses. This has a high impact on the available water resources and has simultaneously subjected basic infrastructure facilities to undue pressure. Service interruptions and down times have been experienced in water distribution and delivery. The resultant effect of all these is poor water quality, which is caused by incessant contamination of portable water and lack of infrastructure concerning water reservoirs and networks.

It was further revealed that only 61% of the population in Northern Greece have access to uninterrupted water supply (Papadakis, Veranis and Arvanitidis 2007). This is also due to poor strategies used to manage water resources at national, regional and local levels of Northern Greece (Papadakis, Veranis and Arvanitidis 2007).The main aim of the study as highlighted by Papadakis, Veranis and Arvanitidis (2007) was to enforce a solution to the sustainable management of water resources in Northern Greece, in relation to interruptive waterflow and delivery at existing domestic service systems. This is because sustainable water resources management is highly essential to ensure adequate supply of water in terms of reliability, quality and quantity.

The methodology adopted in the study is multi-temporal testing of the frequency of service discontinuity in interruptions and delivery within the province. This was implemented via the use of historical data collected from National Statistical Service of Greek, the archives of the Laboratory of Hygiene of the Aristotle University of Thessaloniki and data analysis of relative questionnaires which was assessed by all municipalities of Macedonia and Thrace. Questions which relate with the frequency of water interruption distribution, sufficiency of water and deliveries were asked and compiled. The data analysed and collated from the questionnaires was cross – checked with data obtained from State offices and municipalities. The conclusion of Papadakis, Veranis and Arvanitidis (2007) showed that there is sufficient water in Northern Greece to cover all their agricultural, industrial and domestic needs with particular emphasis on portable water.

In another sustainability studies carried out by Harmancioglu, Freda and Barbaros (2008), a waterware simulation model was adopted to investigate the sustainability of water in Gediz River basin in Turkey. Gezid River is situated in the Aegean coast of Turkey where two major problems occur which are pollution and water shortage. Thus, this will affect the sustainability of water supplied to different sectors. In the study, different water management problems associated with the river were highlighted and solutions proffered. Listed among the reasons for water scarcity in the region include: inefficient water infrastructure, pollution, overexploited groundwater, low availability of renewable water.

An annual water budget simulation model called WaterWare (provided by Environmental Software Systems-ESS, Austria) was used to determine the performance of the existing river network system in terms of the available water. This dynamic (daily) simulation model, i.e. WaterWare, is used to assess the water resources systems in river basins, both the physiographic and hydrological elements. It also represents the institutional and regulatory framework, and the socio-economic driving forces within the basin.

The main elements of WaterWare as described by Harmancioglu, Fedra and Barbaros (2008), include the Land Use Change Model (LUC), the Rainfall-Runoff Model (RRM) and its automatic calibration tool (RRMCAL), and the water resources model (WRM). All these models are available in a web environment accessible with a standard web browser. WaterWare also uses a topological network representation of a river basin, consisting of various node types and the river reaches and canals connecting them. Objects such as sub-catchments, reservoirs, wells, diversions and confluences and areas of water demand represent nodes. The surface water network can be coupled to one or more aquifers to represent conjunctive use scenarios.

The socio economic analysis and developmental scenarios were discussed in terms of population growth, economic analysis, competing water uses and water demand framework was developed. To maintain the sustainability of water shortage, the decision makers assessed the long term impacts of water policies regarding domestic, industrial, irrigation and environmental water demand. At the end of the simulation modelling operations, it was found that the demand for irrigation will be affected by scarcity of water in the future.

Baloch and Tanık (2008) conducted a study on the sustainability of water resources within the Balochistan province in Pakistan. Major environmental resources management issues were highlighted as regards the watershed and the corresponding solutions were recommended. An integrated watershed management (IWM) towards problem identification and management were recommended. Balochistan has challenges ranging from unsustainable water use, poor water resource management, biodiversity, rangelands, forest and crop in soil, and all these poses a major challenge to the environment. Poor planning and management of water resources is a major cause of environmental degradation.

Balochistan exhibits an arid weather pattern and semi-arid land profile hence, the recommended IWM aims at controlling degradation, long-term utilization of natural resources and maintenance of the natural environmental quality (Baloch and Tanık 2008).The study recommended that the entire planning, including problem definition, goal setting, inventory of the existing systems, development and testing of alternative management strategies should be carried out comprehensively. The selection of the best approach to all these should be based on technical and scientific knowledge and research. Also, Baloch and Tanık (2008) recommended that the territorial demarcation of water sheds and establishment of water shed districts should be carried out on the basis of hydrological and geomorphologic characteristics.

After adopting the IWM framework, Baloch and Tanık (2008) concluded that effective conservation of natural resources was achieved within the province of Balochistan. This serves as a model for other watershed management challenges around the world, most especially in developing nations.

Maia and Silva (2009) developed and applied a decision support system (DSS) tool to a river basin in Portugal. The aim of the study was to minimize water deficits according to the requirements of Water Framework Directive (WFD). Strategies for sustainable water resources management were selected based on a performance assessment of strategies and economic analysis. The study therefore adopted two strategies with the aim of minimizing regional ground and surface water resources exploitation risk costs. The case study was Querenca-Silves aquifer in Algarve Region is situated in Portugal.

In Portugal, there exists a major problem of sustainability of water resources (Maia and Silva 2009). The DSS tool employed in the study relies on geographical information system capabilities and on adapted databases. It also allows the user to analyse the water system behaviour under a regional hydrological demand situation. It analyses the implementation impact of different kinds of water management options up to a period of 50 years. The WDS adopted in the study focuses only on direct and environmental costs definition and evaluation,

The WSM–DSS application proved to be an interesting Decision Support System tool suited for the Algarve region water resources analysis. Two different strategies were evaluated to minimise regional ground and surface water resources exploitation risks and cost was performed. The result indicated that both strategies showed a good efficiency value and it was concluded that the Querença-Silves aquifer proved to be able to recover in terms of water storage on an inter-annual basis (Maia and Silva 2009).

Hadadin *et al.* (2010) conducted a study on water shortage in Jordan. The study was motivated due to the largest environmental challenge that Jordan faces, which is the scarcity of water. The most important resource for human population is water. Jordan is a water–limited country due to the country's increasing population. This has chocked the current water supply because water demand is more than supply. Jordan shares most of its resources with neighbouring countries and their control on water has a partially disallowed its fair share which makes the situation intensive. In this study, the primary evaluation of this problem was carried out while appropriate solutions were suggested. The methodology in the study was public awareness method, where the part of the population and a number of governmental and non-governmental organisations are actively involved in educating the populace about water shortage. Also the method was drawn up to a contract on planned schemes for sustainable water solutions. Some of the proposed solutions were collection of data, creation of data banks, conducting research and studies, funding support training programs techniques assistance, public awareness through education and organised land used planning (Hadadin *et al.* 2010)

In a bid to solve water resources planning problems, a study was conducted by Weng, Huang and Li (2010). In this study, an integrated scenario based multi-criteria decision support system for water resources management and planning was developed called SMC-DSS. This tool is a decision support tool has system composition, scenario generation, scenario quantification, multi-objective optimization and scenario evaluation as its components. This SMC-DSS was applied to solve the water resources planning problems of Haihe River basin in China.

According to Weng, Huang and Li (2010), this SMC-DSS techniques incorporates scenario analysis, multi-objective programming(MOP) and multi criteria decision (MCDA) within a decision support system. In SMC-DSS, scenario analysis was adopted to model the policies for water resources management, MOP was used to handle multiple conflict objectives, and MCDA was used to accomplish the scenario evaluation. According to Weng, Huang and Li (2010), this method is suitable for identifying the real problems where the decision is based on the information presented and therefore set for possible outcomes. The model scenario that was proposed for water resource management was under uncertainty and it is single objective.

Various water management policies were undertaken, which include: saving water policy, protecting water resources policy, South–North water transfer project. The results of the study proved that SMC-DSS can solve complex water resources management planning problem which may involve multiple conflict objectives and need to concern uncertainty in a long-term period. The results indicated that different water management policies can lead to varied results for regional economic development. The results obtained from the study are valuable for supporting (i) water management policies, which are crucial to solve water shortage problems and to support regional sustainable development; (ii) water transfer project from South to North is essential and should be undertaken as soon as possible; (iii) saving water policy should be enforced from a long-term perspective; (iv) environment protection is very important for regional sustainable development, but it should be combined with the other water management policies.

Water is the one of most important physical resources for the survival and development of people and this prompted Qu, Gong and Dong (2013) to apply a water management strategy based on efficient prediction and resource allocation to predict China's water demand from the year 2013 to 2025. The aim of the study was to ensure that the water resources can meet the use of China demand for the years stated above. Along with the rapid growth of population and development of the society since the twentieth century, human demand for water is growing day by day, which is in stark contrast with the increasingly serious water shortage. The methodology used in the study is a water resources prediction model. Second exponential smoothing method was used to find out the demand for freshwater. Also, the water supply was calculated by classifying them into three categories: surface water, underground water and others. This was categorized based on different ratios for consumption.

Furthermore, a water resource allocation model (WRAM) was used with the general objective of minimizing the total cost of water resource allocation (Qu, Gong and Dong 2013). It identifies the cities which are suffering from water shortage and also classify them as coastal and non-coastal cities. The results of the study showed that due to high speed of development, the limited water resources should be maximized as a function of the growing needs of man. The model is of high economic efficiency and works well in the water allocation problem. However, based on the immediate and long term consideration, they recommended that government should make a sound development strategy to build up water conservancy projects as well as vigorously promote water saving concepts (Qu, Gong and Dong 2013).

2.2 TECHNIQUES USED IN HYDROLOGICAL MODELLING

Hydrological modelling is a crucial aspect of water resources management and planning. In regions such as arid and semi-arid, which are generally regarded as water stressed, there is a need to effectively manage the available water resources. Therefore, effective streamflow and rainfall modelling has become a necessity in a way to effectively manage the operations of water resources systems. Dong, Schoups and van de Giesen (2013) described the fundamental goal of water resource planning and management as matching the demand for water by the socio-economic system with the supply (quantity and quality) of the water system through administrative control and management (water regulations/laws and infrastructure), without compromising the sustainability of the ecosystem.

As a result, numerous techniques have been adopted by decision makers in the water sector to solve the complex and nonlinear problems associated with water resources planning and management with regards to streamflow and rainfall modelling, which forms an important part of the hydrological processes. Generally speaking, models used for hydrologic modelling are classified into two different types namely: process driven and data driven (Oyebode and Adeyemo 2014). Data driven models have found popular use in the modelling of hydrological variables in the last few decades due to the strength it possesses over the process – driven models. This chapter provides a comprehensive review of the modelling techniques and methods adopted in water resources management, which are also relevant to the scope of this research. The review introduces the techniques, its application in hydrological modelling, advantages and disadvantages and finally areas of improvement.

2.3 STATISTICAL PROCEDURES IN HYDROLOGICAL MODELLING

2.3.1 Introduction

Diverse statistical procedures and methods have been majorly applied in hydrological modelling. Since it is important to manage water resources in a way that demand will be commensurate with supply, water experts and researchers have adopted many techniques to the complex and non-linear problems of water resources modelling. The extreme value distributions of hydrologic variables such as rainfall and streamflow play a key role in the design of water-related infrastructure around the world (Leonard, Metcalfe and Lambert 2008). Probabilistic approaches have often been used to estimate the average recurrence period of a given drought event. However, probabilistic model fitting by conventional methods, such as product moment or maximum likelihood in areas with low availability of long records often produce highly unreliable estimates (Núñez *et al.* 2011). Among these statistical methods are probabilistic approach, frequency analysis, generalized least square (GLS) regression analysis.

2.3.2 Application of Statistical methods in hydrological modelling

The use of probability distribution in hydrological modelling is receiving a wide attention around the world. Clausen and Pearson (1995) applied frequency analysis to model the annual maximum streamflow drought in three geographical regions of New Zealand. This was presented as a method for investigating the spatial and temporal variability of droughts in the country. The study considered only the magnitude and duration of rainfall events over a period of time. Data of daily streamflow for 44 New Zealand sites over a period of 27 years was used for the study. Regional analyses of the mean standardised annual maximum severity were achieved by using correlation analysis and multiple regressions on catchment characteristics. Relevant catchment characteristics were identified and grouped in order to obtain estimates of extreme droughts in those three regions. This study showed that annual maximum drought severities and their corresponding durations can be defined and analysed using frequency analysis.

In 2002, a study was carried out in KwaZulu – Natal (KZN) province in South Africa. In this study, Kjeldsen, Smithers and Schulze (2002) adopted a regional flood frequency analysis for the annual maximum series in this region using index – flood method. Homogeneous regions were identified and also, suitable regional frequency distribution was achieved. Annual maximum series were available for 29 flow gauging weirs within the province and peak discharge was recorded after a rainfall event. The results obtained by using L - moments were in agreement with previous studies of annual maximum series of flood flow in the KZN province.

Griffis and Stedinger (2007) used generalized least squares (GLS) regression analysis to estimate the parameters of a model within a river basin. It was adapted to a regional flood study with 162 sites in South Carolina. GLS have been known for their use in virile capability in estimating flood quantiles especially for ungauged locations or limited data locations (Haddad and Rahman 2012). A regional model of the standard deviation was developed using GLS regression, and models for a 100 year - event was obtained using both estimators of the sampling covariance matrix. Model errors were accounted for using three metrics: the model error variance, the average variance of prediction, and a new pseudo- R^2 appropriate for use with GLS regression. In addition, the study included an evaluation of the benefit of pooling data from different regions to increase the number of sites used to develop regression models of the 100-year event, as opposed to simply developing a separate model for each region. The results showed that GLS regression is robust for flood control.

Leonard, Metcalfe and Lambert (2008) investigated the distributions of seasonal and annual rainfall maxima for numerous locations around Australia and a detailed analysis, involving both seasonal and climatic partitions were made. The study used data for the daily streamflow of the Murray–Darling Basin in Australia. In the study, the relationship between the intensity, frequency and duration of extreme values was evaluated using observed annual maximum values. These maximum values occur within a given season. The relationship between seasonal maxima and annual maxima was derived using a climatic index. The study considered four seasons of three months duration over the April-March water-year. The results demonstrated significant differences between seasonal distributions within and between climatic states. The application of seasonal extremes to an urban design scenario was also illustrated for Scott Creek in the Adelaide Hills, South Australia. The authors concluded that the methodology presented can be used in a general setting to gain insight into the relationship between extremes from seasonal and climatic periods to their annual counter-parts.

Saf (2010) examined the effects of discordant sites on regional flood frequency analysis in Turkey. Flood observations in hydrological data sets contain frequently outliers was observed, which cause challenges for water researchers if not properly addressed. This prompted the study in order to analyse how outliers affect the identification of regional probability distributions using L-moment methods. The main objective of the research was to assess the effect(s) of discordancy detection measures on regional flood probability types and the accuracy of the estimates based on the regional analysis in the region of the Menderes River Basins in Turkey. The other objective was to show whether a probability model type and flood estimation based on the model was reliable if discordance sites in the region were not detected. The homogeneity of the basin was done using L – moment method. The results showed that the homogeneous region determined from the robust discordancy measure is more accurate than the region identified using the classical robust measure.

Núñez *et al.* (2011) used regional frequency analysis to map out drought regimes in the arid and semi-arid regions of Chile. A regional frequency analysis method based on L-moments (RFA-LM) was used for estimating and mapping drought frequency. In addition, a new 3-parameter distribution, the Gaucho, which is a special case of the 4-parameter Kappa distribution, was introduced, and the analysis procedure was improved by the developments of two new software tools named L-RAP, to perform the RFA-LM analysis. L-MAP was used to generate the resulting drought maps. The RFA-LM performed brilliantly because it showed that droughts with a 40% precipitation of the normal have return periods that ranged from 4 years at the northern arid boundary of the study area to 22 years at the southern sub-humid boundary.

Haddad and Rahman (2012) proposed an approach using Bayesian Generalised Least Squares (BGLS) regression in a region-of-influence (ROI) framework for regional flood frequency analysis (RFFA). These techniques were adopted for ungauged catchments in Australia. Data from 399 catchments in eastern Australia were collected and this was used to construct BGLS-ROI in order to regionalise the flood quantiles (Quantile Regression Technique (QRT)). The main objective of this study was to compare the BGLS regression approaches using a fixed and ROI framework that seeks to minimise the Bayesian model error variance (predictive uncertainty). Prediction equations were developed for the flood quantiles of average recurrence intervals (ARI) of 2–100 years using QRT and for the first three moments of the log-Pearson type 3 (LP3) distributions (Parameter Regression Technique (PRT). Haddad and Rahman (2012) therefore concluded that both BGLS; QRT-ROI and PRT-ROI produced smaller average root mean square errors (RMSE) and RE when compared to the fixed region regression approach. Based on this, parameter regression technique is a viable alternative to quantile regression technique in regional flood frequency analysis for the ungauged catchment cases.

Hassan and Ping (2012) adopted flood regional frequency analysis to LuahHe basin. Rainfall regionization was used to extend data to regions which are ungauged hence, no rainfall data due to low rainfall densities. The basic aim of the study was to use a combined methodology of cluster analysis and L-moment methods to quantify regional rainfall patterns of LuahHe basin using annual rainfall of 17 stations for the period of 1932-1970. Five parameter distribution methods were used in the four homogeneous regions namely: generalized logistic (GLO), generalized extreme value (GEV), generalized normal (GNO), Pearson type-3 (PE III) and generalized Pareto distributions (GPA). The best regional distribution function for each group was also identified using the goodness-of-fit test measurement. Hassan and Ping (2012) recommended that a combination of cluster analysis together with L-moment method is highly applicable in different geographical and climate regions to prove the relationship between rainfall regimes and rainfall distribution functions.

Shamir, Georgakakos and Murphy Jr (2013) adopted frequency analysis of the 7th to 8th December, 2010 extreme precipitation in Panama Canal watershed, USA. The study was prompted because the record of rainfall and streamflow after the rainfall event are almost twice as much as the previously observed large events in the area. Therefore, the main objective of the study is to deduce whether a return period estimate using the historical record and the commonly used statistical asymptotic distributions of extreme values could have indicated that such an event is probable before the event took place at all. However, the daily and 24 – h mean annual rainfall data in the watershed was examined using Generalized Extreme Value (GEV), Gumbel, and Generalized Pareto distributions. The GEV was found to be the most adequate distribution for this analysis while the Gumbel distribution yielded a good fit to the annual maxima series.

The use of frequency analysis in hydrological modelling is proved further by Guru and Jha (2015). Annual Maximum (AM) flood series and Peak over Threshold (POT) flood series were used to carry out flood frequency analysis for Tel basin of Mahanadi river system, India. The analysis was carried out for flood series data of two gauging stations Kesinga (upstream) and Kantamal (downstream) for the years 1972-2009. Fourteen different flood frequency distributions were conducted for AM and POT flood series data for both Kesinga and Kantamal gauging stations. The results obtained using Generalized Pareto (GP) distribution shows better results for AM flood data series with all goodness of fit tests. However, for POT flood data series Log Normal (3P) distribution showed best results followed by GP distributions with all goodness of fit test. The distributions most suitable for POT data sets are same for the distribution being used globally for flood forecasting.

Burgess *et al.* (2015)examined the frequency analysis configuration for varying probability distribution functions (PDF), plotting point functions (PPF) and parameter estimation methods (PEM) in Jamaica. Frequency analysis configuration was adopted to verify existing intensity duration frequency (IDF) curve. The study also examined the effect of extension and in filling of the AMS with data from 1895 and through to 2010 using empirical and downscaling techniques. Furthermore, the temporal trends in frequency analysis parameters were also determined. Thereafter, an estimation of future climate IDF was made for year 2100. The result showed that frequency analysis with temporal trends in the location, scale and shape parameters had high goodness of fit.

2.4 APPLICATION OF SIMULATED REAL – TIME SUSTAINABLE MODELS

Water resources are very vital to human lives. It was affirmed that water scarcity is prevalent in both arid and semi-arid regions of the world (Nkondo *et al.* 2012).

Water is a non-linear, complex problems and as such requires mathematical models to be solved (Adeyemo 2011). Diverse models have been developed and adopted in the sustainability and management of real – time water resources around the world. Some of these research works are reviewed below.

Giupponi *et al.* (2004) developed a decision support system tool, based on computer software for the sustainable management of water resources. This model named MULINO – DSS, integrates socio – economic and environmental modelling with geo–spatial information and multi–criteria analysis. Multi-sectorial, integrated and operational decision support system (MULINO-DSS) is a decision tool used for the sustainable water resources management at the catchment scale. The decision variables for this tool as outlined by the European Union Water Framework are: (i) the improvement of water quality discharged into the Venice lagoon (Italian case study, Vela catchment); (ii) the preservation of Venetian coastal aquifer to combat saltwater intrusion and subsidence due to over-pumping (Italian case study, Cavallino catchment);(iii) the reservoir management and multi-sector competition in a trans-boundary river basin (Portuguese case study, Caia catchment); (iv) the abatement of nitrate concentrations in ground water (Belgian case study, Dyle catchment); (v) the preservation of drinking water resources and the adaptation of national management practices to the WFD requirements (Romanian case study, Vahlui catchment); and (vi) the allocation of water abstraction among conflicting water users (English case study, Bure and Yare catchments).

The computer tool presented in the study was designed by applying theoretical background and assumptions to a concrete design for software modules (such as hydrologic modelling, scenario development, and multi-criteria analysis) that are integrated into a unique DSS tool. Such a process has produced software that, even if at an intermediate stage of development, presents considerable complexity. It is expected that the potential for future operational applications of the DSS tool will depend on the balance between the quest for simplicity, while dealing with intrinsically complex systems, such as highly developed catchments, and the tentative to provide a tool specifically targeted to the sustainable water management domain, while maintaining a sufficient flexibility to deal with various socio-economic and environmental contexts.

Avlonitis *et al.* (2007) implemented a flexible wireless broadband network in a modern system to control data acquisitions and computers to help in water resource management. It was noted that water resources are scattered in remote areas with low accessibility and impossible permanent wire connections, they are also of a long distance to one another and the communities they serve. Therefore, in a bid to solve this challenge, Avlonitis *et al.* (2007) applied a combination of technologies such as wireless broadband networks, modern systems of signal control and data acquisition, computers/software and telematics to provide an excellent solution to this problem. In the work, the process of planning and installation of a system for the telematics control and management of eleven wells, storage installations and distribution process were done. This was applied to the Municipality of Thira in Greece. The installation checks the pumping stations, the levels of water tanks as well as qualitative data of the water supplies, all from a distance through a wireless network. The system interacts automatically or manually with the installations and to present points, giving complete records of the data and alarms to any malfunction or oncoming breakdown at any point in time. The designed system according to Avlonitis *et al.* (2007) was unique, stable, expandable, reliable, inexpensive, easy to install and maintain.

The water quality and condition of the reservoir must be measured and controlled by the water company. This system reduced the cost of employing people in the organisation in terms of controlling, monitoring and maintaining installation since there is no need for constant human interventions. The wireless broadband network is an excellent solution to the problem of water resources sustainability hence; the flexible broadband was installed to check the pump stations, level of water in the tanks or dams as well as qualitative data of water suppliers from a distance. The systems interrelate automatically or manually with the installations. The future of sustainable water resources management practice will involve simultaneous management of supply and demand. It was noted that the flexible broadband network also assists in detecting water loss along the reticulation leaking reservoirs. Avlonitis *et al.* (2007) highlighted the advantages of this proposed system as follows: (1) it is a tested and reliable technology (ii) it has significantly lower cost of installation and maintenance compared to any other solution (iii) it maximizes the control on every aspect and every part of the installation in real time (iv) it reduces labour costs (v) it reduces malfunctions and also identifies the points where malfunction is taking place (vi) it also prevents further damage and helps on estimation for direct restoration and (vii) it ensures the water quality with on-line surveillance. It was concluded by Avlonitis *et al.* (2007), that the system was expandable to many other areas, thereby making the wireless broadband technology a robust model for excellent management of water resources.

Changes in climate and hydrological variance have forced water managers to develop diverse strategies for managing water resources around the globe. This is evident in the study conducted by Zeng *et al.* (2012). The study involved the development of a web based decision support system (DSS) for the effective management and support of water resources. A water resources management model, based on genetic algorithms was developed in the DSS. This model facilitates efficient allocation of water resources among different regions within a city. Also incorporated is the water management information system (WAMIS).

As defined by Giupponi *et al.* (2004), DSS is a computerized management advisory system that utilizes databases, models, and dialog systems to provide decision makers with timely management information. An advantage of adopting DSS is that it helps stakeholders to further manage water resources on a large scale (Maia and Silva 2009). Therefore, Zeng *et al.* (2012) designed an architectural network of DSS for water resources management. The objectives of the study include: (i) to develop architecture of decision support system for water resources management in Daegu city, based on the National Water Management Information System (WAMIS); (ii) to develop river flow or flood forecasting method based on hydrologic software HEC-HMS; (iii) to develop an urban water demand forecasting model using artificial neural network (ANN); and (iv) to develop a mathematical model for optimal water resources allocation using genetic algorithm (GA).

Incorporated into the DSS are: technologies including the real time hydrological model, urban water demand forecasting model and water management model. This helps in dealing with urban water resource management problems, such as flood early warning and water allocation between stakeholders. With the applications of ANN for water demand forecasting and GA for water resources allocation, the system could deal with the problems of complex and nonlinear water resources system, both in water demand and optimal water allocation aspects. The results show that the present condition is that water is unequally distributed in space and time, and the contradiction in the supply and demand of water has developed a critical restriction for development. There were debates about the model base, Knowledge base and Graphical user interface but however, the developed DSS has proved to be a very useful tool in the management of water resources. The developed tool has been recommended for use in other countries since it deals with the expansion of water resources management and its problems.

A storm water management model (SWMM) was developed by Jang *et al.* (2007) for hydrologic impact assessment. The effects of urbanization were to be minimized through designing detentions storage for urban drainage system. An entry point to the study is that, using urban hydrological models (UHM) for pre and post development conditions representing urbanized conditions is better in watershed management. Though, earlier studies have adapted UHM to regions where observed data is available to calibrate and verify the model performances. Therefore, Jang *et al.* (2007) adapted SWMM to cases where disaster impact assessment had been already carried out. SWMM are known for modelling of urban water cycle but its applicability in watershed management is unknown.

In order to determine the applicability of SWMM to watershed management, both discharge and rainfall data from the experimental watershed called Seolma-cheon watershed and two of the International Hydrologique Programme (IHP) watersheds —Weecheon and Pyung-chang River watersheds were utilized. These SWMM model was compared with UHM models to compare their performances. SWMM was applied to the three rainfall events each at Seolma-Cheon, Weecheon, and Pyung-chang River watershed. Hydrograph method was used from step by step approach in applying the synthetic hydrograph for predevelopment condition, while the hydrological model post development condition was applied in the urban. Nevertheless, this apparently reasonable choice which will lead to ironical assessment of smaller peak and condition making assessment on the limited peak time for urbanization results will have to be excluded in the peak flow which is determined by the used design of detention pond.

The conceptualizations of different models were with associated measures. Hydrological method depends on experiential derived formulas from each region. Pre and post development were selected on the sites where there were disaster management impact assessments which will show unrealistic assessment based on smaller peak flow or longer time. Results were represented in two approaches one which was existing combination of synthetic hydrograph-urban hydrology model and other was pre and post development for SWMM. The two models were compared in order to identify problems encountered by the use of the same model on the same case study, and the results shows that SWMM performed better when used in modelling natural watershed than when synthetic hydrograph models are adopted to watershed management (Jang *et al.* 2007). It was found that SWMM gives best results when the watershed is modelled as single watershed for uncalibrated condition.

2.5 HYDROPOWER ENERGY OPTIMIZATION FRAMEWORK

In the management and sustainability of water resources, it is important to note that water and energy are interwoven. This is because both resources support human life and existence. A rich study on the connectivity between water and energy was done by Dubreuil *et al.* (2013). In the study, water allocation problems were incorporated in an energy optimization model with a dedicated water module. The developed model was tested and applied to the water scarce region of Middle East, in a way of considering opportunities for water re-use. Renewable water resource is seen as highly essential for human life sustainability especially in water scarce regions of the world.

Water supply and water demand depends on water accessibility and availability for human needs. In the Middle East, the water demand is high in all sectors but the availability of resources is very scarce. Also, the accessibility of water in this region is constrained and this has adversely affected water quality. Water is highly essential to create power, which is used for economic development such as transportation of water. Water shortage and energy demand are the source that is required to be developed (Dubreuil *et al.* 2013).

The importance of the power sector in the development of a nation cannot be overemphasized. This sector is strategic in forging economic growth and infrastructural development. This calls for the development of improved strategies for generation, distribution and proper management of power in all countries of the world (Loucks and Bee 2005; Salami 2007). Hydropower is a renewable form of electrical energy generated from the free fall of water from a high elevation to a relatively lower elevation. Hydropower production involves the conversion of potential energy of stored water into electrical energy through combinations of hydraulic turbines and electric generators (Ajenifuja 2009; SIDALA 2010). Some benefits of hydropower include quick response to changing utility loads, relatively low operating costs and a low environmental pollution factor (Salami 2007). According to Ajenifuja (2009), greenhouse gas (GHG) emission factors for hydropower plants have been found to be 30 to 60 times lesser than factors for fossil fuel generation in some instances. Presently, hydropower accounts for roughly 85 percent of renewable energy in the European Union and approximately 20 percent of global electricity. Development of half of the world's economically feasible hydropower potential could reduce GHG emissions up to 13 percent and global carbon dioxide pollution by up to 7 billion tons a year (Ajenifuja 2009). Therefore, harnessing more hydropower from existing water sources is germane in minimizing GHG emissions and mitigating the undesirable effects of global climate change.

Recent results from expert analysis has shown that South Africa has moderate hydroelectric potential and establishing a number of small hydroelectric power plants around the country may help provide sustainable supply of energy in the future (SIDALA 2010). Consequently, the South African government is in the process of authorizing independent power producer licenses. This aims to diversify the country's energy mix by bringing in renewable energy technologies especially small hydropower plants (<10MW) to retrofit and contribute to a national target of 10 000 GWh of energy by 2013 (SIDALA 2010). A global world energy model was proposed to analyse changes in both water and energy with regards to water demands. This model is called TIAM-FR and it is a bottom-line energy optimization model, and also a dedicated water module based on the same model principle. Energy-economic models, which analyses long term results and climate policies were adopted. The Energy economic models are based on the joint allocation of water and energy in a single – bottom TIAM-FR model. The optimization energy system was created in 1980 by framework of Energy Technology System Analysis Program (ETSAP). The TIAM-FR model is based on linear programming. The model outputs are optimal solutions as determined by the decision variables. This modelling approach, which involves the use of an energy system model applied to water, enables us to estimate the structural and technological changes induced to meet the anticipated water demand. Trends in electricity demand over time in the Middle East region using the standard energy model show that energy demand will triple between 2005 and 2050. It also proved that water supply in Middle East is lower than the demand. However, it was discovered that under a water-saving scenario applied to irrigation efficiency, 22% of electricity could be saved in 2050, and 60% of CO_2emissions avoided.

Other factors that affect changes in energy demand are water uses, electricity demand, and these could be underestimated by nearly 40%. Dubreuil *et al.* (2013) iterated that the energy used has an effect on climate change and increases water scarcity. This hard link opens up the potential for future research dealing with adaptation and mitigation challenges. The analysis of water allocation also allows the use of non-conventional resources to compensate water security which enables us to analyse the high effect of irrigation efficiency. In order to alleviate the scarcity of water, electricity generation and water resource management (e.g. conserving or recycling water resources, reallocating them, improving agricultural cropping efficiency, and combining power generation and desalination in a single plant) must be considered (Dubreuil *et al.* 2013).

Evolutionary algorithms (EAs) have been successfully applied for optimising the multi – reservoir system operations. This was evident in the study carried out by Adeyemo and Otieno (2010b) conducted a study on the maximization of hydropower using the strategy of Differential Evolution (DE), which is a family of evolutionary algorithms. The case study used in the study is Vanderkloof dam in the lower orange river of South Africa. This study was conducted to know the sustainability of the dam for hydropower generation without hindering other competing water users from receiving adequate supply from the reservoir. Ten different DE strategies were adopted in solving this optimization problem. From the results, differential evolution strategy (DE/best/2/exp) is the best for this model by generating 510 GWH of energy using 11,389.49 Mm^3 of water. It is concluded that differential evolution strategies with exponential crossover method are better than differential evolution strategy with binomial crossover method for the model presented in the study.

Also, Reddy and Kumar (2006) optimized the hydropower production using DE algorithm. They modified the mutation operator to randomly select four different individuals in order to increase the convergence rate. They reported that the developed DE algorithm was superior to dynamic programming P in calculation speed and provides a new approach for optimal reservoir operation.

Arunkumar and Jothiprakash (2013) optimized the operations of Koyna Hydro Electric Project reservoirs by adopting chaotic evolutionary algorithms in order to maximize the hydropower production. They used both Genetic Algorithm (GA) and DE algorithms in conjunction with chaos technique to enhance the search process by generating a better and healthier initial population. They concluded that the chaos technique along with evolutionary algorithms have enhanced the global pursuit of the optimisation method by having better beginning populace furthermore unites rapidly.

Regulwar, Choudhari and Raj (2010) applied DE to the operation of multipurpose reservoir in India and the main purpose is to maximize the use of water for hydropower purposes. The results of their study showed that DE is also a robust global optimization technique and can be adopted in solving complex non-linear optimization problems.

Another hydropower study was carried out by Yuan *et al.* (2008). They initiated a hybrid chaotic genetic algorithm (HCGA) model for water scheduling for hydropower purposes over short term duration. In their study, the initial population was generated as chaotic sequence and they introduced a self-adoptive error back propagating mutation in order to prevent premature convergence. It was reported that HCGA was robust, efficient and ideal for the large scale non-linear optimization problems with constraints.

In conclusion, in order to improve the access of water, energy is a driving force which means the more water saved, the less energy needed. However, the use of energy has a major effect on water shortage and climate change.

2.6 TOOLS FOR WATER RESOURCE SUSTAINABILITY

Water resources management and planning problems are often regarded as complex, non – linear in nature. It is very difficult to find optimal solutions to them without using some mathematical modelling techniques (Adeyemo and Otieno 2010a). Models will be developed and solved using different algorithms which are capable of solving these multi-objective problems. This section presents a review of some optimization tools adapted to sustainability of water resources management.

Karaouli *et al.* (2009) studied the sustainability of water resources in the mining basin of Gafsa in Tunisia. Wastewater was considered as a potential additional water resource in order to avoid over-exploitation of the groundwater resources in the region. The study developed an integrated water resources management (IWRM) and this approach is based on the three pillars of economic, efficiency, equity and environmental sustainability. The confrontation between available resources and water demand for all sectors in the phosphate basin shows that the current global balance is in surplus (Karaouli *et al.* 2009).

The Gafsa has a semi-arid climate, which is characterised by low and irregular rainfall hence; it presents an ever increasing threat in terms of quantitative and qualitative deterioration of the groundwater resources which are very vulnerable. Meetings were conducted with stakeholders. The results of the study show the comparison between the quantitative and qualitative requirements by each sector and the availability of resources. It also showed the meetings with stakeholders were organised in order to discuss potential alternative and scenarios for sustainable water management among them the use of non-conventional resources. The authors therefore recommend the use of treated waste water as a means of adding to the supply of water resources in the area since it would contribute to soil and water conservation improvement.

An optimization tool was developed by Miao *et al.* (2013), which solves the problem of water resources systems planning. The fuzzy programming method was created to be applied to water resource management systems. The authors observed that numerous studies have been conducted and inexact fuzzy programming methods have been developed for the planning of water-resources management systems under uncertainty. However, most of them do not allow the parameters in the objective and constraints of a programming problem to be functional intervals (i.e. the lower and upper bounds of the intervals are functions of impact factors). Therefore, in their study, an interval fuzzy bi-infinite De Novo programming (IFBDP) method was developed to address the concern stated above.

The IFBDP model in this study can be solved through a two-step method by transformed into two sets of deterministic sub models, which correspond with the lower and upper bounds of the preferred objective function value. It can also deal effectively with uncertainties expressed as fuzzy sets and functional interval values in single and multi-objective problems. The IFBDP model was applied to a case study of (i) water resources systems planning, which designs an inexact optimal system with budget limit and different weight, and (ii) illustrating its advantages over the previous approach such as inexact De Novo programming (IDNP), and interval-fuzzy De Novo programming (IFDNP) which does not consider bi-infinite programming. A number of scenarios were examined for system uncertainties and decision processes to identify an optimum system design with higher benefits. The results obtained can be used to help decision makers evaluate alternative system designs and to determine which of these designs can most efficiently achieve the desired system objectives.

From the study, it can be concluded that the IFBDP techniques can provide reasonable schemes for effectively allocating water from cities to water users, and designing proper wastewater treatment facilities in water purifying industry, municipality and agriculture Moreover it can be used for analysing various scenarios that are associated with different levels of economic consequences under uncertainty.

2.7 INTEGRATED WATER RESOURCES MANAGEMENT AND FORECAST MODELS AND TOOLS

Forecasts of future events are required in many activities associated with planning and operation of the components of a water resources system. For the hydrologic component, there is a need for both short term and long term forecasts of streamflow events in order to optimize the system or to plan for future expansion or reduction (Kisi 2007). Several studies have been conducted on prediction of water resources around the world (Maier and Dandy 2000; Kisi 2007; Mohamed and Al-Mualla 2010; Zeng *et al.* 2012; Qu, Gong and Dong 2013). A detailed reviewed of some studies are done below.

Nasseri, Moeini and Tabesh (2011) forecasted the monthly urban water demand using extended Kalman filter (EKF) and genetic programming (GP). In this study, genetic programming was developed for water demand forecasting in Tehran. In the development of a model using GP, three items in selecting the optimum formula should be considered: minimum error, shortest depth and length in the created formula. Also, in the progress of this simulation, the following steps were followed: (i) setting the terminals; (ii) setting the initial functions (based on data behaviour); (iii) determining the fitness function (it is in default of GPLAB); (iv) checking values of the model parameters and qualitative in the model for run and (v) criteria for designating a result and terminating a run.

The first issue was to forecast based on the current water demand using GP to achieve explicitly optimum formula. This model replaces the string and numbers by computational codes in the form of free structure formulae while Darwinian operators select the crossover and mutation operations. One of the advantages of using GP is that it does not assume any prior function for the problem solution. After the study, it was concluded that GP with inherent evolutionary rules can play an important role. This type of modelling prepares a proper area for finding touch based and descriptive mathematical formula for complex dataset. Evolutionary and dynamic behaviour of GP makes it an appropriate candidate in simulation of time dependent complex phenomena in science and engineering too.

Also, Mohamed and Al-Mualla (2010) conducted a study on water demand forecasting in Umm Al-Quwain using the constant rate model of the IWR-MAIN software (main code developed by the U.S. Army Corps of Engineers' Institute for Water Resources). Water demand foresting is essential in order to plan for future water demands within a region (Yang *et al.* 2009). It provides a simulated view of the future and helps to identify suitable resource management alternatives in order to balance water supply and demand (Mohamed and Al-Mualla 2010). In forecasting the water demand of Umm Al-Quwain, different approaches were employed to achieve higher efficiencies in power and water sectors in the GCC state. The constant rate model is mainly based on the water use per unit and calculated from the base year water use.

IWR-MAIN is one of the most commonly referenced software in the field of water demand forecasting and was previously used by several researchers and water authorities. Water agencies across USA have validated IWR-MAIN through application with actual case studies. In developing the model, for each forecast year, water demand is calculated as a function of water consumption parameters such as housing units, marginal price and employment. Some of these parameters should be projected before using IWR-MAIN for each forecast year. The IWR-MAIN was used to forecast the water demand in Umm Al Quwain for the next 20 years.

The constant rate model was calibrated using collected data and the calibrating procedures has several simulations which were performed with different base years in order to select the base year that presents demand is more accurate. Data of the average daily water use from 1980 to 2000 was collected and used in the prediction process. About 50 % increase in the current water demand is required to satisfy water needs in Umm Al-Quwain in 2020 and it will be doubled the current demand before 2030.

A water resources modelling for Beijing was done by Xiaoxue, Yijin and Wenyan (2011). The urban water usage is influenced by infrastructure, industrial production and other factors such as population. The study applied unbiased grey model (GM), nonlinear model and combined model to calculate the usage of water in Beijing from the year 2001 to 2010. There were different cities with different natures and each model was used for predicting the water use in each city. With the accurate testing method, the results showed that unbiased grey model with nonlinear model had a highest accuracy than the other single model. The error on biased grey model was too small but the average absolute was too high but the nonlinear modelling error was high and the average absolute was small. This weighted mixture model can integrate the advantages of the two models and make the results more accurate and consistent, which can be used for short term and long term prediction of urban water usage.

Yang *et al.* (2009) conducted a study on environmental flow requirements for integrated water resources allocation in the Yellow River Basin, China. The study shows that in order to have a river basin that is well functioning, the focus must shift from only the water supply to people but also give into consideration to the environment. With such alert, there has then been more recognition of the environmental flow as one of the key players in making sure that water resources are well managed (Yang *et al.* 2009). Environmental flow requirement (EFR) for water resources allocation requires that water must also be left so that it is released into aquatic ecosystem to maintain it in a condition that will give balance support (Zimmerer 2011). The objective of the study was to assess the environmental flow requirements (EFR) which include hydrological index, hydraulic rating, and habitat simulation. Hydrological method was adopted which uses flow data to estimate the EFR, however they don't give high confidence EFR estimates, especially with insufficient quantitative information. Results of this study pointed out that water resource allocation in the river reaches of the Yellow River Basin are analysed in the downstream of the basin. The study also shows that water requirements compensate the water losses of evaporation and infiltration for wetlands in the Yellow River Basin in order to maintain the balance of the water quantity.

It is also important to continue conducting such investigations linking to hydrology so as to be always ahead of any uncertainties that might put threat to the formulation of robust operational rules for the management of reservoir. This is because it can also affect the whole water resource management and also planning. This can be directly impact the outcome of the water resources planning and management. Ajami, Hornberger and Sunding (2008) conducted a study on Shasta reservoir in the upper portion of the Sacramento River, California. Four methodologies were used in the study which were; study site, integrated assessment of hydrological uncertainty, reservoir operation and management scenarios and reliability, resilience and vulnerability (RRV).

The study site method was used to collect the necessary data about the watershed. Integrated assessment of hydrological uncertainty used a mathematical conceptualization of complex and spatial distributed watershed processes, which is used as estimate of the current and future hydrologic events. The reservoir management scenarios were constructed for a sample water management to represent the water resources systems.

These models were used in solving the availability and demand equilibrium through simulation. When storage levels falls into buffer zones they released water from the conservation zones to meet the demand in full. Reliability, Resilience and Vulnerability (RRV) were used as indices to assess the performance of water resources system. The results of the study shows that a better reservoir management largely lies on accuracy of climate forecast ensembles, which would mean more accurate hydrological forecasts and effective use of these ensembles. This is because accuracy is accountable for many different sources of uncertainty that affects our forecasted water demands. The inflow to the reservoir provides better or more accurate information to the decision makers and will assist in making sure that water resource operations are used in a sustainable, socially and economically efficient way.

2.8 SUMMARY

Following this extensive review of the application of popular statistical analysis procedures such as regional flood frequency analysis in the modelling of hydrological variables, It can be found that it has a wide use in the water resources modelling. These are techniques that have helped water managers to wisely plan their water resources adequately.

Water is a very important, yet scarce natural resource on the earth. The scarcity of water is becoming a global problem especially in the arid and semi-arid regions of the world hence, it must therefore be sustained. South Africa is a country that experiences low average annual rainfall and the water demand is far above the supply (Karlberg *et al.* 2007). Increase in population, rapid economic development, urbanization, industrialization, tourism, and inefficient irrigation activities, which is often the highest user of water has made river basins in many Eastern and Southern Mediterranean countries suffer from water scarcity (Harmancioglu, Fedra and Barbaros 2008). It is important to manage water resources effectively due to the increase in water demand as a result of industrial, agricultural and economic development. It is therefore necessary to conduct studies on the sustainability of river basins within these regions and river UMdloti in South

Africa has been selected for this study especially with limited dataset available in a developing country like South Africa.

The use of other water sustainability tools like Integrated Watershed Management (IWM), scenario analysis, water supply reliability, multi-objective programming, Decision Support Systems (DSS) were critically reviewed in this literature. These tools and optimization techniques have showcased great potential in this respect, as they can easily be integrated into use for any watershed management and planning.

CHAPTER 3

METHODOLOGY

3.1 DATA COLLECTION

The data used for this study was collected from Department of Water Affairs (DWA), South African Weather Services (SAWS) and Umgeni Water Authority (UW). Three categories of historical data were collected and used for this study. These are average monthly rainfall, average monthly air temperature and the hydrograph of the study area. Monthly reservoir inflow data for Hazelmere Dam was obtained from the Department of Water Affairs, South Africa. The nature of data is streamflow volume in mega litre (Ml) recorded for every month of the year. This was converted to mega cubic meter (Mm^3) for use in the analysis herein. A period spanning 19 years of data (1994 – 2013) was used for the analysis.

3.2 DATA ANALYSIS

3.2.1 Statistical analysis

A summary of the statistics of the monthly series is presented in Table 1. Six parametric probability distribution models were developed for estimating the monthly streamflow at Hazelmere Dam. These probability distribution functions include; Normal, Log-Normal (LN), Pearson III, Log-Pearson type III (LP3), Gumbel extreme value type1 (EVI) and Log-Gumbel (LG). The series was ranked according to Weilbull's plotting position and the corresponding return periods were estimated. Goodness-of-fit tests were adopted for selecting the best fit models among the six parameters. For a comparison between the six probability distribution models, the Mean Relative Deviation (MRD) and Mean Square Relative Deviation (MSRD) statistics were used to measure the goodness-of-fit. Detailed analysis of streamflow events within the Hazelmere Dam, with the aim of determining ways by which future occurrences can be predicted or estimated within certain degrees of freedom, is of importance to this study. In frequency analysis, an assumed probability distribution is fitted to the available data to estimate the magnitude corresponding to return periods and the appropriate distribution models that represent the data is chosen. The choice of the probability distribution model is almost arbitrary as no physical basis is available to rationalize the use of any particular function and the search for the proper distribution function has been the subject of several studies (Adeyemo and Olofintoye 2014).

Table 1: Summary of statistics for monthly streamflow of Hazelmere Dam (1994 – 2013)

	Statistics					
Month	Mean value, (Mm^3)	Standard deviation, (Mm^3)	Skewness coefficient, G	Median (Mm^3)	Minimum (Mm^3)	Maximum (Mm^3)
Jan	104.37	411.03	4.36	7.04	0.78	1801.28
Feb	159.74	459.89	2.92	5.09	0.37	1661.37
Mar	175.61	518.28	2.94	3.67	1.55	1883.40
Apr	171.50	512.17	2.96	3.18	1.13	1869.84
May	107.47	450.39	4.36	2.18	0.75	1967.11
Jun	178.18	533.98	2.91	1.67	0.57	1907.45
Jul	88.09	361.93	4.24	1.46	0.66	1538.27
Aug	85.06	362.41	4.36	1.32	0.60	1581.61
Sep	89.36	371.37	4.24	1.60	0.47	1577.43
Oct	90.56	383.25	4.36	2.09	0.66	1673.16
Nov	91.52	379.73	4.36	2.75	1.42	1659.53
Dec	108.47	414.49	4.24	7.15	1.02	1768.69

3.2.2 Evaluation of probability distribution models

The monthly series were ranked according to Weibull’s plotting position and the corresponding return periods were estimated. Weibull’s plotting position is the most efficient formula for computing plotting position for unspecified distribution and is now the most commonly used for most sample data (Warren and Gary 2002). The Weibull’s plotting position is given as:

$$P = \frac{m}{n+1} \tag{1}$$

Where:m is the series of event ranking, 1 for highest value and so on in descending order; *n* is the number of events; *P* is an estimate of the probability of values being equal or greater than the ranked value.

The return period (T_r) is estimated as the reciprocal of the probability as follows:

$$T_r = \frac{1}{p} \tag{2}$$

The monthly series were evaluated using six methods of probability distribution functions, Normal, Log-Normal (LN), Pearson III, Log-Pearson type III (LP_3), Gumbel extreme value type1 (EVI) and Log-Gumbel (LG). These models were used to determine the best fit models among the six in the monthly series. The choice of the probability distribution model is almost arbitrary as no physical basis is available to rationalize the use of any particular function and the search for the proper distribution function has been the subject of several studies.

3.2.3 Comparison of streamflow models

Mathematical expressions obtained from each of the parametric probability distribution models were used to estimate streamflows for different return periods. The goodness-of-fit of the return period and the estimates of the probability distributions were obtained and compared using Mean Relative Deviation (MRD) and Mean Square Relative Deviation (MSRD) statistics. These statistics are defined as follows (Jou *et al.* 2009a; Olofintoye and Salami 2011; Olofintoye and Adeyemo 2012b):

$$MRD = \frac{1}{n}\sum_{i=1}^{n}\frac{|x_i - \hat{x}_i|}{x_i}\times 100 \qquad (3)$$

$$MSRD = \frac{1}{n}\sum_{i=1}^{n}\left(\frac{x_i - \hat{x}_i}{x_i}\times 100\right)^2 \qquad (4)$$

Where *x* and $\hat{x}$ are the observed and estimated stream flows respectively and *n* is the sample size. In general, lower values of MRD and MSRD indicate better fit (Jou *et al.* 2009a). MRD and MSRD values were computed for each developed model, and the model with the minimum values of MRD is chosen as the best-fit model. MRD and MSRD are useful for comparing the uncertainty between different measures of varying absolute magnitude. It also provides precision measures for a limited number of repetitive measurement. There were limitations of data like floods and temperature to explain the annual extreme events.

3.3 OPTIMIZATION MODELS FOR HYDROPOWER GENERATION

This study also determined the amounts of monthly and total annual energy that can be generated from Hazelmere reservoir based on turbines efficiencies of 75%, 85% and 90%. Normal, Log-Normal (LN), Pearson III, Log-Pearson type III (LP_3), Gumbel extreme value type1 (EVI) and Log-Gumbel (LG)models were formulated to maximize hydropower generation within the constraints of existing abstractions, hydrological and system constraints. Differential evolution (DE) optimization method was adopted to resolve the optimization models. The methodology was applied for an operating season.

3.3.1 Proposed system configuration

An axial flow vertical Kaplan turbine with discharge of 40 m^3/s and a minimum operating head of 10m was adopted as suggested by SIDALA (2010). This type of turbine is useful in dams with low heads. The powerhouse is located at ground level with the turbines located at the minimum reservoir level (61 mASL). The penstock inlet is set at 71 mASL and specifies the minimum operating level for hydropower generation. This corresponds to reservoir storage of 7.15 Mm^3. The maximum reservoir volume (17.858 Mm^3), which corresponds to a reservoir elevation of 85.98 mASL, defines the maximum operating level. The power plant installed capacity is assumed to be 10 MW while the turbine efficiencies are varied between 75, 85 and 90 percentages.

3.3.2 Estimation of monthly reservoir inflows

Reservoir operations require that inflows into the reservoir over the planning period be estimated ahead of operations. Probability distribution models were employed to perform streamflow frequency analysis for the reservoir. Monthly reservoir inflow data for Hazelmere Dam was obtained from the Department of Water Affairs, South Africa. The nature of data is streamflow volume in mega liter (Ml) recorded for every month of the year. This was converted to mega cubic meter (Mm^3) for use in this analysis. A period spanning 19 years of data (1994 – 2013) was used for the analysis. The monthly series were ranked according to Weilbull's plotting position and the corresponding return periods were estimated. The series were evaluated using six methods of probability distribution functions, Normal, Log-Normal (LN), Pearson III, Log-Pearson type III (LP_3), Gumbel extreme value type1 (EVI) and Log-Gumbel (LG). The fit of the mathematical expressions obtained for each function were compared using Mean Relative Deviation (MRD) and Mean Square Relative Deviation (MSRD) statistics (Jou *et al.* 2009b; Olofintoye and Salami 2011; Olofintoye and Adeyemo 2012c). The best model for each month was used to estimate medium flows into the reservoir. Operating a reservoir without failure under a medium flow condition suggests that the reservoir will perform reliably at least 75 percent of the time (Scott and Smith 1997).

3.3.3 Development of reservoir storage relationships

Storage relationships are useful in computation of reservoir storage head and surface area necessary for estimation of generating head for hydropower and reservoir evaporation. In this study, linear relationships were developed to model the storage-elevation and storage-area relationships since the reservoir is small (capacity <50Mm^3) (Salami 2007).

3.3.4 Model formulation

Differential Evolution (DE) was applied to optimize the operation of Hazelmere reservoir in a season (May to April). The dam was operated under a medium flow condition. The full capacity of the reservoir (17.858 Mm^3) was used as the starting storage for the reservoir. The decision date for reservoir operation in South Africa is May 1 when reservoir operating analysis is undertaken to decide how the reservoir should be operated in the coming year.

3.3.4.1 Decision variables and Objectives

The main aim of the study was to determine the monthly water releases for hydropower generation at the dam while meeting the existing water demands on the dam. The existing water demands for irrigation, domestic and other uses were obtained from DWA and held as constraint that must be satisfied. The decision variables in this study are the monthly turbine releases for hydropower generation *RTurbine* (Mm^3) and the existing monthly water abstractions from the dam *RExisting* (Mm^3). The objective of the reservoir operation optimization problem was formulated as:

Objective: *Maximize total annual hydropower generation*

Annual hydropower generation is maximized to generate electricity for the citizens at a cheaper cost. Equation (5) is used for maximizing energy generation from reservoirs (Loucks and Bee 2005; Salami 2007; Ajenifuja 2009):

Maximize

$$Hp_{Total} = \sum_{t=1}^{12} 2.725 \times RTurbine(t) \times H(t) \times \varepsilon; \qquad t = 1,2,\ldots,12 \tag{5}$$

Where Hp_{Total} is total annual hydropower generation over the operating period in megawatt hours (MWH). *RTurbine(t)* is the volume of water released through the hydropower turbines during month t in mega meter cube (Mm^3), ε is the turbine efficiency in converting the mechanical energy of water to electrical power, and this is varied between 75, 85 and 90%. *H (t)* is the average hydropower generating head in month t in metres (m). H is specified as the vertical distance between the water surface elevation in the reservoir that is the source of the flow through the turbines and the maximum of either the turbine elevation or the tail water elevation (Loucks and Bee 2005).

3.3.4.2 Problem constraints

The single objective reservoir optimization problem of maximizing total annual hydropower generation at the dam is subject to the following constraints:

Constraint 1: *Mass balance equation*

The storage continuity equation defining the relationship between inflow and outflow variables at the reservoir site must be satisfied. This is presented in equation (6) (Loucks and Bee 2005; Salami 2007).

$$S(t+1) = S(t) + Q(t) - E_{net}(t) - R(t) - Ls(t) \tag{6}$$

where;

$$R(t) = RExisting(t) + RTurbine(t); \tag{7}$$

$$E_{net}(t) = P(t) - E(t); \tag{8}$$

$$Ls(t) = 0; \tag{9}$$

where S(t+1) is the reservoir storage at the end of month *t*, *S(t)* is the storage volume in the reservoir at the beginning of month *t*, *Q(t)* is the streamflow into the reservoir during month *t*, *P(t)* is precipitation on the reservoir surface during month *t*, *E(t)* is gross evaporation from the reservoir surface in month *t*, *Ls(t)* is seepage loss in month *t*, *RExisting(t)* is the existing water demand in month *t.* All variables are measured in volumetric units of mega cubic metres (Mm^3). Seepage losses are assumed to be negligible in this study.

Constraint 2: *Limit on reservoir releases*

The values of monthly releases through the turbines and other water outlets must lie between the minimum and maximum releases allowed through the outlets. Existing water demand is not maximized in this study but held as a constraint that must be satisfied. The constraints on the reservoir releases are presented in equations 10 and 11:

$$RExisting(t) = DExisting(t) \tag{10}$$

$$DTurbine(t) \le RTurbine(t) \le CTurbine(t) \qquad (11)$$

Where DExisting (t) and *DTurbine (t)* (Mm^3) are monthly existing demands and turbine demands respectively. C*Turbine (t)* (Mm^3) is the discharge capacity of the turbines in month *t*.

Constraint 3: *Limits of reservoir storage*

The monthly reservoir storages are allowed to vary between the minimum and maximum operating levels for hydropower generation. This constraint is specified in equation (12):

$$S_{\min} \le S(t) \le S_{\max} \qquad (12)$$

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

Constraint 4: *Sustainability constraint*

For the operation of the reservoir to be sustainable, the storage at the end of the operating period must not be less than the starting storage. This constraint is presented in equation (13):

$$S(13) \ge S(1) \qquad (13)$$

Where S(13) (Mm^3)is the storage volume at the end of the operating period which also represents the starting storage at the beginning of the next operating season. *S(1)* (Mm^3) is the storage at the beginning of the operating period.

Constraint 5: *Limit on hydropower plant capacity*

The maximum electrical energy that can be produced from a hydropower generating plant at any time is limited by installed plant capacity *P* (MW) and the plant factor *f*. The total energy produced (MWH) during any period cannot exceed the product of the plant factor *f*, the number of hours in the period *h*and the plant capacity *P*, as defined in equation (14)(Loucks and Bee 2005; Salami 2007):

$$Hp(t) \leq (Hp_{\max}(t) = Ph(t)f) \qquad (14)$$

$Hp_{max}(t)$ is the maximum hydropower that can be generated in month t in megawatt hours (MWH). $Hp(t)$ (MWH) is hydropower produced in month t.

In determining the potential of hydropower in Hezelmere Dam, it was considered that the dam should meet all the other demands. The Hazelemere Dam has a storage capacity of less than 50Mm³ and water are mainly used for irrigation, domestic and other uses. Hydropower has not been considered in the dam. This study now considers using the dam for hydropower while all these uses are still satisfied. Details of this are given in Chapter 5 of this thesis.

CHAPTER 4

ESTIMATION OF MONTHLY STREAMFLOW IN HAZELMERE DAM USING PROBABILITY DISTRIBUTION MODELS

4.1 OVERVIEW

This chapter presents the study of monthly streamflow in Hazelmere Dam. The results were obtained from the estimation of monthly streamflow using parametric probability distribution models and hydro–meteorological statistical analysis of the study area. The relevant literature has been discussed in Chapter 2 of this thesis while various methodologies adopted have been adequately discussed in Chapter 3 of this thesis. The results of the various methodologies with regards to all the objectives of this study as stated in Section 1.3 of this thesis are hereby presented.

4.2 ESTIMATION OF MONTHLY STREAMFLOW USING PARAMETRIC PROBABILITY DISTRIBUTION MODELS

The estimation of monthly streamflow in the Hazelmere Dam, South Africa, using six parametric probability distribution models is hereby presented. The parametric model developed include; Normal, Log-Normal, Pearson's III, Log-Pearson's III, Gumbel and Log-Gumbel models. Dataset covering a 19–year period (1994 to 2013) was used for the analysis. The monthly series were ranked according to Weibull's plotting positions and the corresponding return periods were estimated. The Weibull's plotting position is given as

$$P = \frac{M}{N+1} \qquad (15)$$

The return period (T_r) is estimated as the reciprocal of the probability as follows:

$$T_r = \frac{1}{P} \tag{16}$$

Where, *N* is the length of series and *M* is a ranked value; *P* is the non-exceedance probability of the order ranked rainfall data that is commonly referred to as a plotting position.

The mathematical expressions obtained for the six probability distribution functions for each month are presented in Table 2.

Table 2: Summary of developed probability distribution model equations for each month

	Probability Distributions					
Month	Normal	Log-Normal	Pearson III	Log-Pearson III	Gumbel	Log-Gumbel
Jan	Qp =104.37 + 411.03K	Qp =Antilog (0.94 + 0.70K)	Qp =104.37 + 411.03K'	Qp =Antilog (0.94 + 0.70K'')	Qp =-80.59 + 320.61YT	Qp =Antilog (0.63 + 0.55YT)
Feb	Qp =159.74 + 459.89K	Qp =Antilog (0.96 + 0.89K)	Qp =159.74 + 459.89K'	Qp =Antilog (0.96 + 0.89K'')	Qp =-47.21 + 358.71YT	Qp =Antilog (0.56 + 0.69YT)
Mar	Qp =175.61 + 518.28K	Qp =Antilog (0.86 + 0.87K)	Qp =175.61 + 518.28K'	Qp =Antilog (0.86 + 0.87K'')	Qp =-57.62 + 404.26YT	Qp =Antilog (0.47 + 0.68YT)
Apr	Qp =171.50 + 512.17K	Qp =Antilog (0.72 + 0.91K)	Qp =171.50 + 512.17K'	Qp =Antilog (0.72 + 0.91K'')	Qp =-58.97 + 399.49YT	Qp =Antilog (0.31 + 0.71YT)
May	Qp =107.47 + 450.39K	Qp =Antilog (0.53 + 0.77K)	Qp =107.47 + 450.39K'	Qp =Antilog (0.53 + 0.77K'')	Qp =-95.20 + 351.30YT	Qp =Antilog (0.18 + 0.60YT)
Jun	Qp =178.18 + 533.98K	Qp =Antilog (0.51 + 0.98K)	Qp =178.18 + 533.98K'	Qp =Antilog (0.51 + 0.98K'')	Qp =-62.11 + 416.51YT	Qp =Antilog (0.07 + 0.76YT)
Jul	Qp =88.09 + 361.93K	Qp =Antilog (0.42 + 0.78K)	Qp =88.09 + 361.93K'	Qp =Antilog (0.42 + 0.78K'')	Qp =-74.78 + 282.31YT	Qp =Antilog (0.07 + 0.61YT)
Aug	Qp =85.06 + 362.41K	Qp =Antilog (0.34 + 0.74K)	Qp =85.06 + 362.41K'	Qp =Antilog (0.34 + 0.74K'')	Qp =-78.03 + 282.68YT	Qp =Antilog (0.01 + 0.58YT)
Sep	Qp =89.36 + 371.37K	Qp =Antilog (0.36 + 0.75K)	Qp =89.36 + 371.37K'	Qp =Antilog (0.36 + 0.75K'')	Qp =-77.76 + 289.67YT	Qp =Antilog (0.02 + 0.59YT)
Oct	Qp =90.56 + 383.25K	Qp =Antilog (0.49 + 0.72K)	Qp =90.56 + 383.25K'	Qp =Antilog (0.49 + 0.72K'')	Qp =-81.90 + 298.93YT	Qp =Antilog (0.17 + 0.56YT)
Nov	Qp =91.52 + 379.73K	Qp =Antilog (0.67 + 0.69K)	Qp =91.52 + 379.73K'	Qp =Antilog (0.67 + 0.69K'')	Qp =-79.36 + 296.19YT	Qp =Antilog (0.36 + 0.54YT)
Dec	Qp =108.47 + 414.49K	Qp =Antilog (0.94 + 0.75K)	Qp =108.47 + 414.49K'	Qp =Antilog (0.94 + 0.75K'')	Qp =-78.05 + 323.30YT	Qp =Antilog (0.60 + 0.58YT)

Qp – Estimated streamflow using a probability distribution model

K – Normal variate obtained from Normal distribution tables for a given return period

K′ - Variate obtained from Pearson distribution tables for a given return period and skew coefficient

K″ - Variate obtained from Pearson distribution tables for a given return period and the log transform of the skew coefficient

YT – Reduced variate computed as YT = -ln[-ln(1 – $^{1}/_{T}$)] for a given return period T.

The computed values of Mean Relative Deviations (MRD) and Mean Square Relative Deviations (MSRD) for each of the parametric distributions models are presented in Tables 3 and 4 respectively.

Table 3: Values of Mean Relative Deviation (MRD)

Month	Normal	Log-Normal	Pearson III	Log-Pearson III	Gumbel	Log-Gumbel
Jan	7653.3738	38.8778	2522.3322	28.9654	6339.4696	26.4724
Feb	12981.1681	69.8279	4535.9223	43.8097	10102.7504	46.5786
Mar	8605.7387	105.2771	4037.0756	36.6784	7120.0553	69.0630
Apr	12401.3714	133.4173	5793.0288	51.4296	10283.2975	92.0112
May	15502.9449	79.2238	5602.4476	23.1989	13165.8209	51.6523
Jun	22715.2669	180.2385	10362.8648	66.6701	18539.3157	125.4193
Jul	14716.7799	84.6297	5545.7982	19.5408	12528.0624	56.0196
Aug	17039.5738	91.4180	6448.5071	25.5913	14549.3711	66.0512
Sep	18857.8897	100.7987	6712.6227	39.8180	15873.5858	77.5525
Oct	14241.7348	81.7746	5188.6289	36.6573	12076.1626	62.6435
Nov	8216.5246	68.3646	3102.9674	25.3741	7033.2498	48.2681
Dec	8084.9976	35.9282	2594.2422	29.5311	6793.9974	24.1917

Table 4: Values of Mean Square Relative Deviation (MSRD)

Month	Normal	Log-Normal	Pearson III	Log-Pearson III	Gumbel	Log-Gumbel
Jan	325179755.3382	2347.8365	25167579.4902	2203.1757	194176150.4179	1552.3195
Feb	1453835941.7970	7238.4898	106615859.9572	3497.7883	802917722.6312	3260.8803
Mar	186110739.5738	17585.4922	28200357.6601	3241.1582	117891714.4427	8527.2790
Apr	363030925.2970	35864.5540	55973677.8487	6539.8904	232215695.3754	19069.4365
May	666855177.3376	9792.1337	61989995.5621	924.1017	436004910.2089	4386.8940
Jun	1345568158.8198	70171.3984	183311721.5002	11222.6673	822649861.1327	37239.6349
Jul	535501832.2961	10501.9863	52404591.9958	848.4142	355613828.6395	4726.7759
Aug	694568239.8593	12764.8452	70562670.8092	1271.7052	460105607.9616	7663.7652
Sep	1003371701.3666	18114.5126	85327317.2577	3112.4757	645731503.1631	12905.4770
Oct	580010515.9375	11747.1431	53793318.5754	2755.6194	375352908.8161	8677.8228
Nov	160767348.6685	6852.8510	16238215.1363	1682.9121	109100630.6396	4597.4595
Dec	270037073.2567	2045.4972	18805055.3333	1324.4162	172953297.0184	1158.1836

Table 5 presents the Best-fit model for each month based on minimum values of calculated Mean Relative Deviation

Table 5: 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

Flow duration curves for each month for each model were also made to provide insight as to how well the models fit the data (See Figures 2 to 13).

4.2.1 Flow duration curve on monthly basis for each probability distribution model adopted

This section presents the flow duration curve of the output of each probability distribution models per month (i.e January to December). The flow duration curve is a plot of discharge against the percentage of time the flow was exceeded (Warren and Gary 2002). Streamflow data is arranged in a descending order of magnitude. These curves contain the cumulative frequency distribution and magnitude of flow on an average monthly basis. It contains details of observed data and fitted probability distribution models adopted. Figures 2 to 13 show the details as explained above.

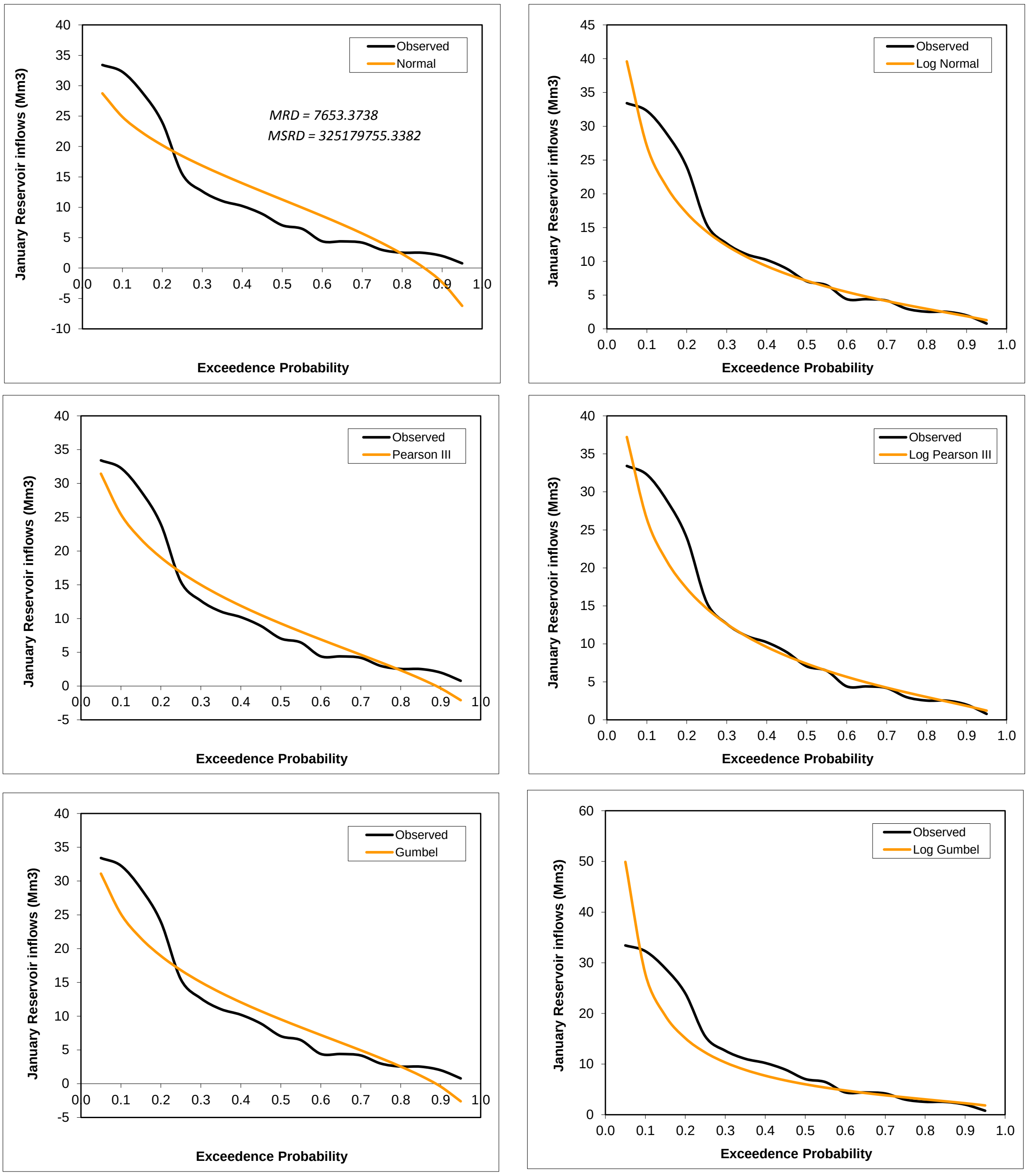

Figure 2:Flow duration curves for the months of January

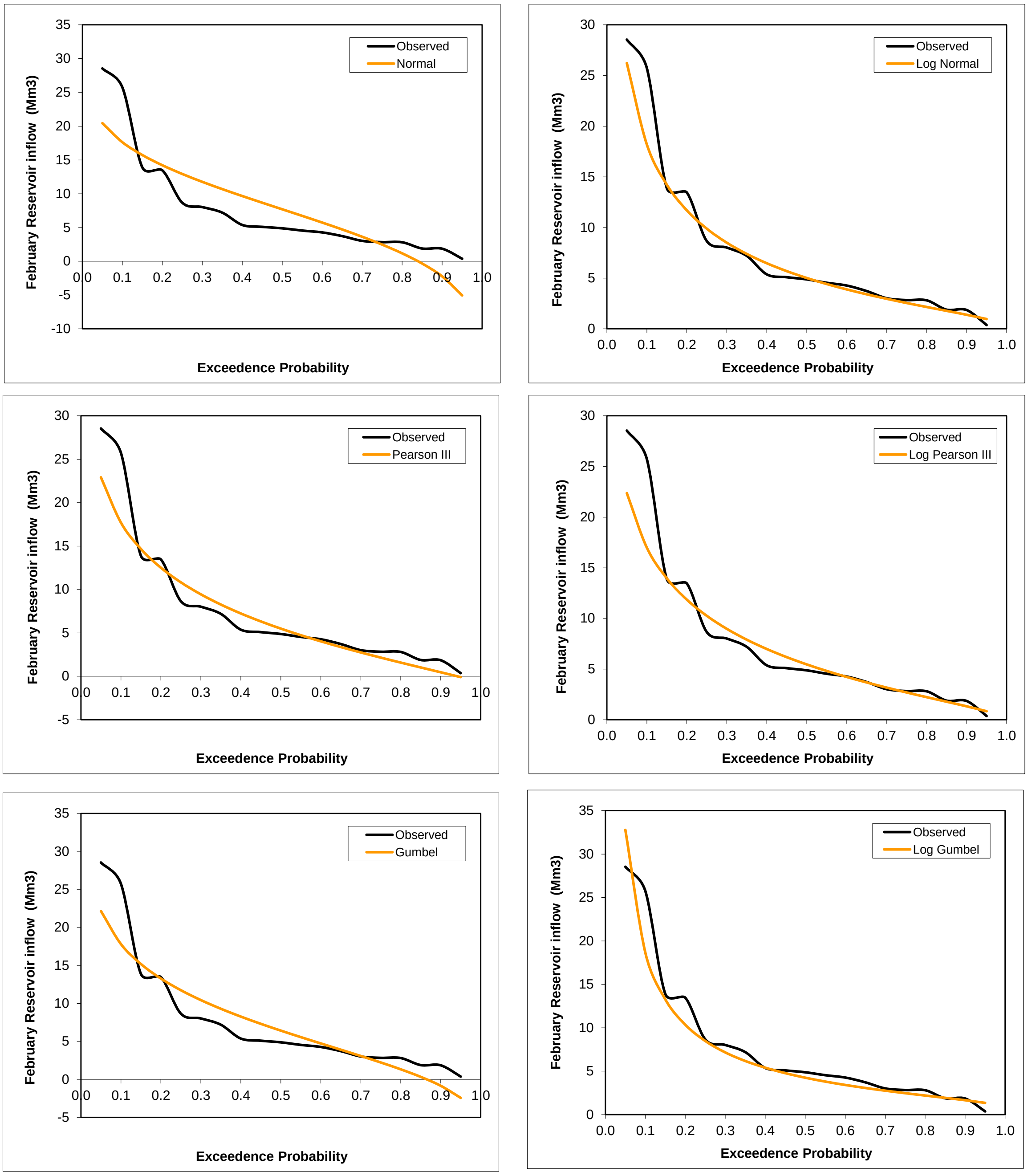

Figure 3: Flow duration curves for the months of February

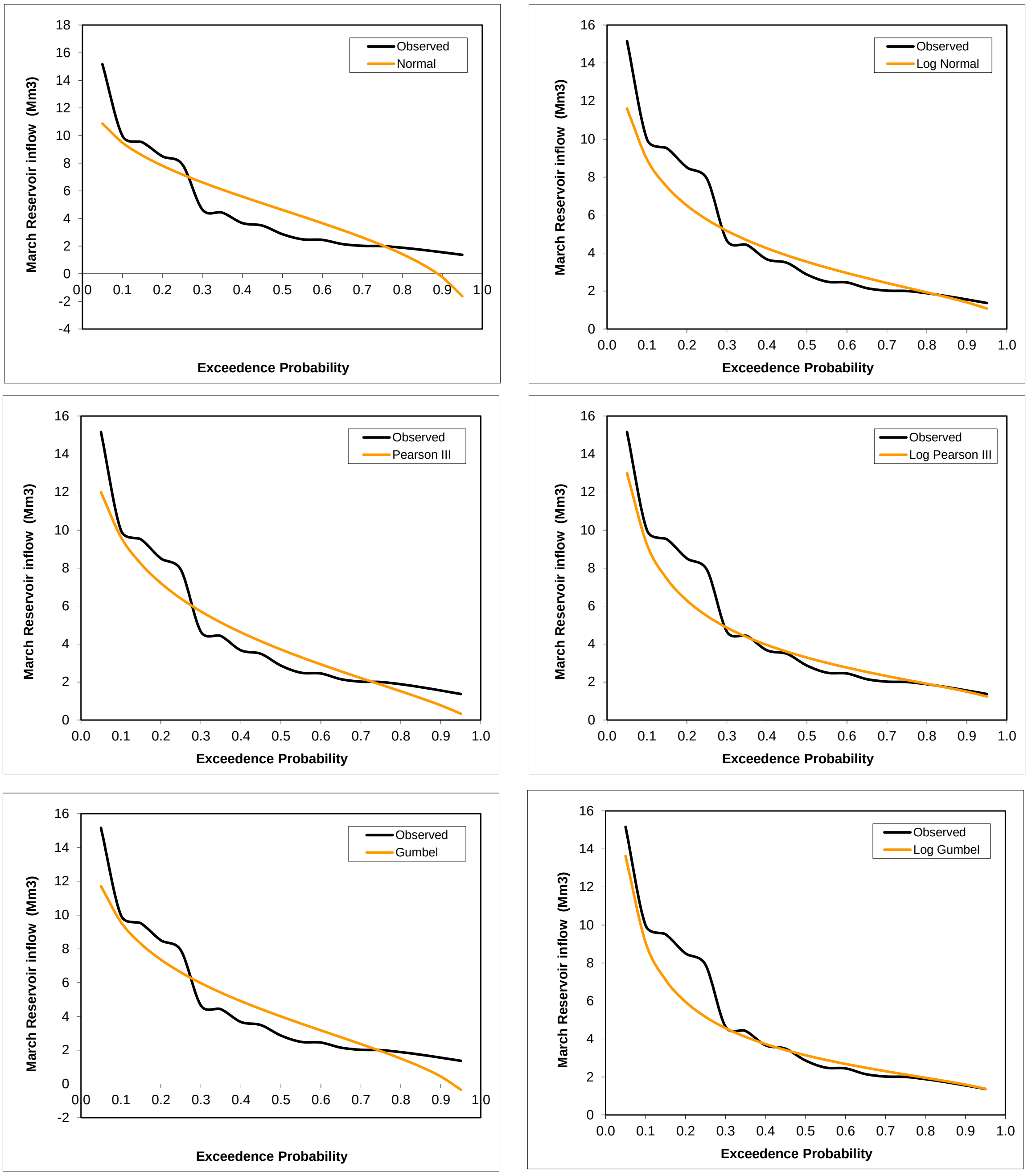

Figure 4: Flow duration curves for the months of March

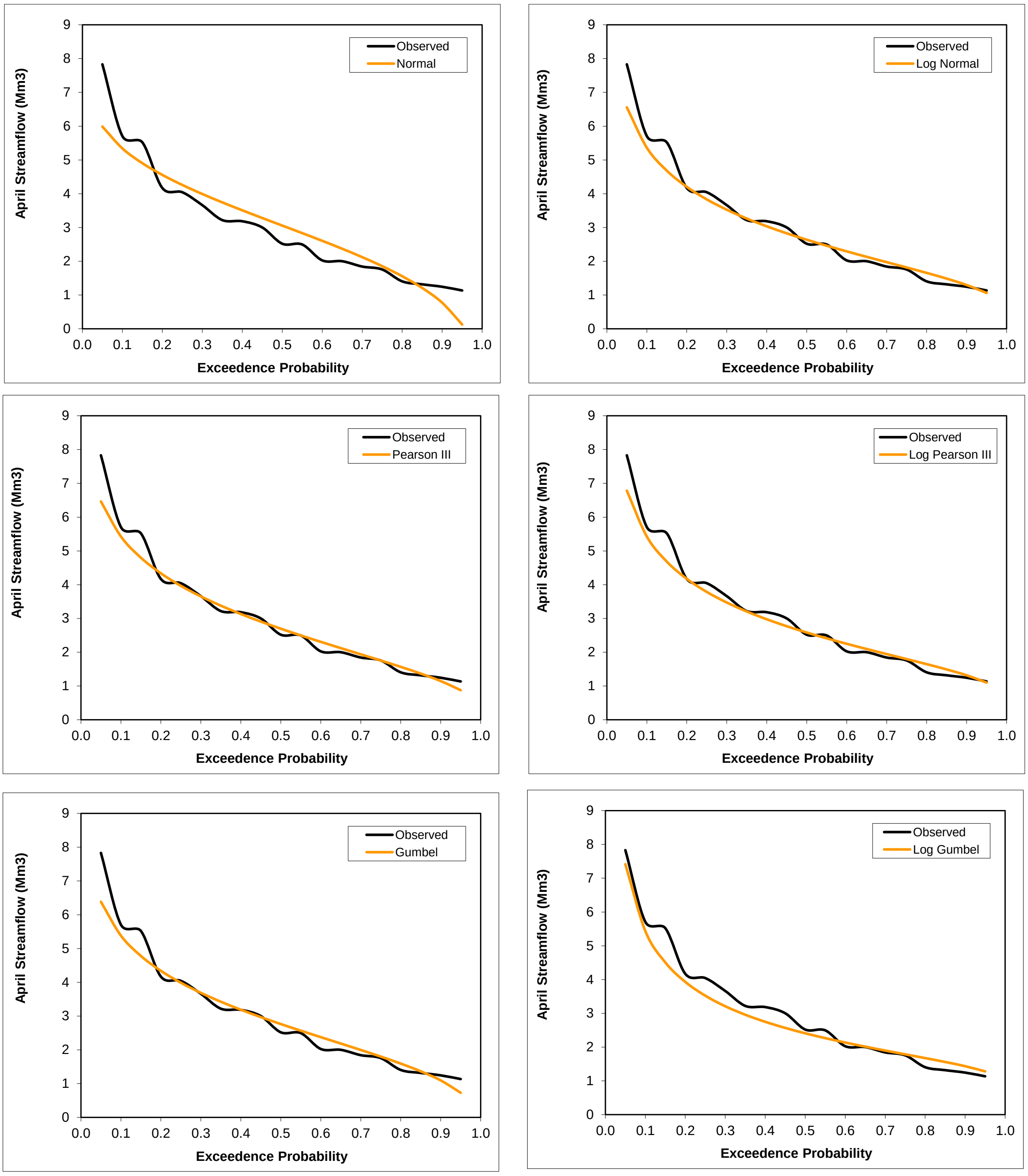

Figure 5: Flow duration curves for the months of April

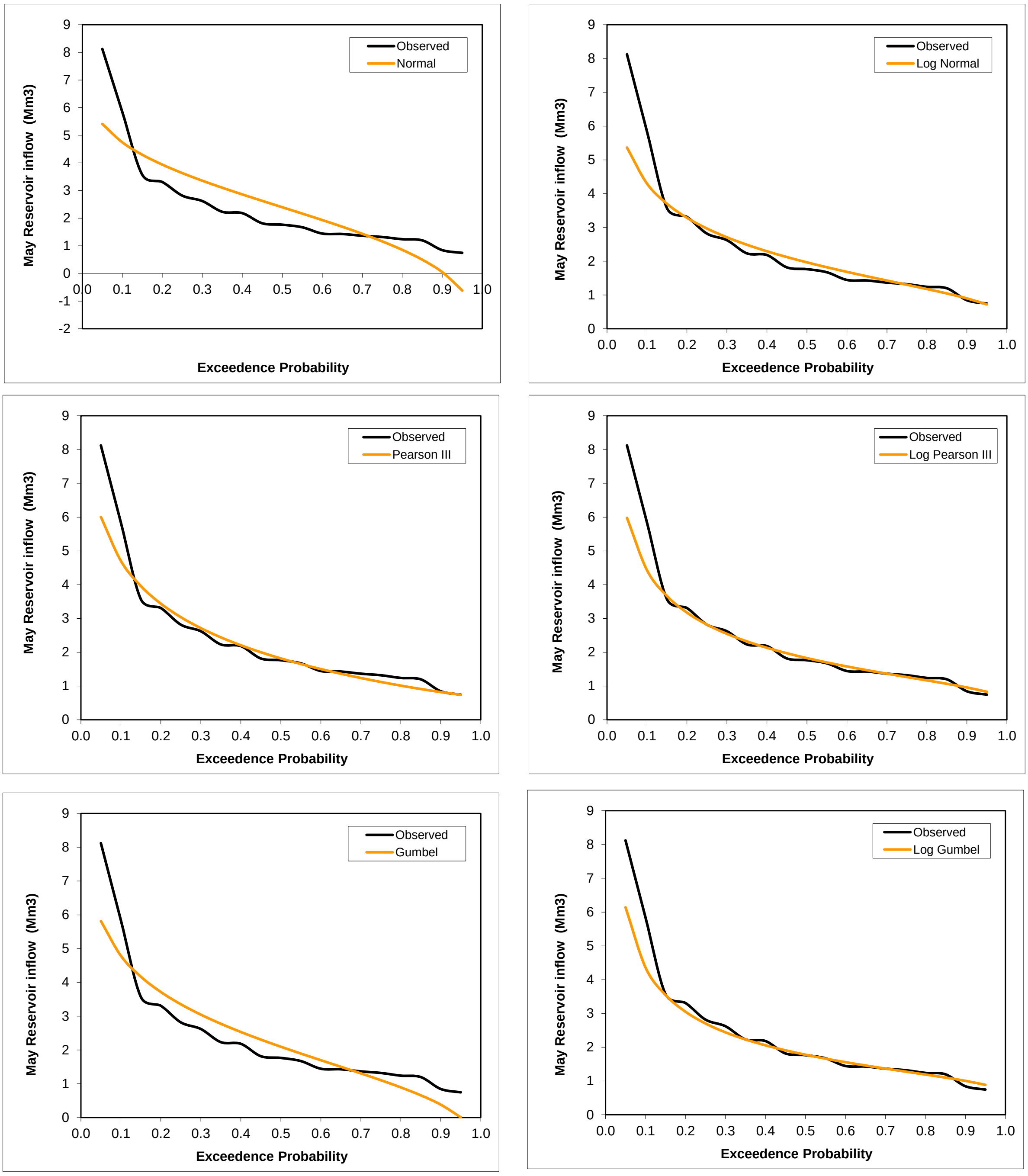

Figure 6: Flow duration curves for the months of May

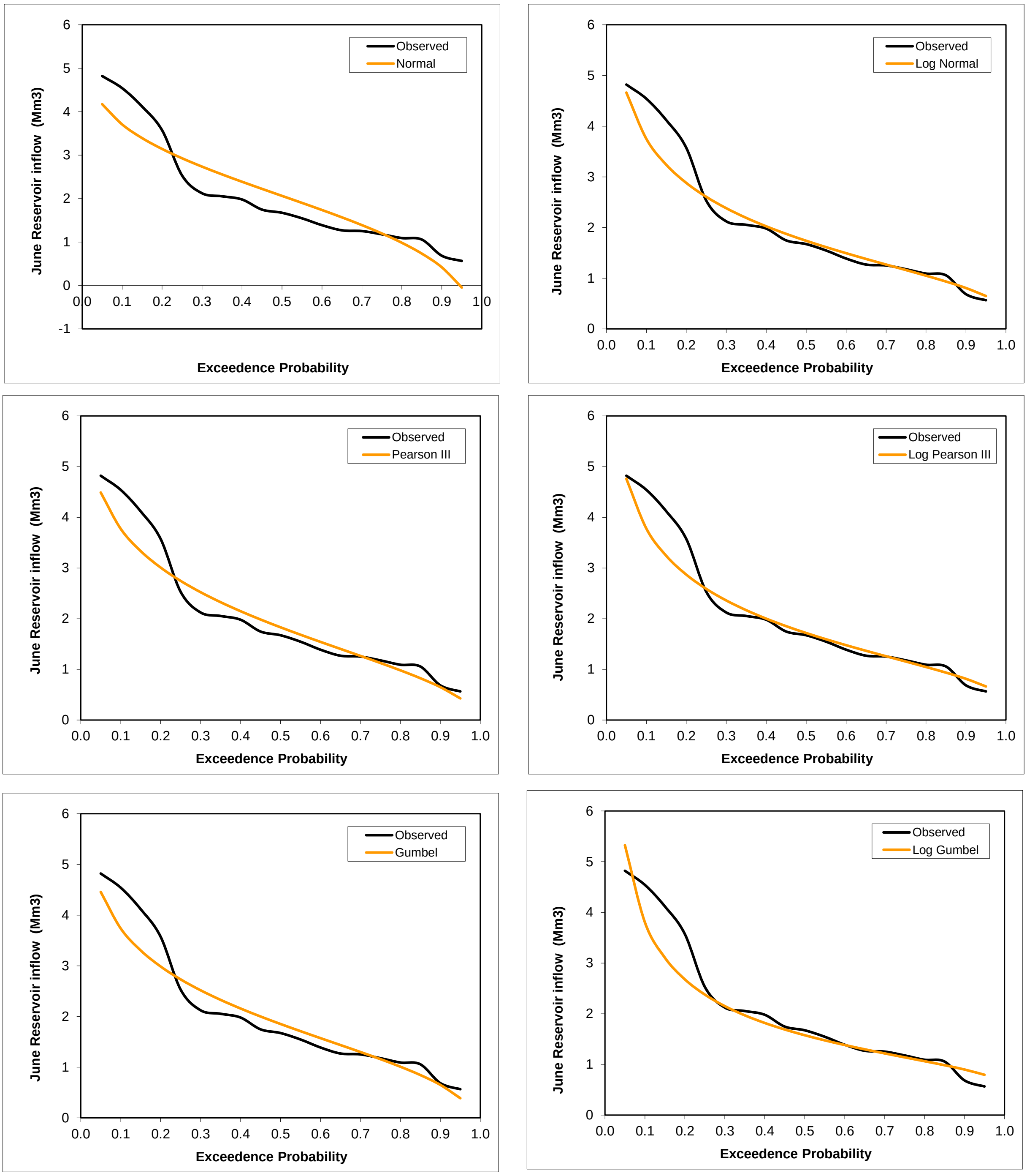

Figure 7: Flow duration curves for the months of June

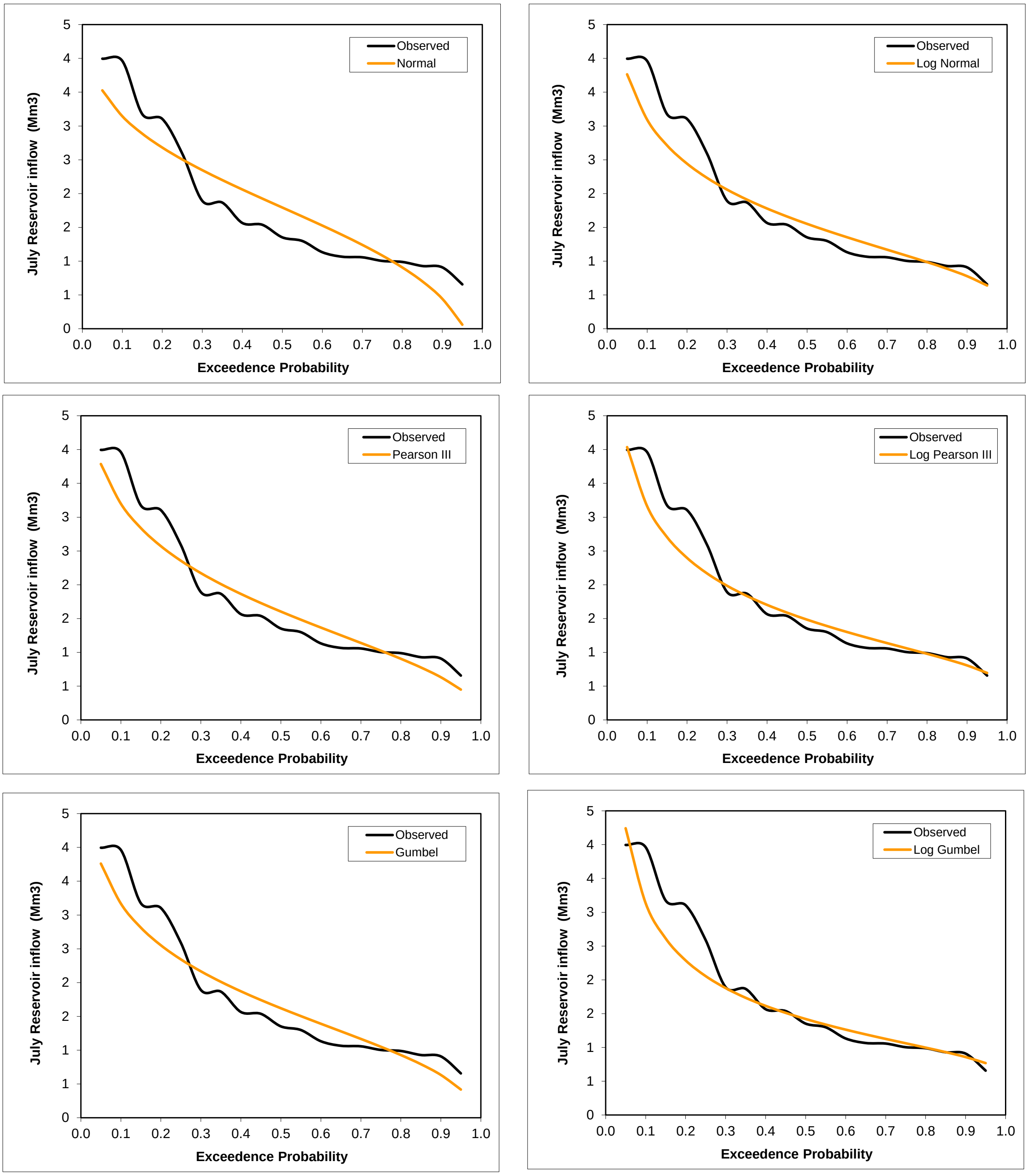

Figure 8: Flow duration curves for the months of July

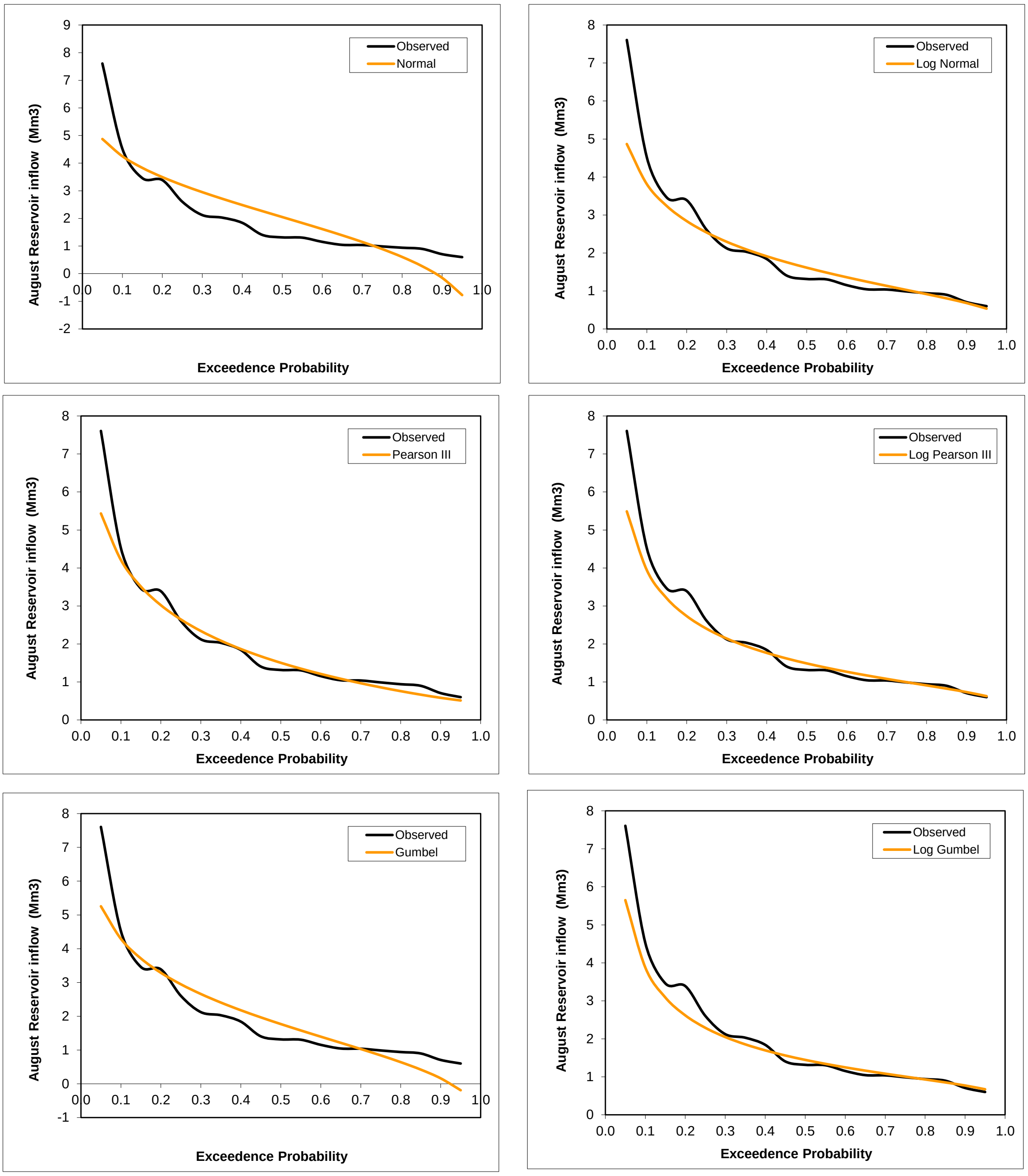

Figure 9: Flow duration curves for the months of August

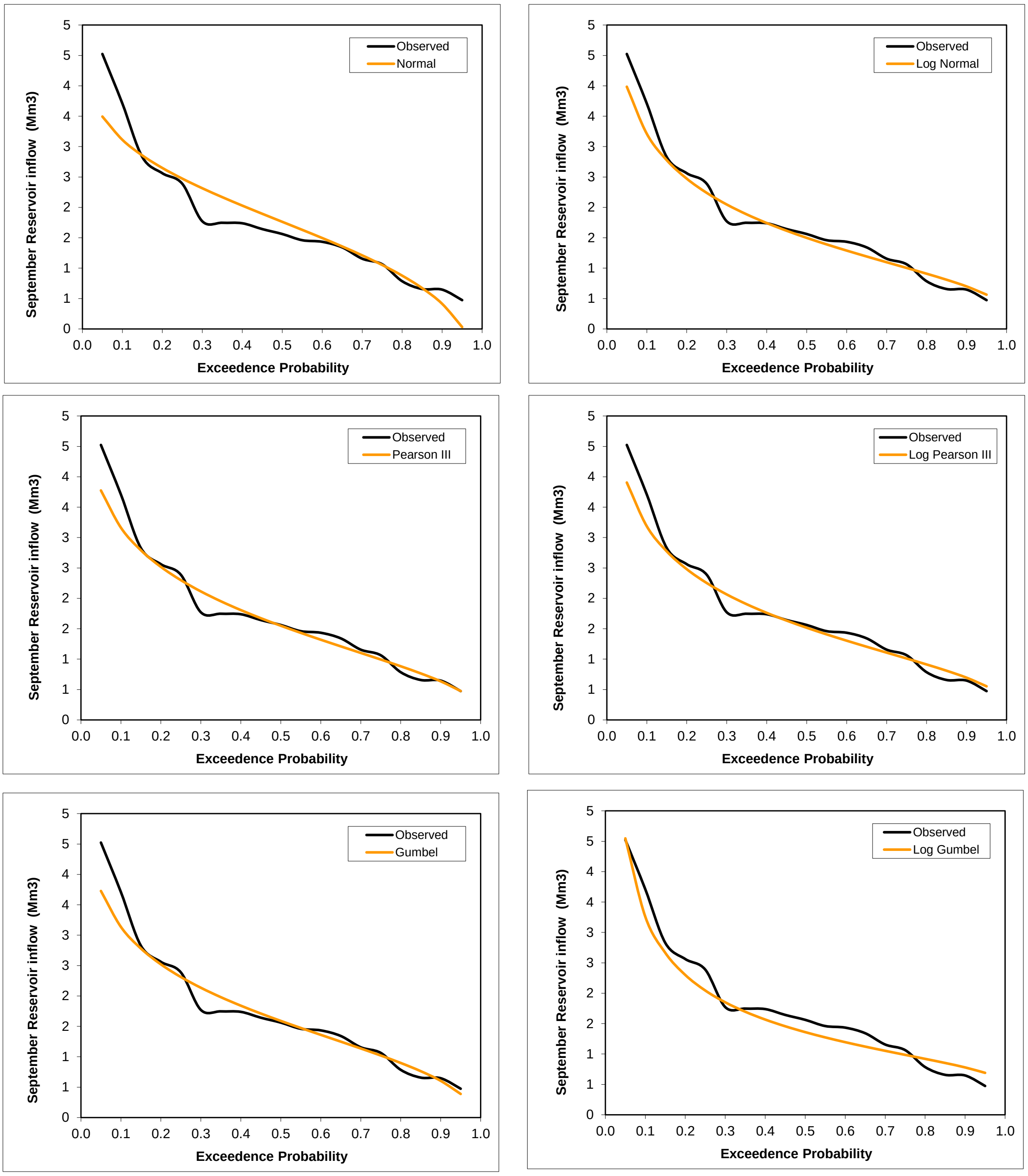

Figure 10: Flow duration curves for the months of September

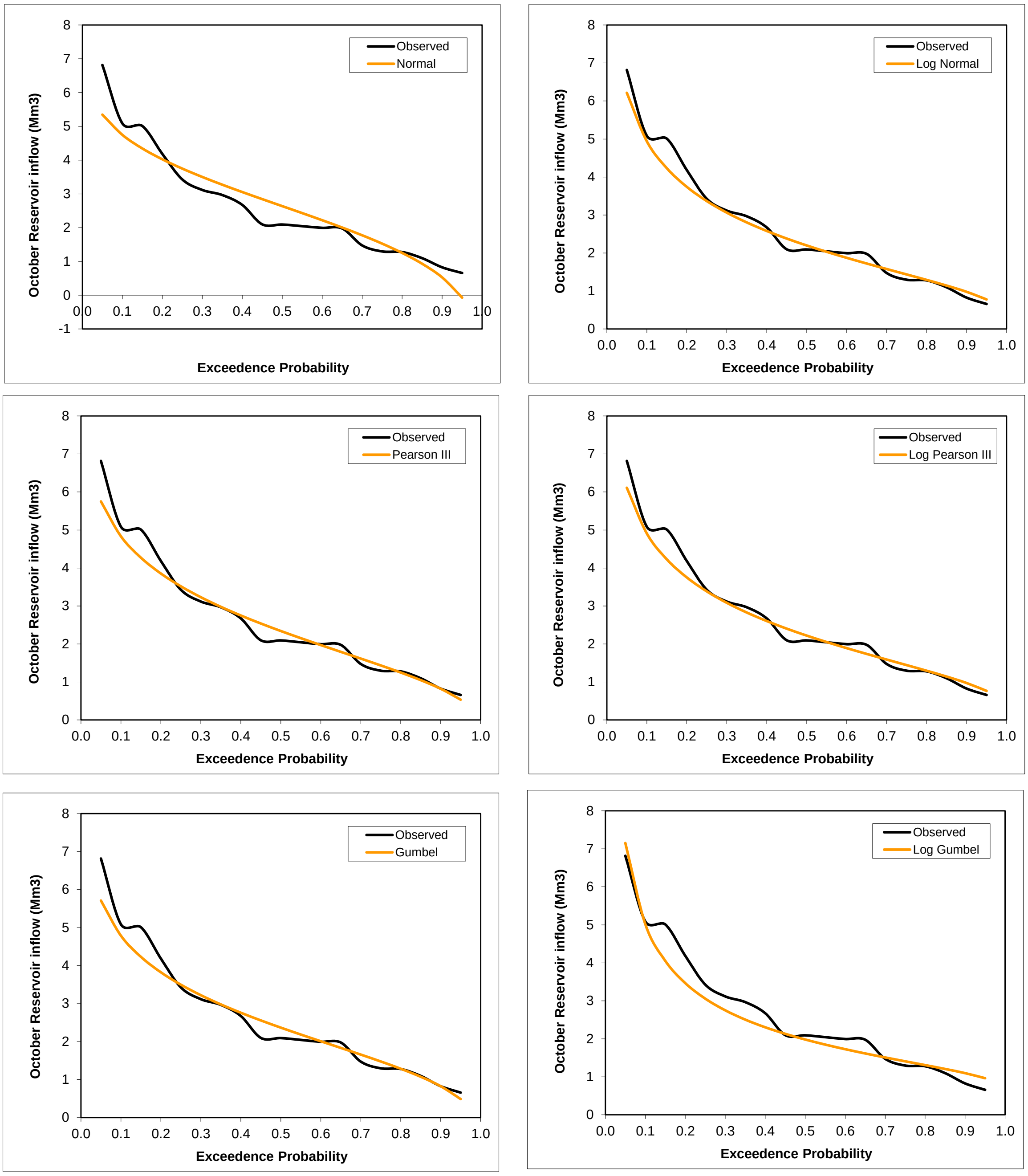

Figure 11: Flow duration curves for the months of October

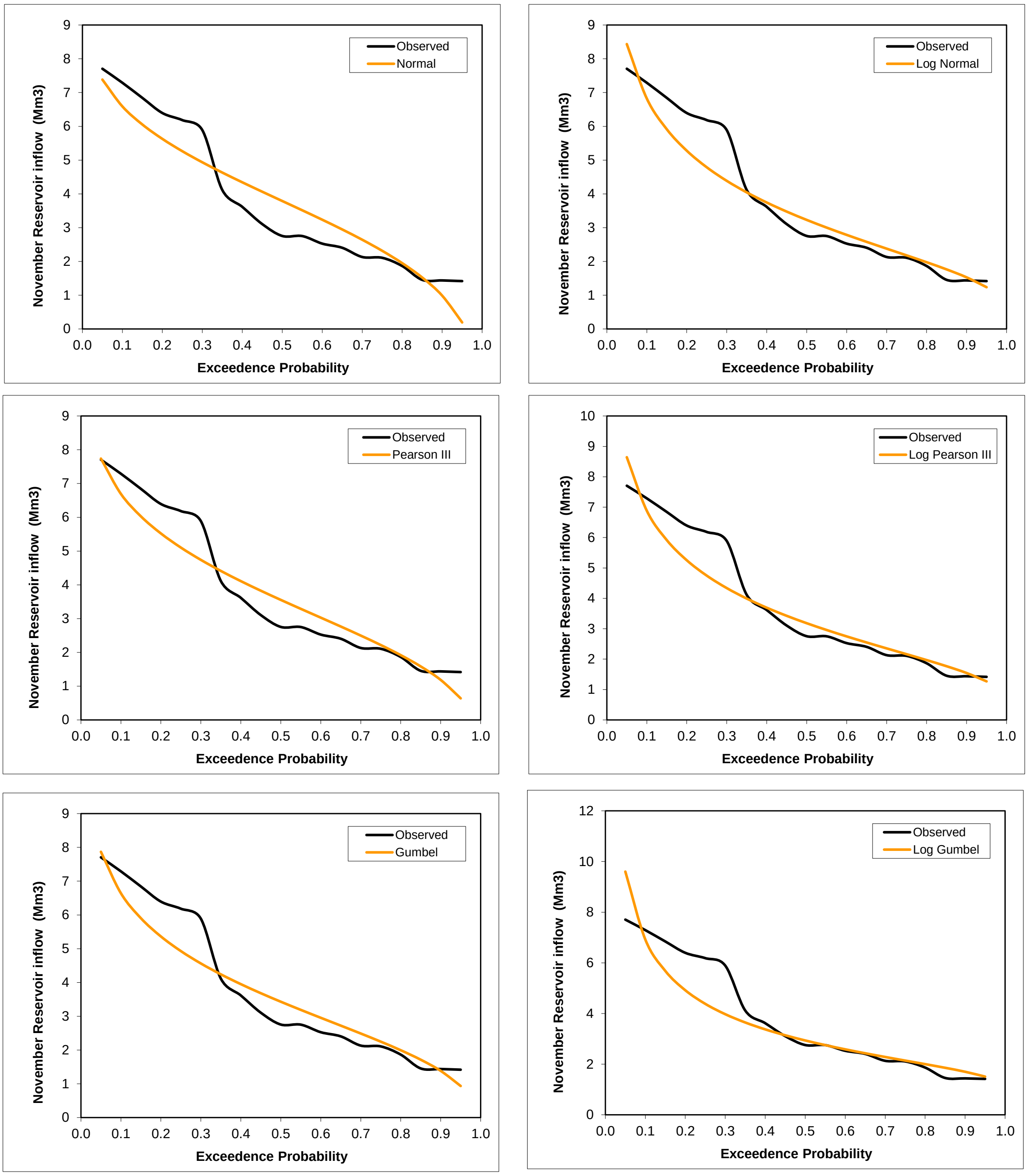

Figure 12: Flow duration curves for the months of November

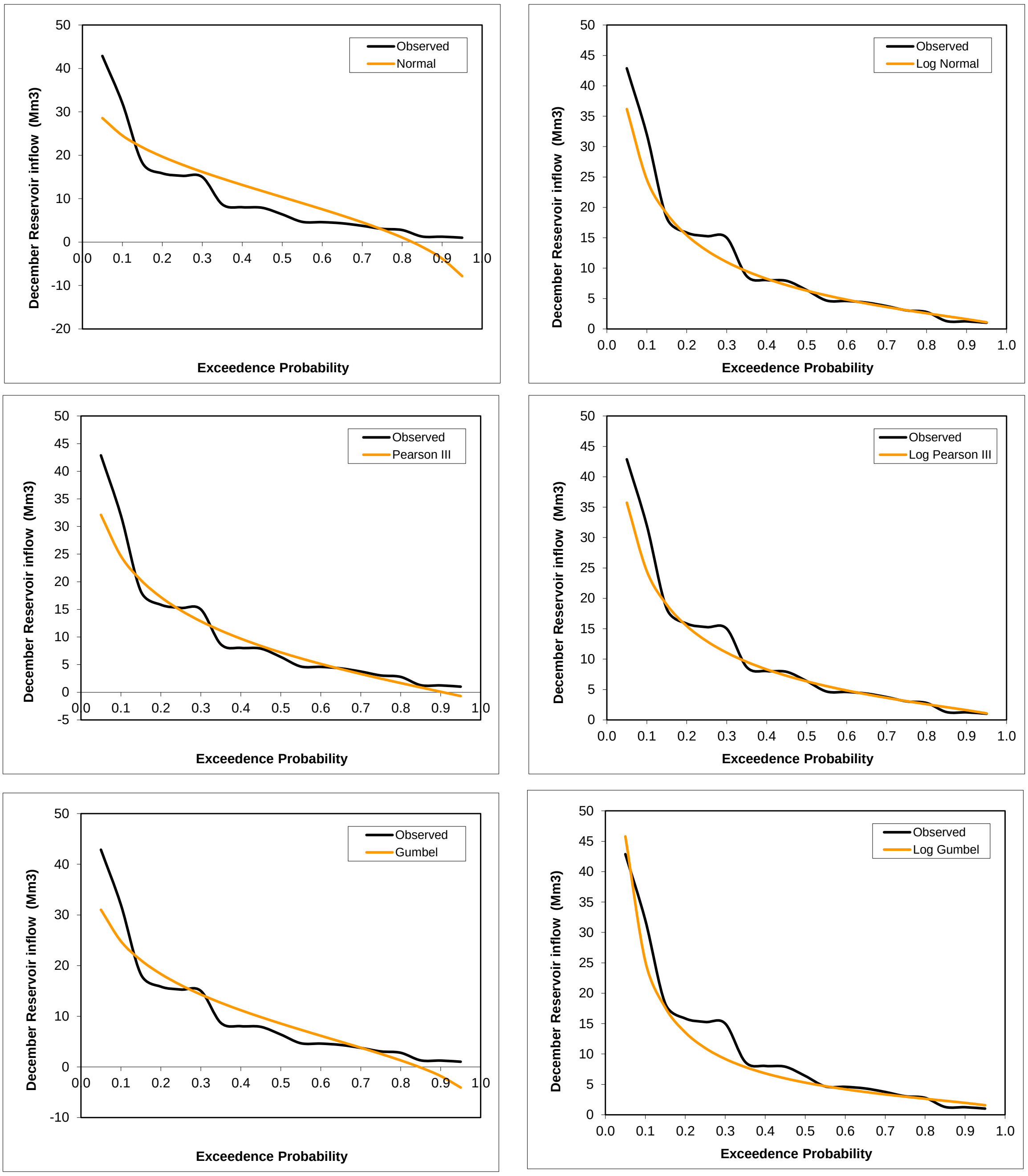

Figure 13: Flow duration curves for the months of December

4.3 DISCUSSION OF RESULTS

This section presents the discussion of the results from the estimation of monthly streamflow using probability distribution models. Parametric probability distribution models were fitted to the monthly streamflow series of Hazelmere Dam in South Africa. These models were fitted because the data was collected using finite number of parameters. According to the results of the MRD and MSRD statistical goodness of fit tests in Tables 3 and 4 respectively, Log-Pearson III distribution performed best (10 out of 12 months). This is consistent with the suggestions of Ehike and Reed (1999); Olofintoye and Adeyemo (2012a) that Log-Pearson III be generally adopted for analysing monthly streamflows. Also monthly streamflows are generally skewed (USDA. 2007), therefore Log-Pearson III which makes use of the skew coefficient in fitting is expected to perform excellently. The Log Gumbel model performed better than all the other probability distribution models (MRD= 26.47, MSRD= 1552.3) for the month of January. Log-Pearson III performed better than other probability models for the month of February (MRD=43.8, MSRD=3260.9). The Log-Pearson III distribution also performed best amongst the probability models in fitting to the streamflow of March (MRD= 36.67, MSRD= 8527). For the month of April, it was found that the Log-Pearson III distribution produced the best values of the test statistics than all other probability distribution functions (MRD = 51.43, MSRD= 19069.4). In May, the Log – Pearson III model produced the best values of the test statistics than all other models (MRD=23.19, MSRD= 4386.9).Likewise in the month of June, the Log – Pearson III model outperformed all other models (MRD= 66.7, MSRD= 37239.6). In the month of July, Log – Pearson III model performed better in fitting to the streamflow than all the other models (MRD= 19.5, MSRD= 4726.77).

For the month of August the Log – Pearson III model performed better than all the other models (MRD= 25.6, MSRD= 7663.76). In September, Log–Pearson III also out performed all other models (MRD= 39.8, MSRD= 12905.5). Results of the goodness-of-fit test statistics also shows that the Log – Pearson III model is the best fit model for the month of October (MRD=36.6, MSRD= 8677.8). The Log–Pearson III model also emerged as the best fit model for the streamflow of

November (MRD= 25.37, MSRD= 4597.45). Finally for the month of December, Log Gumbel model outperformed every other probability distribution models (MRD= 24.19, MSRD= 1158.18).

Log-Gumbel performed well in two cases (December and January). These two months corresponds to months with extreme rainfall (summer). Gumbel-distribution has been found excellent in fitting extreme events (University of Western Ontario 2011). Also, Log – Pearson III model performed well as the best fit model in ten months (February to November). This is the outcome of the goodness-of-fit test carried out on all the models by comparing the one with the lowest values of MRD and MSRD. From the six developed probability distribution models, it can be seen that Normal distribution performed poorly. Normal distribution assumes data is not skewed whereas this is not the case in the analysis of streamflow data (Olofintoye and Adeyemo 2012a). Therefore, the use of this distribution should be restricted in analysing streamflow for this dam.

Viessman, Lewis and Knapp (1989) noted that many hydrologic variables exhibit skewness partly due to the influence of natural phenomena. The computed monthly skew coefficients from the observed data (Table 2) revealed that the monthly streamflow estimate at Hazelmere Dam is positively skewed. Also, the 3-parameter Pearson an distributions, which take into cognizance the use of the skew coefficient in the estimation of future rainfalls, were found to exhibit very good fits as they produced lower values of MRD and MSRD than other models. In view of this, it can be said that the monthly streamflow estimation of Hazelmere Dam in South Africa can be predicted conveniently by using Log Gumbel and Log-Pearson III distributions.

In this study, the best fit developed models for each month exhibits good fit to the data. The Log Gumbel and Log – Pearson III models were chosen as the best-fit model as they produced the lowest values of MRD and MSRD (see Table 3 and 4; Figures 2 to 13). Also the problem of models deviating from the end of the distribution as noted by Jou *et al.* (2009c) was overcome.

4.4 HYDRO – METEOROLOGICAL RELATIONSHIPS

This section discusses the various relationships between the rainfall and meteorological data collected for the study area. Air temperature was analyzed based on the available 19 years (1994-2012) data from one station near Mount Edgecombe. The maximum average temperature occurrences fall to the month of February while the minimum average temperature occurrences were in the month of June. However, the variation between different months was not significant as is indicated by rather low values of their corresponding standard deviations (see Table 4). The precipitation data was analyzed from four stations in the UMdloti river watershed. The length of the recordings varied between the stations with maximum being 19 years (1994-2012). The analysis showed that the pattern and character of rainfall varied in different parts of the country due to geographical location and topography. The wet season is between September and January, the winter season runs from February to May while dry season usually occurs from June to September. The standard deviation of the rainfall data for each month was calculated based on all stations and it showed the variation between the stations was high during the wet season (142 mm in December) and low in dry season (3.5 mm in July).

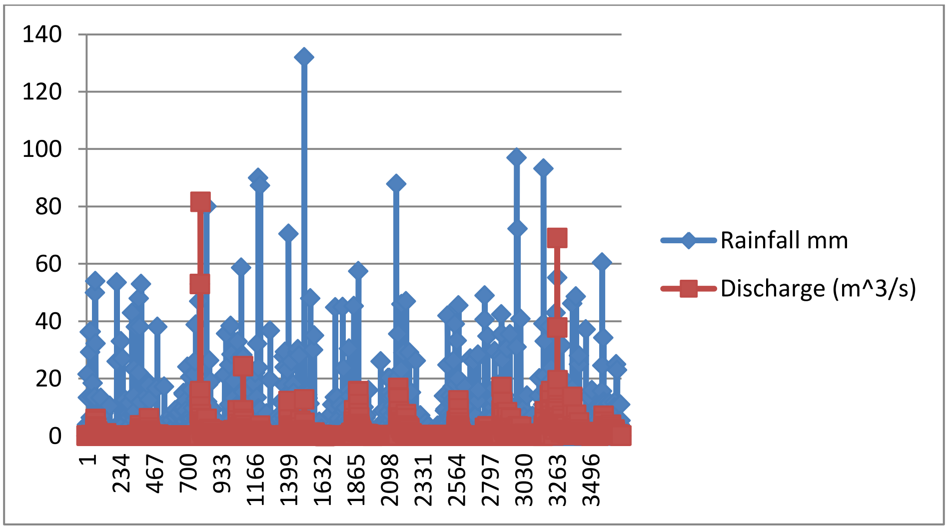

Figure 14:Graph showing maximum rainfall and discharge in the watershed

4.4.1 Flow regime of Hazelmere Dam

The flow regimes of Hazelmere Dam and UMdloti River was analysed using 19 years of observed stream flow data (1994-2012).The average annual depth of runoff in the watershed was estimated at 96 mm.The wettest year 2012 with 82 mm discharge k and driest with 0.3 mm discharge in the year 2012. The coefficient of variation on an annual basis is about 0.2 and the flow regime is characterized by elongated periods of medium to high flow and shorter intermingled periods to low flow.

From the frequency analysis, it was shown that the exceedance probability from the mean annual value is 138 mm, which shows that the mean is exceeded by 1.3%. The shape of the monthly duration curve which was almost flat towards the end of the graph suggests a good storage capacity potential in the watershed. The average monthly rainfall trend forms a mono-modal curve with a peak in November.

4.4.2 Spatial distribution of rainfall data

The major limitations of hydrological modelling to large areas are spatial variability associated with precipitation (Shamir, Georgakakos and Murphy Jr 2013). Four rainfall gauges were used in the study, the spatial distribution in relation to the watershed area could be considered to be inadequate. The hydrographs showed poor base flow recession time in comparison to the observed flow. This could be the combined result of their commonly being the steepest and dominated by relatively shallow soils in comparison with others.

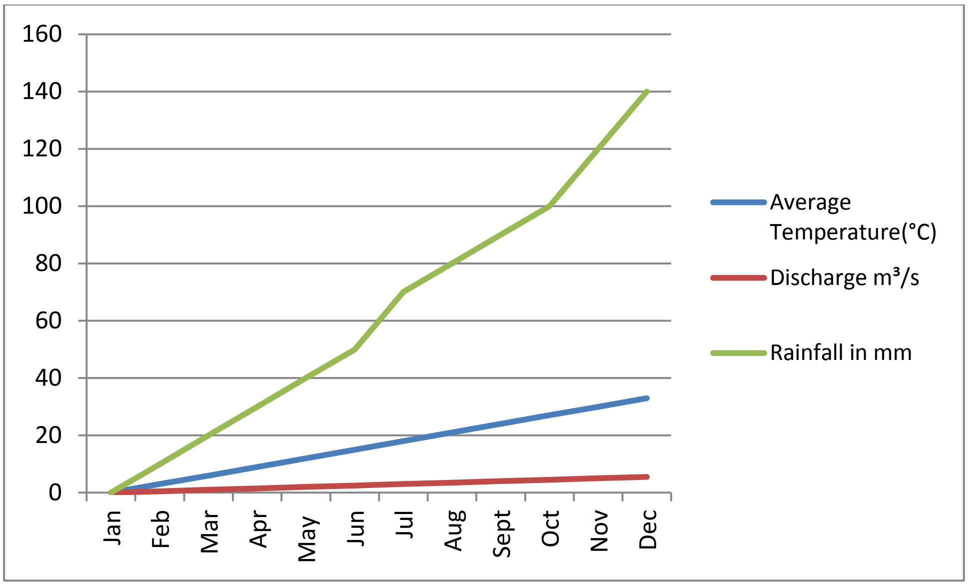

Figure 15: Graphical presentation of average month temperature (°C), rainfall (mm) and discharge (mm)

The exceedance probability of the rainfall data starts from 0.5 mm to 0.95 mm for the 19 year period (1994 to 2012).The observed rainfall data from December to March has a maximum value of 42.88 mm because this is the wettest season of the year.

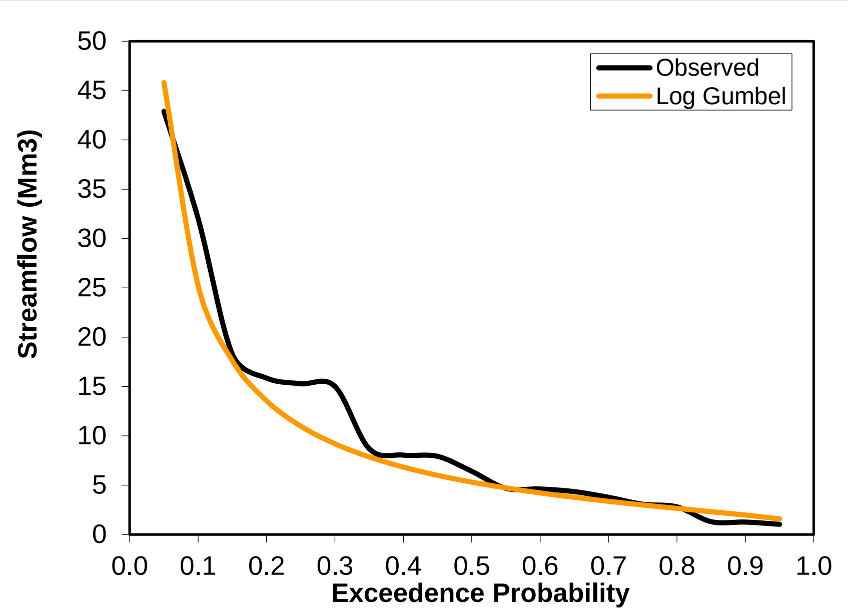

Figure 16: Log Gumbel model (best fit model) for December showing the increase of stream flow in UMdloti River watershed due to rain

The months of April to November has a maximum rainfall data of 7.7060 mm because it is slightly wet. Also, June to July has a maximum rainfall value of 4.8210 mm, which symbolises a dry season. According to the flow duration curves of each month (Figures 2 to 13), the inflow of water into Hazelmere Dam is high at the beginning of the curve, and at the end of the curve, the observed data and the models link together. This shows a good potential storage in the dam. From Figure 16 above, it can be seen that there is a high inflow of water into the Hazelmere Dam during the months of December.

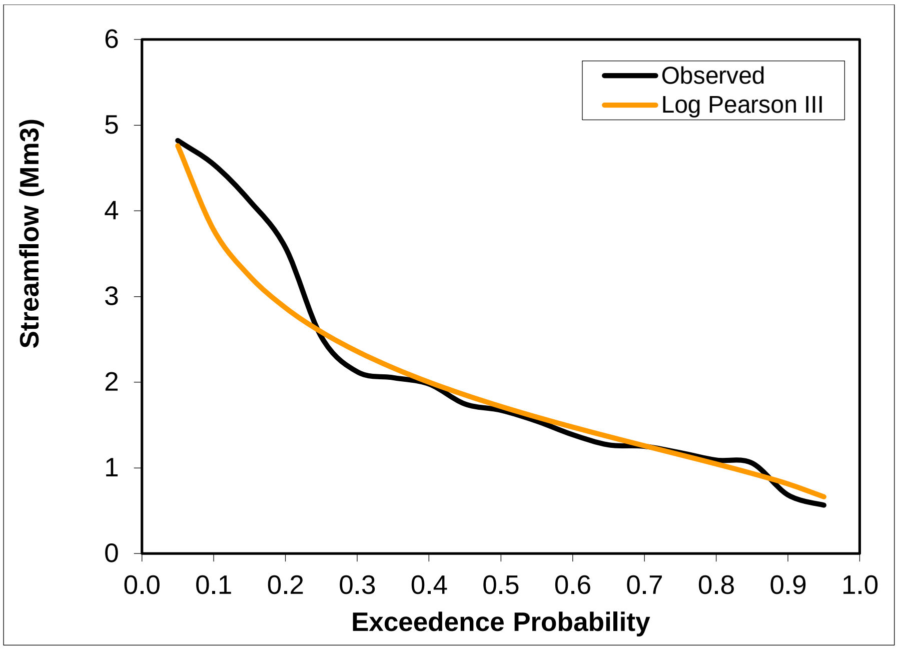

Figure 17: Log – Pearson III model (best fit model) for the month of June showing the decrease of stream flow in UMdloti River watershed

4.4.3 Relationship between Rainfall and Streamflow in Hazelmere Dam

The analysis of the streamflow measurement versus exceedance probability was presented on monthly basis (January to December) in Figures 2 to 13. In South Africa, from the months of December to February, the summer season is experienced. Summer is characterised by a very high average rainfall volume. Since this is a season of heavy rainfall, it is imperative to consider the effect of climate on water resources sustainability within UMdloti river catchment.

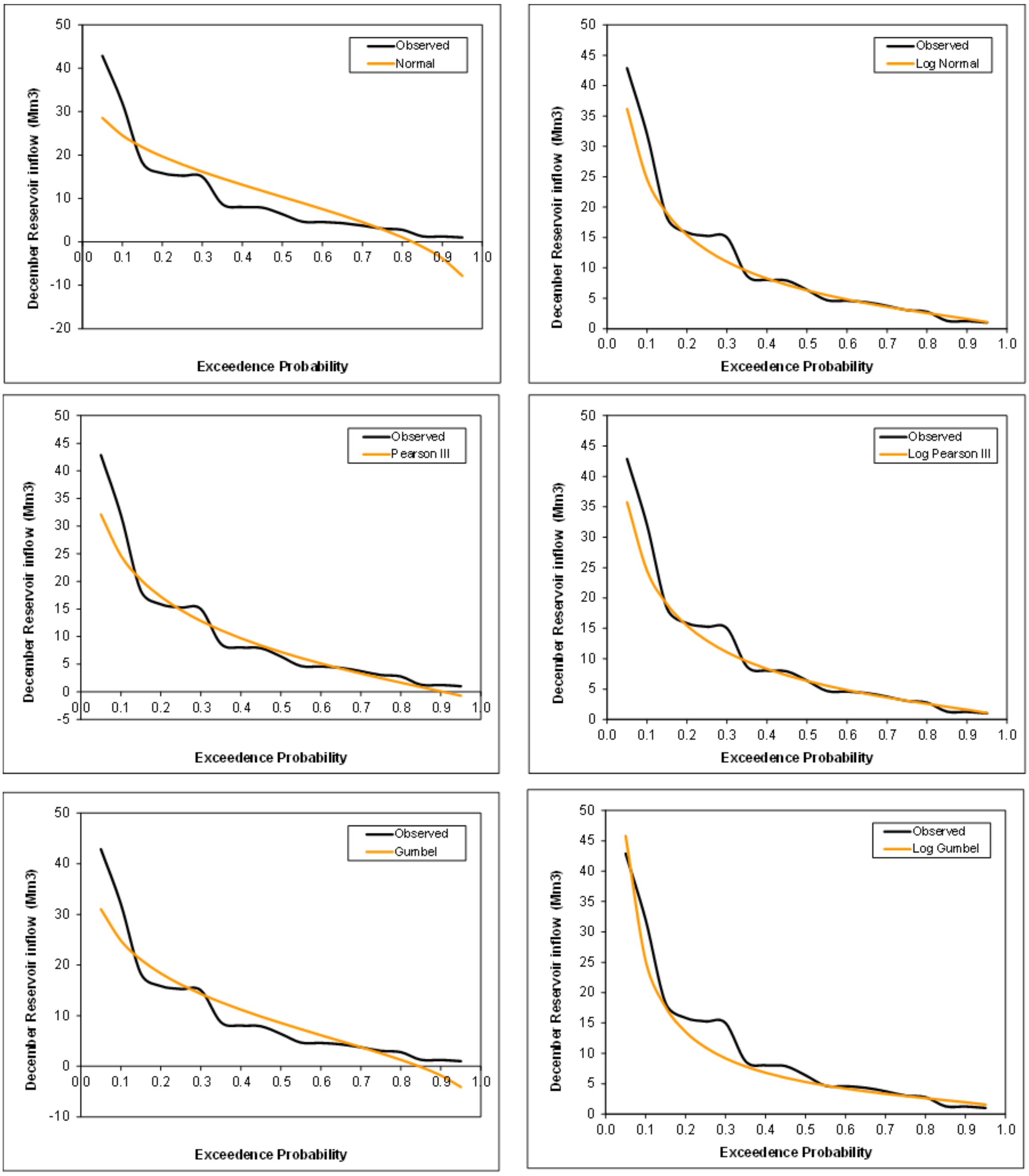

Figure 18: Flow duration curve for the month of December

4.4.3.1 Summer Analysis Results

The exceeded probability is from 0.0500 to 0.09500, while the observed rainfall data is 42.8780 in December 1995 .The Log – Gumbel model gives 45.7968mm in the same month and Gumbel model gave the lowest value of 1.5746mm.All the

Log models gave very high values in December when compared with the Normal models. This is due to heavy rainfall events which characterised the summer season (Figure 18).

Table 6: Statistical analysis of the month of December

STATISTICS	***O***	**X=Log (*O*)**
AVERAGE	10.37	0.80
STD. DEVIATION	11.06	0.46
SKEW	1.89	-0.04
MEDIAN	6.39	0.81
VARIANCE	122.41	0.21
Length of Data	(N)	**19**

The statistics on the Table 6 has a calculated median of 6.39 on the Normal and 0.81 on the Log Normal. The statistics on the table shows a negative skew value of -0.04 in the month of December because is a wet season.

From Figure 19, the exceeded probability is from 0.0500 to 0.09500. The observed rainfall maximum value is 33.4160mm in January 2012 .The Log Gumbel model gives 49.9124mm in the same month while Gumbel model gave the lowest value of -2.6109. All the Log models were very high in January due to heavy rain in summer season compared to Normal models.

Table 7: Statistical analysis of the month of January

STATISTICS	***O***	**X=Log (*O*)**
AVERAGE	11.26	0.85
STD. DEVIATION	10.63	0.45
SKEW	1.17	-0.20
MEDIAN	7.04	0.85
VARIANCE	112.90	0.21
Length of Data	(N)	**19**

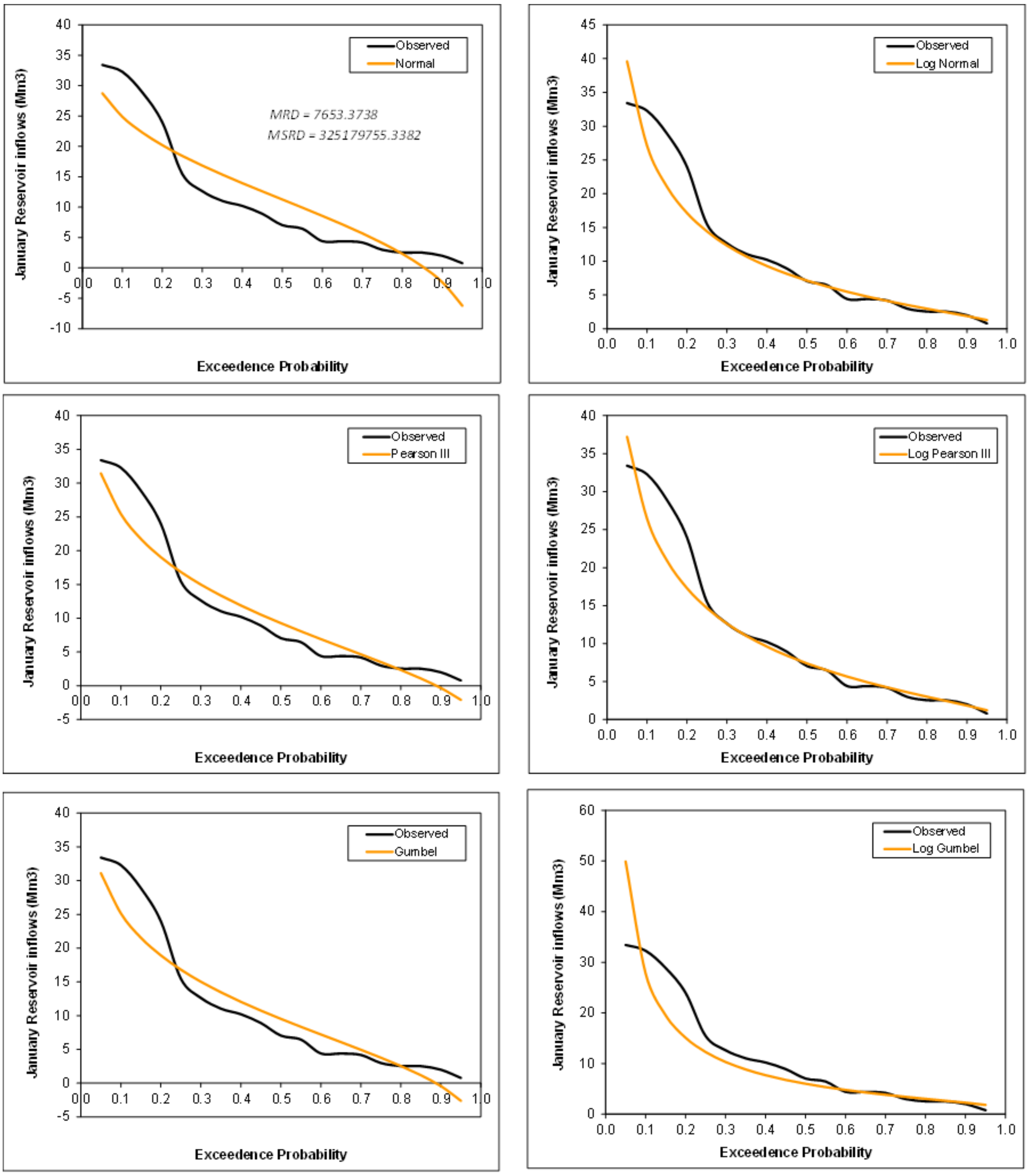

Figure 19: Flow duration curve for the month of January

The statistics on the Table 7 has a calculated median of 7.04 on the Normal and 0.85 on the Log Normal. The statistics on the table shows that the curve is skewed by -0.20 in the month of January because is a wet season summer.

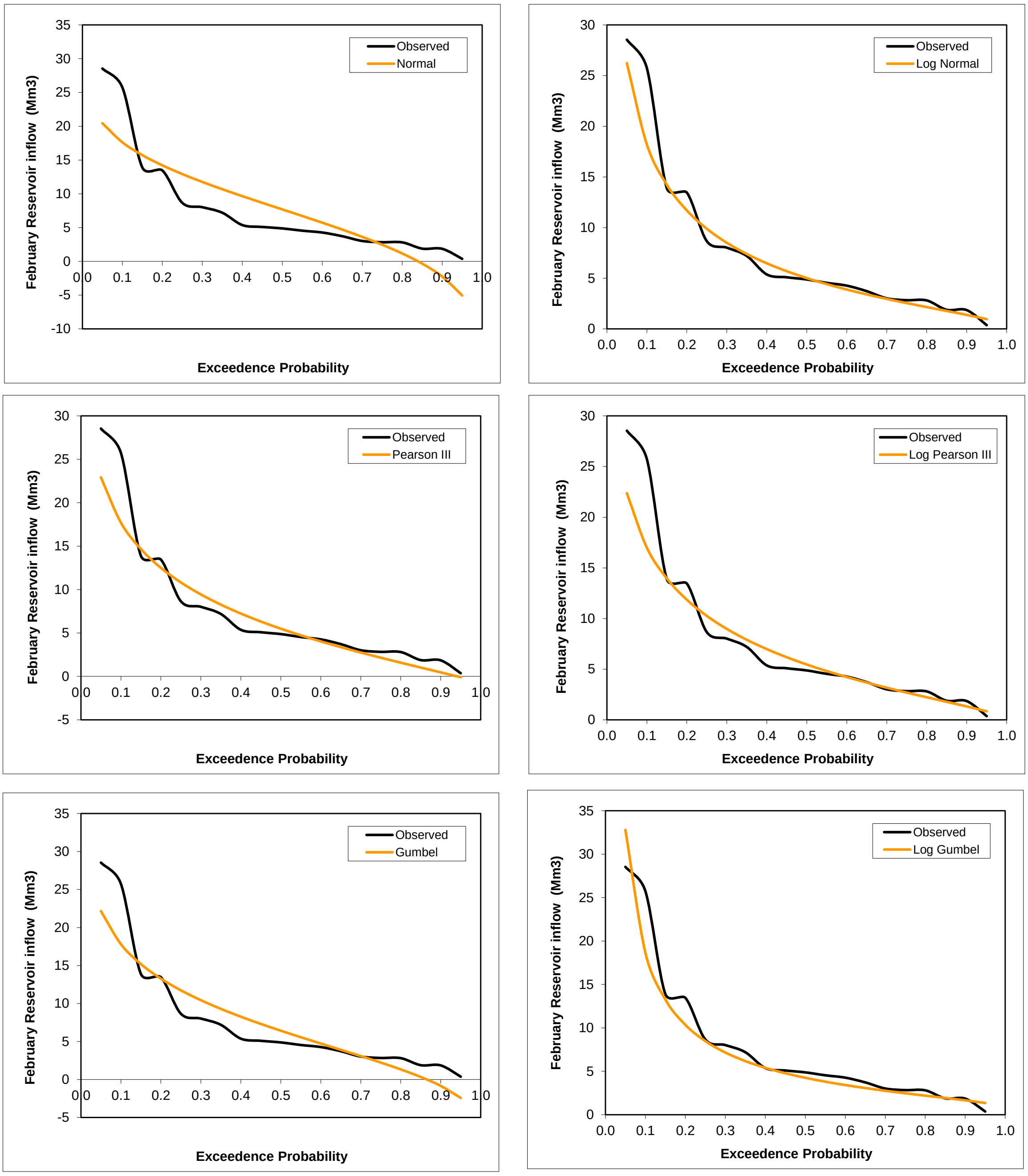

Figure 20: Flow duration curve for the month of February

The exceeded probability is from 0.0500 to 0.09500.The observed maximum rainfall value is 28.5450 in February. The Log Gumbel gave a value of 32.7896 in the same month and Gumbel gave the lowest value of -5.0625. All the Log models were very high in February due to heavy rain in summer compared to Normal models.

Table 8: Statistical analysis of the month of February

STATISTICS	***O***	**X=Log (*O*)**
AVERAGE	7.69	0.70
STD. DEVIATION	7.75	0.44
SKEW	1.88	-0.51
MEDIAN	4.88	0.69
VARIANCE	60.10	0.19
Length of Data	(N)	**19**

The statistics on the Table 8 has a calculated median of 4.88 on the Normal and 0.69 on the Log Normal. The statistic on the table shows the flow curve is skewed by-0.51 in the month of February because in South Africa it is approaching autumn season which is a little dry.

4.4.3.2 Winter Analysis Results

The winter season in South Africa spans between the months of June and August. This season is characterized as dry and lot of wind occurs. According to the analysis of the results during the months of the winter season, the flow duration curves below shows that the UMdloti River discharges less water to the downstream. The downstream water is needed to sustain the dam and other users. This section hereby analyses the results of the months of June, July and August. The results of the analysis are given below with adequate discussions.

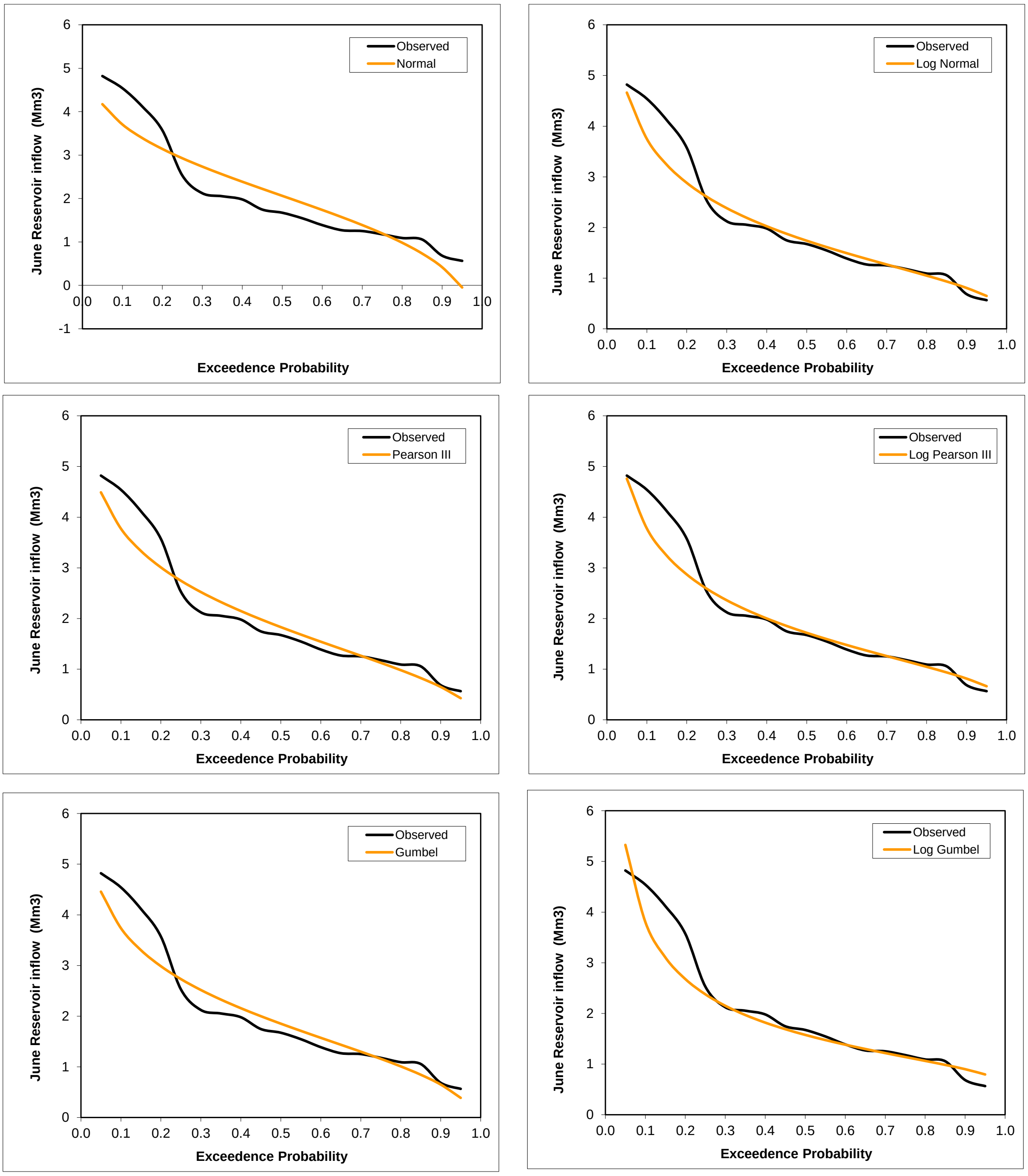

Figure 21: Flow duration curve for the month of June

The exceeded probability is from 0.0500 to 0.09500. Also, the observed maximum rainfall value 4.8210mm in June 2012 .The Log Gumbel model gave the highest value of 5.3262 in the same month while Gumbel model gave the lowest value of-0.0482. All inflows in June were low because of dry seasons compared.

Table 9: Statistical analysis of the month of June

STATISTICS	***O***	**X=Log (*O*)**
AVERAGE	2.06	0.24
STD. DEVIATION	1.28	0.26
SKEW	1.13	0.12
MEDIAN	1.67	0.22
VARIANCE	1.65	0.07
Length of Data	(N)	**19**

The statistics on the Table 9 has a calculated median of 1.67 on the Normal and 0.22 on the Log Normal. The statistics on the table shows that the flow curve is skewed by 1.13 in the month of June because it is a dry season.

The exceeded probability is from 0.0500 to 0.09500. The observed maximum rainfall value is 3.9960 mm in July 2002 .The Log Gumbel model gives a value of 4.2428 mm in the same month while Gumbel model produced the lowest value of 0.0596 mm. All the Log models were low in July due to dry season compared to summer seasons and Normal models.

Table 10: Statistical analysis of the month of July

STATISTICS	***O***	**X=Log (*O*)**
AVERAGE	1.79	0.19
STD. DEVIATION	1.05	0.23
SKEW	1.12	0.50
MEDIAN	1.35	0.13
VARIANCE	1.11	0.05
Length of Data	(N)	**19**

The statistics on the Table 10 has a calculated median of 1.35 on the Normal and 0.13 on the Log Normal. The statistics on the table shows that the flow curve is skewed by 1.35 in the month of July because it is a dry season winter.

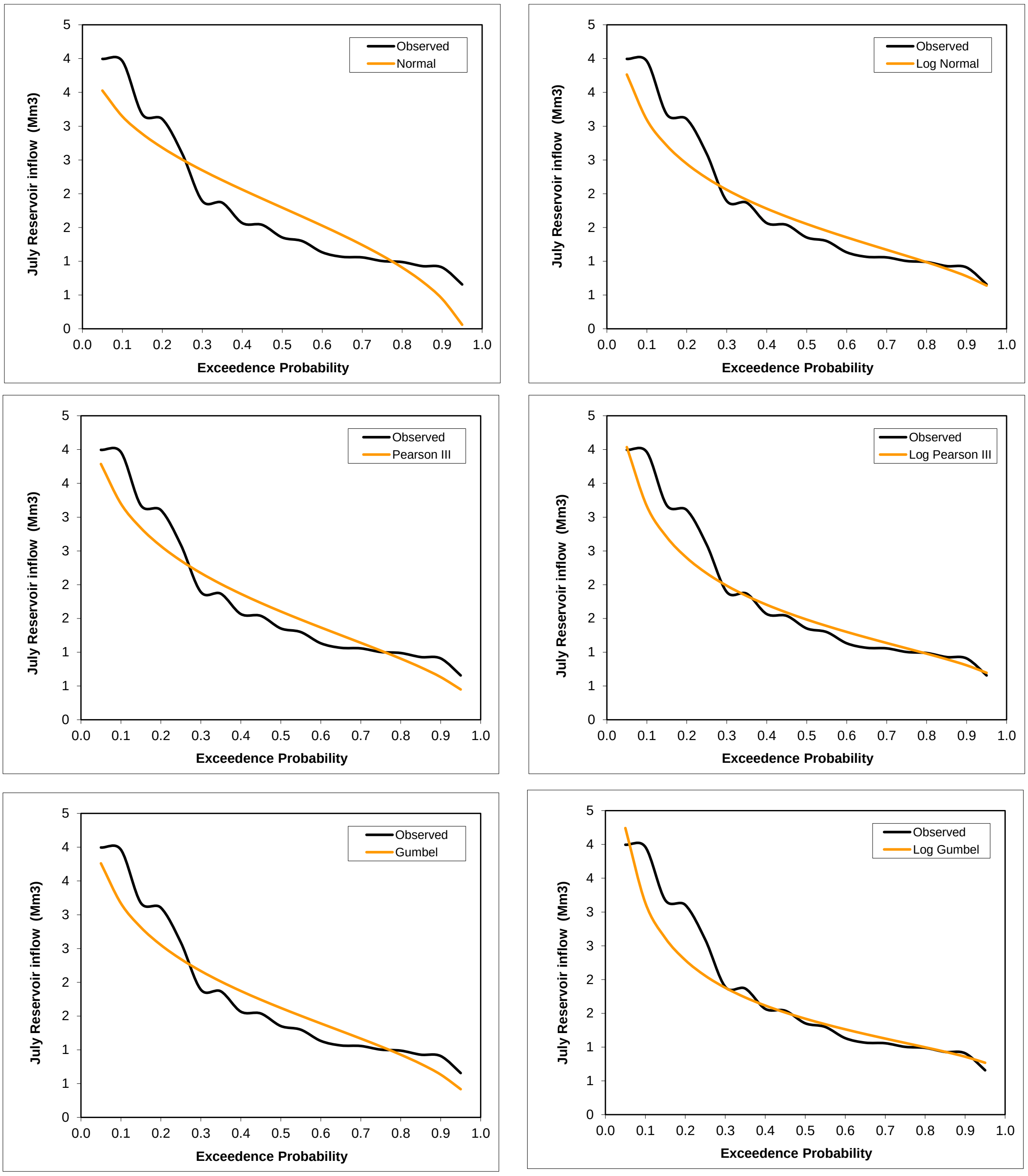

Figure 22: Flow duration curve for the month of July

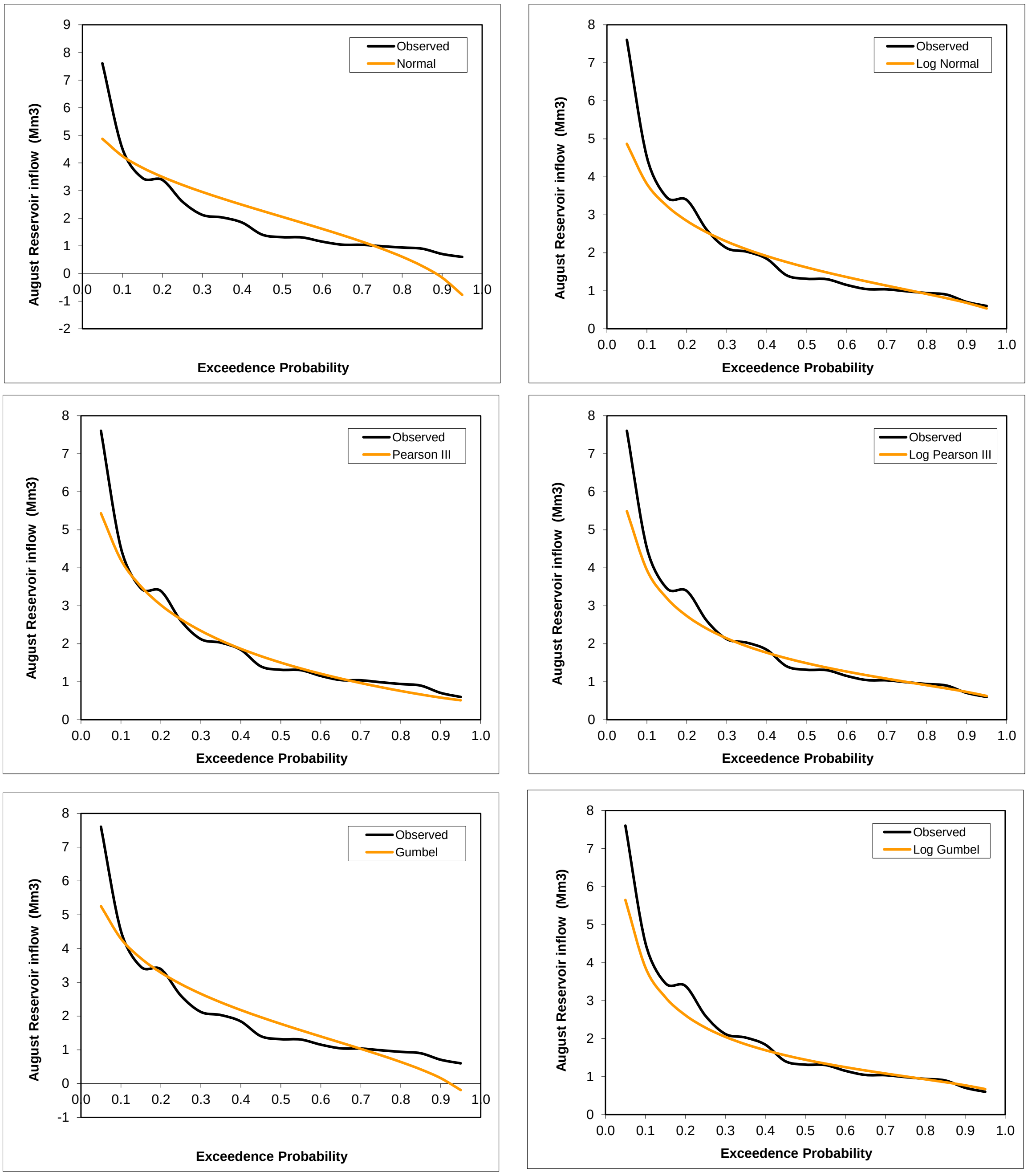

Figure 23: Flow duration curve for the month of August

The exceeded probability is from 0.0500 to 0.09500. The maximum observed rainfall value is 7.6070 Mm³ in August. The Log Gumbel model gave a value of 5.6497 Mm³ in the same month while Gumbel model produced the lowest value of 0.1915Mm³. Log normal,log Pearsons and log Gumbel models were low in August due to dry season compared to summer seasons and Normal models.

Table 11: Statistical analysis of the month of August

STATISTICS	***O***	**X=Log (*O*)**
AVERAGE	2.05	0.21
STD. DEVIATION	1.72	0.29
SKEW	2.19	0.74
MEDIAN	1.32	0.12
VARIANCE	2.95	0.09
Length of Data	(N)	**19**

The statistics on Table 11 has a calculated median of 1.32 on the Normal, and 0.12 on the Log Normal. The statistics on the table shows that the flow curve is skewed by 2.19 in the month of June because it is a dry season winter.

CHAPTER 5

MAXIMIZATION OF HYDROPOWER GENERATION FROM HAZELMERE DAM IN SOUTH AFRICA

5.1 OVERVIEW

Harnessing more energy from existing water sources within the frontier of the country is germane in capacitating the South African Government's commitment to reduction of the country's greenhouse gas emissions and transition to a low-carbon economy while meeting a national target of 3 725 megawatts by 2030. This study aims to determine the amount of energy that can be generated from Hazelmere Dam on the uMdloti River, South Africa. Behavioural analyses of the Hazelmere reservoir were performed using plausible scenarios. Feasible alternative reservoir operation models were formulated and investigated to determine the best operating policy and power system configuration. The optimization models were formulated to maximize hydropower generation while keeping within the limits of existing irrigation demands. Differential evolution algorithm was employed to search feasible solution space for the best policy. Findings suggest that if the water resource in the dam is properly managed, about 558.54 MWH of annual energy may be generated from the reservoir under medium flow condition without system failure.

5.2 INTRODUCTION

The importance of the power sector in the development of a nation cannot be overemphasized. This sector is strategic in forging economic growth and infrastructural development. This calls for the development of improved strategies for generation, distribution and proper management of power in all countries of the world (Loucks and Bee 2005; Salami 2007). Hydropower is a renewable form of electrical energy generated from the free fall of water from a high elevation to a relatively lower elevation. Hydropower production involves the conversion of potential energy of stored water into electrical energy through combinations of hydraulic turbines and electric generators (Ajenifuja 2009; SIDALA 2010). Some benefits of hydropower include quick response to changing utility loads, relatively low operating costs and a low environmental pollution factor (Salami 2007). According to (Ajenifuja 2009), greenhouse gas (GHG) emission factors for hydropower plants have been found to be 30 to 60 times lesser than factors for fossil fuel generation in some instances. Presently, hydropower accounts for roughly 85 percent of renewable energy in the European Union and approximately 20 percent of global electricity. Development of half of the world's economically feasible hydropower potential could reduce GHG emissions up to 13 percent and global carbon dioxide pollution by up to 7 billion tons a year (Ajenifuja 2009). Therefore, harnessing more hydropower from existing water sources is germane in minimizing GHG emissions and mitigating the undesirable effects of global climate change.

Recent results from expert analysis has shown that South Africa has moderate hydroelectric potential and establishing a number of small hydroelectric power plants around the country may help provide sustainable supply of energy in the future (SIDALA 2010). Consequently, the South African government is in the process of authorizing independent power producer licenses. This aims to diversify the country's energy mix by bringing in renewable energy technologies especially small hydropower plants (<10MW) to retrofit and contribute to a national target of 10 000 GWh of energy by 2013 (SIDALA 2010). This study investigates the potential of Hazelmere Dam for generating electricity. The aim was to determine the amounts of monthly and total annual energy that can be generated from the reservoir based on turbines of various efficiencies for a plausible system configuration under medium a flow condition without system failure. The method adopted involved formulating optimization models to maximize hydropower generation while keeping within the limits of existing irrigation and domestic water demands. Estimating the amount of electrical energy that can be generated from the Hazelmere reservoir is relevant in capacitating the South African Government's commitment towards equity and poverty eradication. It is also germane to reducing the country's GHG emissions and transition to a low-carbon economy by 2030 (SIDALA 2010; DOE 2014).

5.3 METHODOLOGY

This study determines the amounts of monthly and total annual energy that can be generated from Hazelmere reservoir based on turbines efficiencies of 75%, 85% and 90%. Optimization models were formulated to maximize hydropower generation within the constraints of existing abstractions, hydrological and system constraints. Differential evolution (DE) optimization method was adopted to resolve the optimization models. The methodology was applied for an operating season.

5.3.1 Study area

The study area is Hazelmere Reservoir on UMdloti River in South Africa. The Dam is a combined concrete gravity type dam and it resides in KwaZulu Natal province of South Africa on latitude 29°36'1'' S and longitude 31°2'30'' E. It was established in 1977 primarily to serve for irrigation and domestic use. The reservoir has a capacity of about 17.858 million m^3 at an elevation of 85.98 mASL and a surface area approximately 1.81square kilometres when full. The minimum reservoir elevation is 61.00 mASL which corresponds to a storage volume of zero Mm^3. Total catchment area contributing to flow in the reservoir is 377 km^2. Mean annual precipitation is 967 mm, mean annual runoff is 70.7 million m^3 while annual net evaporation is 1 200 mm. The main water use activities in the catchment are irrigation, dryland sugar cane, domestic use, commerce and industry. Figure 1 presents the general layout of the dam.

Figure 24: Hazelmere Dam, South Africa. (Source: Adapted from http://www.fishtec.co.za, 2015)

5.3.2 Proposed System configuration

An axial flow vertical Kaplan turbine with discharge of 40 m^3/s and a minimum operating head of 10m was adopted as suggested by (SIDALA 2010). This type of turbine is useful in dams with low heads. The powerhouse is located at ground level with the turbines located at the minimum reservoir level (61 mASL). The penstock inlet is set at 71 mASL and specifies the minimum operating level for hydropower generation. This corresponds to reservoir storage of 7.15 Mm^3. The maximum reservoir volume (17.858 Mm^3), which corresponds to a reservoir elevation of 85.98 mASL, defines the maximum operating level. The power plant installed capacity is assumed to be 10 MW while the turbine efficiencies are varied between 75, 85 and 90 percentages.

5.3.3 Estimation of monthly reservoir inflows

Reservoir operations require that inflows into the reservoir over the planning period be estimated ahead of operations. Probability distribution models were employed to perform streamflow frequency analysis for the reservoir. Monthly reservoir inflow data for Hazelmere Dam was obtained from the Department of Water Affairs, South Africa. The nature of data is streamflow volume in mega litre (Ml) recorded for every month of the year. This was converted to mega cubic meter (Mm^3) for use in this analysis. A period spanning 19 years of data (1994 – 2013) was used for the analysis. The monthly series were ranked according to Weibull’s plotting position and the corresponding return periods were estimated. The series were evaluated using six methods of probability distribution functions, Normal, Log-Normal (LN), Pearson III, Log-Pearson type III (LP_3), Gumbel extreme value type1 (EVI) and Log-Gumbel (LG). The fit of the mathematical expressions obtained for each function were compared using Mean Relative Deviation (MRD) and Mean Square Relative Deviation (MSRD) statistics (Jou *et al.* 2009b; Olofintoye and Salami 2011; Olofintoye and Adeyemo 2012c). The best model for each month was used to estimate medium flows into the reservoir. Operating a reservoir without failure under a medium flow condition suggests that the reservoir will perform reliably at least 75 percent of the time (Scott and Smith 1997).

5.3.4 Development of reservoir storage relationships

Storage relationships are useful in computation of reservoir storage head and surface area necessary for estimation of generating head for hydropower and lake evaporation. In this study, linear relationships were developed to model the storage-elevation and storage-area relationships since the reservoir is small (capacity < $50Mm^3$) (Salami 2007).

5.4 MODEL FORMULATION

DE was applied to optimize the operation of Hazelmere reservoir in a season (May to April). The dam was operated under a medium flow condition. The full capacity of the reservoir (17.858 Mm^3) was used as the starting storage for the reservoir. The decision date for reservoir operation in South Africa is May 1 when reservoir operating analysis is undertaken to decide how the reservoir should be operated in the coming year (Adeyemo and Olofintoye 2014{Mugumo, 2011 #106)}.

5.4.1 Decision variables and Objectives

The main aim of the study was to determine the monthly water releases for hydropower generation at the dam while meeting the existing water demands on the dam. The existing water demands for irrigation, domestic and other uses were obtained from DWA and held as constrain that must be satisfied. The decision variables in this study are the monthly Turbine releases for hydropower generation *RTurbine* (Mm^3) and the existing monthly water abstractions from the dam *RExisting* (Mm^3). The objective of the reservoir operation optimization problem was formulated as:

Objective: *Maximize total annual hydropower generation*

Annual hydropower generation is maximized to generate electricity for the citizens at a cheaper cost. Equation (1) is used for maximizing energy generation from reservoirs (Loucks and Bee 2005; Salami 2007; Ajenifuja 2009):

Maximize

$$Hp_{Total} = \sum_{t=1}^{12} 2.725 \times RTurbine(t) \times H(t) \times \varepsilon; \qquad t = 1,2,...,12 \tag{1}$$

Where Hp_{Total} is total annual hydropower generation over the operating period in megawatt hours (MWH). *RTurbine(t)* is the volume of water released through the hydropower turbines during month *t* in mega meter cube (Mm^3), ε is the turbine efficiency in converting the mechanical energy of water to electrical power, and this is varied between 75, 85 and 90%. *H (t)* is the average hydropower generating head in month *t* in metres (m). *H* is specified as the vertical distance between the water surface elevation in the reservoir that is the source of the flow through the turbines and the maximum of either the turbine elevation or the tailwater elevation (Loucks and Bee 2005).

5.4.2 Problem constraints

The single objective reservoir optimization problem of maximizing total annual hydropower generation at the dam is subject to the following constraints:

Constraint 1: *Mass balance equation*

The storage continuity equation defining the relationship between inflow and outflow variables at the reservoir site must be satisfied. This is presented in equation (3) (Loucks and Bee 2005; Salami 2007).

$$S(t+1) = S(t) + Q(t) - E_{net}(t) - R(t) - Ls(t) \tag{3}$$

where;

$$R(t) = RExisting\,(t) + RTurbine(t); \tag{4}$$

$$E_{net}(t) = P(t) - E(t); \tag{5}$$

$$Ls(t) = 0; \tag{6}$$

where S(t+1) is the reservoir storage at the end of month *t*, *S(t)* is the storage volume in the reservoir at the beginning of month *t*, *Q(t)* is the streamflow into the reservoir during month *t*, *P(t)* is precipitation on the reservoir surface during month *t*, *E(t)* is gross evaporation from the reservoir surface in month *t*, *Ls(t)* is seepage loss in month *t*, *RExisting(t)* is the existing water demand in month *t.* All variables are measured in volumetric units of mega cubic metres (Mm^3). Seepage losses are assumed to be negligible in this study.

Constraint 2: *Limit on reservoir releases*

The values of monthly releases through the turbines and other water outlets must lie between the minimum and maximum releases allowed through the outlets. Existing water demand is not maximized in this study but held as a constraint that must be satisfied. The constraints on the reservoir releases are presented in equations 7 and 8:

$$RExisting\,(t) = DExisting\,(t) \qquad (7)$$

$$DTurbine(t) \leq RTurbine(t) \leq CTurbine(t) \qquad (8)$$

Where D Existing(t) Turbine(t) (Mm^3) are monthly existing demands and turbine demands respectively. C *Turbine(t)*(Mm^3) is the discharge capacity of the turbines in month *t*.

Constraint 3: *Limits of reservoir storage*

The monthly reservoir storages are allowed to vary between the minimum and maximum operating levels for hydropower generation. This constraint is specified in equation (9):

$$S_{\min} \leq S(t) \leq S_{\max} \qquad (9)$$

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

Constraint 4: *Sustainability constraint*

For the operation of the reservoir to be sustainable, the storage at the end of the operating period must not be less than the starting storage. This constraint is presented in equation (10):

$$S(13) \geq S(1) \qquad (10)$$

Where S(13) (Mm^3) is the storage volume at the end of the operating period which also represents the starting storage at the beginning of the next operating season. *S(1)* (Mm^3) is the storage at the beginning of the operating period.

Constraint 5: *Limit on hydropower plant capacity*

The maximum electrical energy that can be produced from a hydropower generating plant at any time is limited by installed plant capacity *P* (MW) and the plant factor *f*. The total energy produced (MWH) during any period cannot exceed the product of the plant factor *f*, the number of hours in the period *h* and the plant capacity *P*, as defined in equation (11) (Loucks and Bee 2005; Salami 2007):

$$Hp(t) \leq (Hp_{\max}(t) = Ph(t)f) \qquad (11)$$

$Hp_{max}(t)$ is the maximum hydropower that can be generated in month *t* in megawatt hours (MWH). *Hp(t)* (MWH) is hydropower produced in month *t*.

5.5 RESULT AND DISCUSSION

The reservoir operation optimization problem of maximizing annual hydropower production was solved using DE. Figure 24 depicts the hydropower generated for 75, 85, and 90% turbine efficiencies.

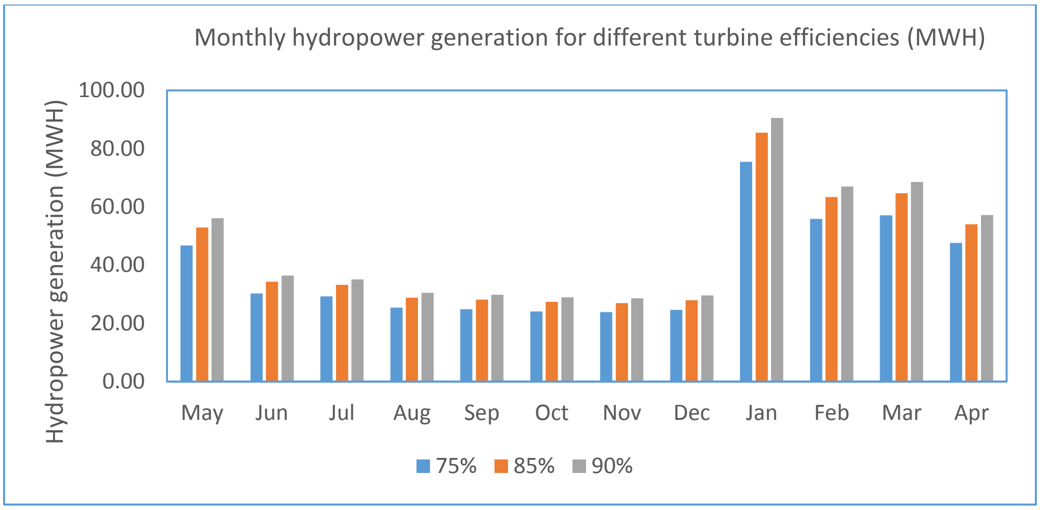

Figure 25: Monthly hydropower generation for different turbine efficiencies at Hazelmere Dam

The findings in this study indicate that, in general, the DE algorithm performed well in finding optimal solutions to the problem stated. In a single simulation run, DE found solutions that provide optimal monthly water allocation for hydropower generation at the dam. Results of analysis show that it is possible to generate hydropower from the dam while still meeting the existing water demands on the dam. Figure 2 shows that the maximum hydropower potential is during the peak of summer in January while the minimum is in November. A total of about 91 MWH of power can be generated in January using a turbine of 90% efficiency while roughly 86 MWH and 75 MWH may be generated using turbines with efficiencies of 85% and 75% respectively. In November, 28.6 MWH can be generated by employing a turbine with an efficiency of 90%. About 27 MWH and 24 MWH may be produced by employing turbines with efficiencies of 85% and 75% respectively. A total annual energy of 558.54 MWH may be generated when using a turbine efficiency of 90% while 527.51 MWH and 465.45 MWH may be produced by employing turbines with efficiencies of 85% and 75% respectively.

Results of analysis in this study indicate that under a medium flow condition it is possible to generate hydropower from the dam while meeting all existing water demands on the dam without failure of the system. This suggests that the hydrology of the dam can sustain its current water demands and provide annual hydropower up to 527.51 MWH under the prevailing climate situation without excessive storage depletion.

5.6 CONCLUSION

Reservoir behavioural analysis was conducted to inspect the feasibility of generating hydropower from the Hazelmere reservoir under normal flow conditions. Optimization models were formulated to maximize hydropower generation from the dam. DE was employed to resolve the formulated models within the confines of the system constraints. It was found that 527.51 MWH of annual energy may be generated from the dam without system failure. Storage was maintained above critical levels while the reservoir supplied the full demands on the dam throughout the operating period indicating that the system yield is sufficient and there is no immediate need to augment the system.

Generating hydropower from the dam will provide electricity for the citizens at a cheaper cost. This aligns with the South Africa Government’s commitment towards poverty eradication and reduction of the countries’ greenhouse gas emissions to conform to international standards and reduce the country’s contribution to anthropogenic global climate change (SIDALA 2010). The methodology suggested in this study provides a low cost solution suitable for the sustainable operation of the Hazelmere Dam and other similar dams in South Africa.

CHAPTER 6

CONCLUSION AND FINDINGS

6.1 GENERAL CONCLUSIONS

In this study, the monthly streamflow was estimated using six probability distribution models. These models were developed and fitted into the streamflow data of Hazelmere Dam in South Africa. This dam was built across UMdloti River in KwaZulu – Natal province of South Africa, and this river supplies water to Hazelmere Dam, which is a dam basically used for irrigation and domestic purposes at present. A 19-year period of data (1994 to 2012), which is regarded as limited was available for this study. The six probability distribution models were ranked according to the Weibull’s plotting position and the corresponding return periods were estimated. For a good comparison between the models, the Mean Relative Deviation (MRD) and Mean Square Relative Deviation (MSRD) were adopted to measure their goodness-of-fit. The models developed were successfully used in estimating the monthly streamflow of the dam.

The hydrological distributed characterization of catchments is one of the vital ways of planning for sustainable water management. A hydrological model under limited data conditions is a feasible start in order to improve the reliability of stream flow prediction, particularly in developing countries where data is limited. Even though hydrological model developments are well advanced, there is a challenge in making use of them on the limited data which is available. Nevertheless, when limited data are available (less than 50 years), substantial results can be achieved based on the relevance of the data and collation system adopted.

As outlined in Section 1.3 of this thesis, the main aim of this research was to assess the sustainability of UMdloti River in meeting different water uses downstream. The following specific research objectives were identified:

1. Performance of statistical analysis on hydrological and meteorological data of UMdloti River.
2. Estimation of monthly streamflow using probability distribution models, which is a family of statistical procedures.
3. Suggestion of new management strategies that can be implemented to sustain water resources management under limited data.
4. Identification of the potential of Hazelmere dam for hydropower generation.

Objective 1 was covered in Chapter 2 of this thesis. It reviews the relevant literature that relates to hydrologic modelling and sustainable water resources management strategies. Different methods of hydrological modelling such as statistical analysis which include; frequency analysis, probability distribution functions, regression analysis are discussed.

Chapter three deals with the methodologies adopted throughout the research work under each objective.

In Chapter 4, Log-Gumbel performed well in two cases (December and January). These two months corresponds to months with extreme rainfall (summer). Gumbel-distribution has been found excellent in fitting extreme events (University of Western Ontario 2011). Also, Log-Pearson III model performed well as the best fit model in ten months (February to November). This is the outcome of the goodness-of-fit test carried out on all the models by comparing the one with the lowest values of MRD and MSRD. From the six developed probability distribution models, it can be found that Normal distribution performed poorly. Normal distribution assumes data is not skewed whereas this is not the case in analysis of streamflow data (Olofintoye and Adeyemo 2012b). Therefore the use of Normal distribution should be restricted in analysing streamflow for this dam.

Viessman, Lewis and Knapp (1989) have noted that many hydrologic variables exhibit skewness partly due to the influence of natural phenomena. The computed monthly skew coefficients from the observed data (Table 2) revealed that the monthly streamflow estimate at Hazelmere Dam is positively skewed. Also, the 3-parameter Pearson an distributions, which take into cognizance the use of the skew coefficient in the estimation of future rainfalls, were found to exhibit very good fits as they produced lower values of MRD and MSRD than other models. In view of this, it can be said that the monthly streamflow estimation of Hazelmere Dam in South Africa can be predicted conveniently by using Log Gumbel and Log-Pearson III distributions.

6.2 FINDINGS

In this study, the best fit developed models for each month exhibits good fit to the data. The Log Gumbel and Log-Pearson III models were chosen as the best-fit model as they produced the lowest values of MRD and MSRD (Table 3 and 4; Figures 2 to 13). Also the problem of models deviating from the end of the distribution as noted by (Jou *et al.* 2009a) was overcome. Also, rainfall and temperature observations from the South African Weather Service for the 19 years period (1994 to 2013) were used for the analysis. Streamflow observations and rainfall relationship for the period of data availability was also studied. It was discovered that streamflow into the Hazelmere Dam is influenced greatly by the amount of rainfall events per month. During summer, the streamflow was very high due to the high amount of rainfall experienced at this season. Also, during winter, the streamflow was reduced. This can be adjudged due to the little or no rainfall during the winter season, which is also a dry season of the year. Therefore, the highest impact on streamflow generation in the UMdloti River was felt during summer period. The input impact results further indicated that the methods applied in selecting the input variables used in this study were appropriately evaluated, as all inputs were shown to have contributed to the fitness of the developed models.

It was observed that UMdloti River is smaller when compared with other rivers within the KwaZulu-Natal Province which could make it difficult to implement integrated water resources management. The hydro-meteorological data collected also has some limitations. The meteorological stations are far away to one another and this would make it difficult to attach their readings with the corresponding water basin. The comparison between the observed and simulated streamflow indicated that there was a good agreement between the observed and simulated discharge. Even though, the performance of the model was satisfactory, yet, it should not be generalized equally for all purposes. The erosion on the study area must be addressed by the stakeholders. It must be minimized in order to sustain the water resources of the UMdloti River. Erosion has a bad impact on the environment because it causes environmental degradation as well. Further investigations are recommended that account for the geological characteristics and the source of the base flow to make sure the rate of groundwater is sufficient for any future developments.

Reservoir behavioural analysis was conducted to inspect the feasibility of generating hydropower from the Hazelmere reservoir under normal flow conditions. Optimization models were formulated to maximize hydropower generation from the dam. DE was employed to resolve the formulated models within the confines of the system constraints. It was found that 527.51 MWH of annual energy may be generated from the dam without system failure. Storage was maintained above critical levels while the reservoir supplied the full demands on the dam throughout the operating period indicating that the system yield is sufficient and there is no immediate need to augment the system.

Generating hydropower from the dam will provide electricity for the citizens at a cheaper cost. This aligns with the South Africa Government’s commitment towards poverty eradication and reduction of the countries’ greenhouse gas emissions to conform to international standards and reduce the country’s contribution to anthropogenic global climate change (SIDALA 2010). The methodology suggested in this study provides a low cost solution suitable for the sustainable operation of the Hazelmere Dam and other similar dams in South Africa.

6.3 RECOMMENDATIONS FOR FUTURE RESEARCH

The application of probability distribution models to estimate monthly streamflow in this study can be extended to daily and hourly estimation of streamflows (real – time forecasting) so as to provide short term information about the river catchment. This strategy may help give information about an impending occurrence of flood and drought in the future.

As a result of the success recorded in adopting probability distribution models to estimate monthly streamflow for UMdloti River, the methodology may also be adopted to estimate other river catchments within the country of South Africa, especially in rivers with limited datasets. This is essential in order to plan adequately for sustainability and also find the potentials of such river basins. This will equally help to maximize the available water resources within the country since the country falls within the semi–arid region of the world.

Also, evolutionary algorithms may be adopted to other river basins in a bit to maximize their potential for hydropower generation. South Africa needs to generate more megawatts of power at this time of loadshedding, hence, efforts should be made to create alternative sources of renewable sources of energy as it has been done for UMdloti River. Also, further studies can be directed towards the incorporation of promising evolutionary computation techniques such as GP and DE in climate change studies, especially as it concerns downscaling of climate projections from global climate models (GCMs), and also in uncertainty assessment in process-based hydrological models.

However, after observing the study area, the following recommendations are made concerning ways of sustaining the water resources within UMdloti River catchment;

1. Wastewater may be used to irrigate crops on the farmlands after an initial treatment has been carried out on them in a bit to save raw water use. This will ensure water sufficiency.

2. The members of the public must be adequately educated about strategies of sustaining and saving water. Taps must not be opened carelessly, water consciousness and awareness must be passed into them.

3. Water saving policies must be in place, technologies to control water leakages and also promote re-use of water by taking rational price tarrifs for both domestic and industrial users. Irrigation efficiency must be improved by minimizing the use of water through real-time irrigation scheduling operations in the reservoirs.

4. Water resources policies that will assist in protecting both the groundwater and surface water must be developed.

5. Water transfer projects that will transfer water from rich regions to the deficit regions must be encouraged as well.

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APPENDIX

Average rainfall and discharge from 1994-2013

Year	**Rain (ml)**	**Discharge (m^3/s)**
1994/1995	1266	0.2
1995/1996	2193	0.2
1996/1997	1641	0.2
1997/1998	1520	0.2
1999/2000	1121	0.2
2000/2001	2303	0.2
2001/2002	1596	0.2
2002/2003	2215	0.2
2003/2004	1030	0.296
2004/2005	1248	0.39
2005/2006	2180	1.51
2006/2007	1448	0.64
2007/2008	1676	1.36
2008/2009	997	2.42

2009/2010	1165	0.52
2010/2011	1533	0.97
2011/2012	2057	1.96
2012/2013	1688	1.19