APPLICATION OF WATER EVALUATION AND ALLOCATION PLANNING (WEAP) MODEL TO ASSESS FUTURE WATER DEMANDS AND WATER BALANCE OF THE CALEDON RIVER BASIN

by

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DECLARATION

I, the undersigned, declare that the dissertation hereby submitted by me for the degree *Magister Technologiae* (Engineering: Civil) at the Central University of Technology, Free State, is my own independent work and has not been submitted by me to another University and/or Faculty in order to obtain a degree. I further cede copyright of this dissertation in favour of the Central University of Technology, Free State.

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ABSTRACT

The Caledon catchment is one of the 19 catchments in South Africa and three catchments in Lesotho. It covers part of the south eastern Free State in South Africa and northern part of Lesotho. It is important to evaluate the water resources of the catchment to satisfy the projected water demands and in order to plan for the future and make wise decisions. The objective of this study was to apply the Water Evaluation and Planning System version 21 (WEAP21) as a Decision Support System (DSS) tool for the allocation and development of water resources in the Caledon catchment.

The model was structured according to three scenarios with a current account (2014) and reference period (2015-2050) to predict their possible impacts on the water balance and allocation of the region due to varied water demands. The scenarios are as follows: scenario 1: increase in population growth rates; scenario 2: irrigation activities in Lesotho; and scenario 3: implementation of environmental flow requirement (EFR) on Caledon River at a site referred to as C6. The first two scenarios are consumptive scenarios whereas the third is a non-consumptive scenario. Scenario analysis answers “what if” questions for the future. Population growth has contributed to water scarcity problem in many parts of the world. In this context, scenario 1 deals with the impact of an increase in population growth on the water balance after 2020 by analysing the unmet demands that will be incurred over the reference period. Scenario 2 also analyses the unmet demands if irrigation activities in Lesotho are increased after 2020. Scenario 3 evaluates the impact of the implementation of an EFR site at C6 – which is situated downstream of all demand sites of the catchment – on upstream demands. Projected water demands and unmet demands were evaluated for four water use sectors, namely, domestic, industry, irrigation and livestock. The catchment comprised of 46 demand sites which were categorised into four use sectors: 20 domestic demand sites, 11 irrigation sites, 10 livestock sites and five industrial sites in both rural and urban areas.

The modelling results show that high population growth increases the water shortage to all water use sectors in the catchment. Under a high population growth scenario, the unmet demand occurred between May and October. However, under reference, EFR and irrigation scenarios, the unmet demand occurred only from June to September. The annual unmet demand will increase substantially after 2020 in a high population growth scenario and when the population growth rates are altered. The demand from the irrigation sector is covered or no unmet demands are registered in all years. This is because active irrigation activities happen from December to May when enough water is available from the rivers. The years 2025 and 2050 were chosen to evaluate the water balance situations in terms of supply and demand in the middle and at the end of the reference period under two water use scenarios (high population growth and irrigation added). The result shows that the river flows meet the projected demand in 2025. However, most rivers, including the main river (Caledon River), will not be able to meet the required demands in 2050.

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LIST OF ACRONYMS AND ABBREVIATIONS

AADD	Annual Average Daily Demand
BoS	Bureau of Statistics
BW	Bloem Water
CG (No)	Caledon River Gauging Station
CSIR	Council for Scientific and Industrial Research
DAFFSA	Department of Agriculture, Forestry and Fisheries
DHI	Danish Hydraulic Institute
DRWS	Department of Rural Water Supply, Lesotho
DSS	Decision Support System
DWALS	Department of Water Affairs, Lesotho
DWASA	Department of Water Affairs, South Africa
DWAF	Department of Water Affairs and Forestry, South Africa
DWAS	Department of Water Affairs and Sanitation, South Africa
EFR	Environmental Flow Requirement
ER	Environmental Reserve
FAO	Food and Agriculture Organization
FDC	Flow Duration Curve
GIS	Geographic Information System
IA	International Agreement
LHDA	Lesotho Highlands Development Authority
LHWP	Lesotho Highlands Water Project
LLSPP	Lesotho Lands, Survey and Physical Planning
LLBWSS	Lesotho Lowlands Bulk Water Supply Study
LMS	Lesotho Metrological Services
LNDC	Lesotho National Development Corporation
MCP	Marginal Cost Pricing
MoAFS	Ministry of Agriculture and Food Security, Lesotho
MODSIM	Modular Simulator

nMAR	Natural Mean Annual Runoff
NWA	National Water Act
ORASECOM	Orange-Senqu River Commission
RCC	Roller Compacted Concrete
RDP	Reconstruction and Development Programme
REALM	Resource Allocation Model
RIBASIM	River Basin Simulation Model
RSA	Republic of South Africa
SADC	Southern African Development Community
SEEWA	System of Economic and Environment Accounts for Water
SEI	Stockholm Environment Institute
StatsSA	Statistics South Africa
STDEV	Standard Deviation
UN-IDfa	United Nation Office to Support the International Decade for Action
WAFLEX	Water Allocation Flow Model in Excel
WASA	Water and Sewerage Authority, Lesotho
WASCO	Water and Sewerage Company
WEAP	Water Evaluation and Planning
WEAP21	Water Evaluation and Planning System version 21
WRYM	Water Resources Yield Model
WSA	Water Service Act

NOMENCLATURE

a	annum
bc	buffer coefficient
Bm^3	Billion cubic meters
c	capita
d	day
EF	Efficiency Coefficient
ha	hectare

ℓ	litre
ME	Mean Error
Mm^3	Million cubic meters
MSE	Mean Squared Error
n	number of data
Qm	simulated flow
Qo	observed flow
s	variance
Sb	buffer storage
Sc	conservation storage
sec	second
Sf	flood storage
Sr	reservoir
P	exceedance probability

CHAPTER 1: INTRODUCTION

1.1 Background

Water is one of the most essential resources on Earth and fundamental for life to exist. It is also needed for agriculture and other economic sectors. This natural resource is affected by many factors such as climatic variability, population growth and economic development and create scarcity. Thus this leads to implementation of effective water resources management which becomes particularly important towards determining how much water is available for human use and economic activities that water should be shared between users. Water resource management is a multifaceted issue that becomes more complex when considering multiple nations' interdependence upon a single shared transboundary river basin (Teasley and McKenney, 2013).

Water managers and policy makers require tools in order to achieve a balance in water supply and demand, to ensure equitable use of water resources, protect the environment, promote efficient use of water and develop priorities in shared water resources (Loon and Droogers, 2006). The Water Evaluation and Planning System version 21 (WEAP21) model is one of such tools used for many river basins when dealing with the stochastic nature of streamflow and water use variables. This model was developed by the Stockholm Environment Institute's (SEI) centre in the United States in 1990. It is a generic, integrated water resources planning software tool that provides a comprehensive, flexible and user friendly framework for the development of water balances, scenario generation, planning and policy analyses (Sieber and Purkey, 2015).

The development of water balance through a WEAP model requires a certain set of climate and hydrological data, as well as data on water supply and water demand in order to map the existing water resources and their utilisation within the basin (Demova et al., 2013). The WEAP model integrates water demands with water supply (Yates et al., 2005). This integration of watershed hydrology with the water planning process makes WEAP particularly suitable to evaluate the potential impacts of population growth, economic growth and climate change on the water balance. Understanding the water balance of a basin is essential to determine how much water is available in the basin for consumptive requirements over a specific period of time and how that water should be shared between users in the process of planning.

In this study, the WEAP21 model was used to simulate water resources in the Caledon River Basin and evaluate the water balance under increased service levels due to increased population, increased irrigation development and expanded industrialisation, and to determine water allocation among users. The modelling process consists of two main components, namely, the supply and demand components. The supply component comprises of the hydrological analysis of the river and the demand component comprises a growth projection based on domestic, livestock, industrial, environmental flow requirements (EFRs) and irrigation activities.

1.2 Problem Statement

The Caledon River is a transboundary river shared between the Republic of South Africa (RSA) and the Kingdom of Lesotho. It has a catchment area of 22 127.73 km^2 of which 15 237.73 km^2 is in South Africa and the remaining 6 890 km^2 is in Lesotho. Currently, the catchment area is home to over 2 675 989 people (StatSA, 2011; BoS, 2013). The Caledon River is faced with periodical water scarcities to meet demands. Water scarcity in urban and peri-urban areas in the Caledon catchment area was studied in 2004 by a consulting firm called Mouchel Parkman UK. The study outcome was an optimised programme of investment that will secure the medium- and long-term water supply for human and industrial consumption to the urban and peri-urban population of the Lowlands of Lesotho by the development of water sources and the treatment and transport of the water to demand centres. In order to address the potable water security supply problem, the Government of Lesotho implemented the Lesotho Lowlands Water Scheme under the Lesotho Department of Water Affairs (DWALS) and assigned this a high priority (DWALS, 2004).

The mean annual flow of the river, recorded at the gauging station CG22 near Maseru, is 697.83 million cubic meters (Mm^3). However, the flow has a high variability and exhibits a low flow of approximately 0.02 cubic meters per second (m^3/sec) in the winter dry season and a maximum of approximately 405.09 m^3/sec in the summer rainy season. During low flow periods, the downstream towns, including Maseru and Bloemfontein, face water shortages. To alleviate the shortage of water supply during the dry season, water is released from the Lesotho Highlands Project to augment the Caledon River flow (LHWP, 2003). According to the treaty signed between Republic of South Africa and Kingdom of Lesotho in 1986, the release comprises of 5 Mm^3 of water delivered from the Muela low level outlet valves into the Hololo River system, which eventually flows down Caledon to Maseru and other downstream towns. In view of this, firstly, the water resources of the river is not well managed as there is an excess flow of water in the rainy season and a low flow or no flow in the dry season. Secondly, in response to flow variability, the water resource of the river is not properly allocated among users. As a result, the downstream users, such as those in Maseru and Bloemfontein which are major beneficiaries of the source, receive less water and face shortages during low flow periods. This is because the upstream users utilise the available flow and release whatever is left to the downstream users (DWALS, 2003). Moreover, insufficient attention is paid to the analysis of how much water is available and how much should be shared among users and environmental requirements, particularly during low flow periods. This clearly indicates that there is a need to analyse the water balance of the river basin and to formulate water allocation strategies and principles for present and future planning. In order to implement the water allocation principles, a consolidation of information which shows the relationships between the water usage and water resources is necessary.

1.3 Objectives

The main objective of this study was to apply the WEAP21 as a Decision Support System (DSS) tool for the allocation and planning of water resources in the Caledon catchment area.

The specific objectives were:

1. to analyse the water balance (supply and demand analysis) in 2025 and 2050 in the Caledon River Basin;
2. to determine the present water allocation for domestic, industrial, and environmental demands; and
3. to predict future water demands and allocation based on different development scenarios.

1.4 Structure of Dissertation

The dissertation is divided into five chapters, namely:

Chapter 1: This chapter provides an overview of the problem statement and objectives.
Chapter 2: The literature review chapter describes water and sanitation polices and acts endorsed by Republic of South Africa (RSA) and Kingdom of Government of Lesotho, water allocation principles and guidelines, WEAP model and different Decision Support System (DSS) tools for analysing water balance and allocation of water resources used by different researchers around the world.
Chapter 3: This chapter describes the research approaches and methodology used in this study.
Chapter 4: This chapter presents description of the findings of the research.
Chapter 5: The final chapter addresses conclusions based on the findings in relation to the research objectives and gives recommendations on the effectiveness of WEAP model used for water balance and allocation analyses.

CHAPTER 2: LITERATURE REVIEW

2.1 Introduction

Countries formulate water policies based on the principle of fair, reasonable and equitable usage. The primary aim of water policy is to sustainably manage and develop the available water resources including the management plan of Transboundary Rivers. Proper planning, development and management of water resources are critical for meeting present and future water demands and avoiding potential water scarcity, crisis and conflicts (Sivakumar, 2011). For instance, Lesotho's water and sanitation policy on transboundary water resources is described as "management of transboundary water resources on the basis of Lesotho's sovereignty in a way that ensures maximum benefits while taking cognisance of the obligations to downstream users under international law" (Lesotho Ministry of Natural Resources, 2007). The utilisation of Transboundary Rivers by riparian countries is endorsed by bilateral agreements and treaties. The treaties and agreements between riparian countries bring and ensure mutual benefits to the countries involved. Allocation of available water resources are undertaken objectively to ensure equity, environmental protection, development priorities, balancing supply and demands, and promote efficient use of water in response to scarcity due to unavailability and variability of water resources (Speed et al., 2013). Different models have been developed by researchers for allocating water resources between competing water users and for analysing the water balance of the river basins. WEAP21 is one of the water allocation models which essentially follow a priority rule of allocation (Juizo and Liden, 2010; Arranz and McCartney, 2007; Sieber and Purkey, 2015). Other models, such as MODSIM, MIKE BASIN, RIBASIM and REALM, are also commonly used for analysing the water balance of river basins and as decision support tools in water resource planning and management.

2.2 Water policies and water laws

South Africa has adopted a progressive law and policy framework for water which is based upon the constitutional recognition of the right of access to water which was adopted on 8 May 1996 (Gowlland-Gualtieri, 2007). The right to water found in the constitution has been substantiated by two main acts called the Water Service Act (WSA) in 1997 and the National Water Act (NWA) in 1998 (Gowlland-Gualtieri, 2007). The constitution assigns the responsibility of management of water resources to the national government while local governments (municipalities) are responsible for the management of water and sanitation services. Accordingly, the NWA creates a comprehensive legal framework for the management of water resources, these being rivers, streams, dams and groundwater, which are the responsibility of the national government (Gowlland-Gualtieri, 2007).

In most transboundary rivers the water laws are effected based on the cooperation and mutual benefits (UN-IDfA, 2015). Individual countries, within their areas of political responsibility, have good reasons to implement integrated water resources management to protect and sustainably use water and related ecosystems and to reconcile the demands of different sectors for socio-economic development. Potential transboundary impacts and conflicting interests can best be solved by cooperation, adequate legal and institutional frameworks, joint approaches to planning and sharing of benefits and related cost (UN-IDfA, 2015).

The Lesotho water and sanitation policy (Lesotho Ministry of Natural Resources, 2007) is based on the recognition of the need for a holistic and sustainable water resources management and development approach. It promotes adequate and sustainable supply of potable water and sanitation services to all in the population of Lesotho. The policy is consistent with the global and regional consensus embodied in Agenda 21, the Dublin Principles, the Helsinki Rules, Johannesburg Plan of Implementation, Global Water Partnership, Southern African Development Community (SADC) Declaration, Southern African Vision for Water Management, SADC Regional Water Policy and SADC

Protocol on Shared Water Resources. Two water acts have been enacted by the Government of Lesotho in 1978 and 2008 to provide for the management, protection, conservation, development and sustainable utilisation of water resources.

2.3 Water Allocation Guidelines and Principles

Growing water demands for humankind, economic development and rise concerns placed on the environmental flow requirements intensify the need for proper allocation. Water allocation plans need to consider future scenarios, including changes in water availability, water use efficiency and water demands. Basin water allocation planning is typically to achieve equity among users, environmental protection, development priorities and balancing demands and supplies (Speed et al, 2013).

Dinar et al., (1997) discussed four basic institutional mechanisms for water allocation: user-based allocation, marginal cost pricing (MCP), public allocation and water markets allocation. User-based allocation requires collective action institutions with authority to make decisions on water rights and MCP sets a price for water equal to the marginal cost of supplying the last unit of that water. Public (administrative) allocation of water resources is broadly employed in countries where water is viewed as a public good and the governments allocate and distribute water permits as water use rights to users based on physical norms and political influence (Dinar et al., 1997). Water markets have attractive potential benefits such as distributing secure water rights to users, providing incentives to use water efficiently and gain additional income through the sale of conserved water (Dinar et al., 1997). The application of principles and approaches in water allocation also incorporates cooperation and negotiation between competing users (Wolf, 2002). Cooperation is useful for transboundary negotiation because it provides a range of solutions which will satisfy all users and provides methods to fairly and equitably allocate the resources (Teasley and Mckinney, 2009).

The Orange-Senqu River is one of such transboundary rivers where a commission was established by the Governments of Botswana, Lesotho, Namibia and South Africa through the "Agreement for the Establishment of the Orange-Senqu Commission" on 3 November 2000 in Windhoek, Namibia (ORASECOM, 2000). The preamble to the agreement recognises the Orange-Senqu River system as a major water resource in the region, committing the four member states towards the realisation of the principle of equitable and reasonable utilisation as well as the principle of sustainable development with regard to the river system. It also recognises the treaties made between South Africa and Lesotho for the implementation of the Lesotho Highlands Development Authority (LHDA) Project (ORASECOM, 2000), which is one of the water supply sources for South Africa.

The Lesotho Highlands Project is intended to supplement the natural flow of the Caledon River by means of planned releases of water from the Lesotho Highlands Water Project (LHWP) at Muela Dam during periods of low flow from the Caledon River (August to October). This is realised based on the agreement made between the Governments of South Africa and Lesotho during the implementation of the LHWP (LHDA, 2013).

2.4 Water Resources Management Models for River Basin Simulation

Water resources management involves development, control, protection, regulation, and beneficial use of surface (rivers and reservoirs) and groundwater resources. Computer models play an important role in almost all aspects of water resources management including in the overall water resources management decision-making process (Wurbs, 1994). Computer-based Decision Support Systems (DSS) are useful tools for this because they allow the user to forecast and evaluate the impacts of different possible future trends and management strategies before implementing them (Mugatsia, 2010).

In the following sections, several models commonly used for analysing the water balance of river basins and used as decision support tools in water resources planning and management are briefly discussed.

2.4.1 MODSIM

The modular simulator known as MODSIM is a generic river basin management DSS designed as a computer-aided tool for developing improved basin-wide planning. It was conceived in 1978 at Colorado State University (Shafer and Labadie, 1978), making it the longest continuously maintained river basin management software package currently available. It was designed specifically for developing basin-wide strategies for short-term water management, long-term operational planning, drought contingency planning, water rights analysis and resolving conflicts between urban, agricultural and environmental concerns. An example of its recent use is by Berhe et al (2012) who used MODSIM to analyse the water balance of Awash River Basin in Ethiopia under different levels of irrigation development and determined the water allocation in the Upper, Middle and Lower Valleys in the basin. Simulation was conducted based on four scenarios. Consumptive and non-consumptive uses were considered in allocation modelling. The model results showed that, if the Wonji irrigation scheme is expanded by nearly 70%, the allocation between the Upper, Middle and Lower basins is sustainable until 2018, without affecting the downstream irrigations, including the expansion of Metehara by 3 200 ha (Berhe et al. 2012). The 2005 irrigation level may be sustainable until 2028 without having additional storage at or upstream of Koka Dam. The construction of Kesem Dam and the irrigation project has no significant influence on the Tendaho Reservoir yield as simulated in the river basin model due to insignificant outflow from Gedebessa Swamp at the end of the middle valley (Berhe et al. 2012).

2.4.2 MIKE BASIN

MIKE BASIN was developed by the Danish Hydraulic Institute (DHI) in 2001. It is a mathematical representation of the river basin encompassing the configuration of the main rivers and their tributaries, the hydrology of the basin in space and time, existing as well as potential major schemes, and their various demands on water (DHI, 2003). It couples the ArcView and ArcGIS Geographic Information System (GIS) with hydrologic modelling to provide basin-scale solutions. The networks and nodes of the rivers are also edited in ArcView. MIKE BASIN can be used to determine quantity and quality of water in a river basin in a slowly changing system and is used as a DSS by investigating water sharing issues at international or interstate levels and between competing groups of water users, including the environment. Two recent examples of the model's use are mentioned here. Jaiswal et. al (2014) used a MIKE BASIN-based decision support tool to compute inflows to the Rangawan Reservoir in India during dry, average and wet periods and to address water sharing and irrigation management in real-time considering demand-supply scenarios. Wubet et. al. (2010) conducted a case study of the Blue Nile River Basin in Ethiopia using the MIKE BASIN model to simulate water allocation for major production activities (existing and planned) in the basin and to assess the impacts of upstream water allocation on downstream users.

2.4.3. RIBASIM

The River Basin Simulation Model (RIBASIM) is a generic model package for simulating river basins under various hydrological conditions, (Ramadan et al., 2011). It was developed in 1985 at Deltares (formerly Delft Hydraulics) in the Netherlands. The model package is a comprehensive and flexible tool which links the hydrological water inputs at various locations with the specific water-users in the basin. RIBASIM enables the user to evaluate a variety of measures related to infrastructure, operational and demand management and to see the results in terms of water quantity, water quality and flow composition. RIBASIM can also generate flow patterns which provide a basis for detailed water quality and sedimentation analyses in river reaches and reservoirs, (http://www.delta-alliance.nl/toolboxoverview/RIBASIM).

RIBASIM has a set of features which make it a state-of-the-art river basin simulation package. Water management organisations world-wide use it to support their management and planning activities. Omar (2014) used RIBASIM to simulate the current conditions and evaluate various scenarios for 2017 based on different actions in the Fayoum depression which receives water from the Nile River through the Bahr Youssef Canal in Egypt. The three scenarios evaluated were optimistic, moderate, and pessimistic which represent different implementation rates of the tested actions. The results of this analysis indicated a water shortage of 0.59, 1 and 1.85 billion cubic meters (Bm^3) per year under the simulated scenarios respectively (Omar, 2014).

Ramadan, Negm and Owais (2011) evaluated the effect of new Upper Nile projects on the integrated management of the basin using the RIBASIM model by setting up a methodology to best simulate the existing river system and evaluate different operation scenarios in the future. The research defined a procedure for systematic calibration and verification of the developed model and demonstrated the application of the developed model and procedure in the main River Nile basin and predicted some scenarios for new projects or the suggested projects on the River Nile (Ramadan et al., 2011). When applying the model at the Lower Nile basin before and after the construction of the Aswan High Dam, the results show that the dam has achieved more efficiency in water supply, reduced the water deficit and increased hydropower production (Ramadan et al., 2011).

2.4.4. REALM

The Resource Allocation Model (REALM) is a tool proven to aid in water resource planning and management in both urban and rural water supply systems and to represent the system network. It was developed in close collaboration with a diverse range of users in the water industry (George et. al. 2008). REALM is a network allocation model based on a combination of water balance and a linear optimisation algorithm that enables the use of user-defined penalties and priorities to impose constraints and preferential resource use (George et. al. 2008). REALM has been used in the Musi catchment in India to build a water allocation model and simulate the water supply system that integrates the Musi catchment and the Nagarjuna Sagar project. The results show that the transfer of water from agriculture to the urban users may grow over years and that water must come from Nagarjuna Sagar in the future. Hence, the allocation to irrigation is likely to fall over time unless other sources of water such as runoff recycling and water harvesting are used to meet part of the urban demand, (George et. al., (2008).

2.4.5. WEAP21

WEAP21 is a generic integrated water resource planning software tool that provides a comprehensive, flexible and user-friendly framework for the development of water balances, scenario generation, planning and policy analyses, (Dimova et al., 2013). It can be applied to municipal and agricultural systems, a single watershed or complex transboundary river basin systems (Dimova et al., 2013). It was first formulated by the SEI in 1990 (Loon and Droogers, 2006). WEAP simulates a broad range of natural and engineered components of these systems including rainfall runoff, base flow and groundwater recharge from precipitation, sectorial demand analyses, water conservation, water allocation priorities, reservoir operations, hydropower generation, pollution tracking and water quality, vulnerability assessments and ecosystem requirements. It also has an internal financial analysis module that allows the user to investigate cost-benefit implications for various management alternatives under different future scenarios (Dimova et al., 2013). As a database, WEAP21 provides a system for maintaining water demand and supply information. As a forecasting tool, it simulates water demand, supply, flows and storage as well as pollution generation, treatment and discharge, (SEI, 2015). As a policy analysis tool, it evaluates a full range of water development and management options and takes into account multiple and competing uses of water systems (SEI, 2015).

WEAP21 operates on the basic principles of balance between water supply and demand at various system nodes. It calculates a water and pollution mass balance for every node and link in the system on a monthly time step (Hao et al., 2011). The development of water balance through WEAP requires climate and hydrological data as well as data on water supply and demand in order to map the existing water resources and users within the basin and to allocate the abstraction and discharge of water. Water is allocated to meet in-stream and consumptive requirements, subject to demand priorities, supply preferences, mass balance and other constraints (Yates et al., 2005). Point loads of pollution into receiving bodies of water are computed and in-stream water quality concentrations are calculated (Yates et al., 2005).

WEAP21 operates on a monthly time step from the first month of the current accounts year through to the last month of the last scenario year (Yates et al., 2005). Each month is independent of the previous month, except for reservoir and aquifer storage. Thus, all of the water entering the system in a month (e.g. head flow, groundwater recharge or runoff into reaches) is either stored in an aquifer or reservoir or leaves the system by the end of the month (e.g. outflow from end of river, demand site consumption, reservoir or river reach evaporation, transmission and return flow link losses). Since the time scale is relatively long (one month), all flows are assumed to occur instantaneously. Thus a demand site can withdraw water from the river, consume some, return the rest to a wastewater treatment plant that treats it and return it to the river. This return flow is available for use in the same month to downstream demands (Yates et al., 2005).

WEAP21 model generates also a flow-duration curve (FDC) of the river. FDC represents the relationship between the magnitude and frequency of water flow at different time steps, such as the daily, weekly and monthly stream flows for a particular river basin (Vogel and Fennessy, 1994). The FDC thus provides an estimate of the percentage of time a given streamflow was equalled or exceeded over a historical period (Vogel and Fennesy, 1994). The streamflow record integrates the effects of climate, topography, and geology, and gives a distribution of runoff both in time and in magnitude (Searcy, 1959).

Arranz and McCartney (2007) estimated the water balance and impacts of future water demands in the Olifants River Basin in South Africa using WEAP. Certain scenarios were considered to account for possible changes in the evolution of water demand: the implementation of the Environmental Reserve (ER), International Agreements (IAs), water conservation programmes and infrastructural development such as low, medium and high population growth (Arranz and McCartney, 2007). For each scenario the unmet demands, stream flows and water storage was analysed using 1995 as the baseline. The outputs of the model showed that: (1) water shortages occurred during the 1995 baseline year and will occur in 2025; (2) the implementation of the ER allows more water flow in the rivers but less water is available to meet human demands; (3) the current storage capacity is less than the mean annual flow; (4) the construction of dams will help reconcile the water demands and resources; (5) the application of water conservation and demand management practices help to reconcile the water resources and demands but alone are not sufficient to satisfy all demands; and (6) the combination of new infrastructures and water conservation and demand management practices will enable a situation better than, or similar to, that of the 1995 baseline (Arranz and McCartney, 2007).

Mounir et. al. (2011) assessed future demands in the Niger River Basin using WEAP. Three scenarios were considered. The first scenario was the population growth of the Niamey and Tillabéry Towns which are under constant supply. The second scenario makes use of the Water Year Method and deals with variations in the climatic conditions (stream flow, rainfall, etc.). The third scenario considers whether normal climatic conditions change to abnormal climatic conditions, i.e, should the hydrology of the catchment (stream flows, rainfall, etc.) become extremely dry (Mounir et al., 2011). Results of the analyses show that the unsatisfied demand is observed only in the scenario of higher population growth and variable climate. The study thus recommended the construction of a hydroelectric dam on the Niger River which will help control the flow of water and low water levels in the river as well as provide adequate water supply for the towns facing shortages in 2030 (Mounir et al., 2011).

Juizo and Liden (2010) evaluated the performance of two models, namely, the Water Allocation Flow model in Excel (WAFLEX) and WEAP21 in the Umbeluzi River Basin in South Africa where the Water Resources Yield Model (WRYM) was previously applied as part of a joint river basin study. The results show that the models are possible tools to simulate the Umbeluzi River Basin although the structure and complexity of the models are different (Juizo and Liden, 2010). The study concluded that the choice of model does not affect the decision of best allocation and infrastructure layout of a shared river basin. However, the chosen allocation and prioritisation principles for the specific river basin and the model developer's experience and integrity are important factors in determining the optimal and equitable allocation (Juizo and Liden, 2010).

Dimova et al. (2013) assessed the available water resources and the socio-economic water needs in the Vit River Basin in Bulgaria using the System of Economic and Environment Accounts for Water (SEEAW) and the WEAP model. Key elements in the SEEAW model are setting tables for water supply and use and coupling hydrological and economic information (Dimova et al., 2013). The results show that the electricity and steam producing industries use the largest share of water (63% of supplied water), followed by agriculture and sewerage (16% and 10% respectively). In conclusion, Dimova et al. (2013) indicate that WEAP software is a reliable tool that can easily support the production of water accounts under SEEAW methodology where many of the requested parameters in the SEEAW table cannot simply be obtained as products of reporting but require the setup and outputs of a detailed water management model.

CHAPTER 3: MATERIALS AND METHODS

3.1 Introduction

This chapter describes the methods and procedures used in the study. It focuses mainly on the hydrological and demographic characteristics of the study catchment, input data preparation, conceptual modelling processes and scenario developments. A current account was set to 2014 and the reference years of 2015-2050 were analysed according to three scenarios: (1) change in population growth rate; (2) increase in irrigated land; and (3) implementation of EFRs in the Caledon River at the downstream catchment site designated as C6. WEAP21 represents one supply source (e.g. rivers) and the water demands of five water use sectors (domestic, industrial, livestock, irrigation and environmental water requirements (EFRs)).

3.2 Description of the Study Area

3.2.1 Geography

The Caledon catchment is situated between the latitudes 28°08′00″ - 30°21′08″ South and longitudes 27°00′00″ - 29°21′08″ East. The catchment covers a total area of 22 127.73 km^2 of which 15 237.73 km^2 is in of the south eastern region of the Free State, South Africa, and the remaining 6 890 km^2 is in northern Lesotho (TAMS Consultant, 1996). The Caledon River originates from Mont-Aux-Sources north of the Kingdom of Lesotho (ORASECOM, 2007). It traverses the border between South Africa and Lesotho in a south-westerly direction over a distance of 350 km and eventually joins the Orange-Senqu River near Bethulie in the southern Free State, just before the Gariep Dam (ORASECOM, 2007). The topography of the Caledon River Basin is mountainous at the origin and changes to lowland plateaus in the direction of its flow with its elevation ranging from about 1 500 to 2 700 meters above sea level (DWALS, 2004). Figure 3.1 shows the location of the study catchment as obtained from Department of Water and Forestry, Bloemfontein.

Figure 3.1: Location of the study catchment (Source: DWAF, 2012)

The capital city of Lesotho, Maseru, and district towns such as Butha Buthe, Hlotse, Maputse, Teyateyaneng, Mazenod, Roma and Mafeteng are found in the Caledon (Mohokare) catchment (LLSPP, 1994). The Free State local municipalities such as Dihlabeng (Bethlehem, Clarens, Fouriesburg, Paul Roux and Rosendal), Setsoto (Ficksburg, Meqheleng and Caledon Park; Clocolan and Hlohlowane; and Marquard and Moemaneng), Mantsopa (Ladybrand, Hob House, Tweespruit, Thaba Phatswa and Excelsior) and Naledi (Wepener and Dewetsdorp) all fall in this catchment area (DWAF, 2011/2012). Figure 3.2 shows a description of demand areas which fall in the study catchment, Caledon River and tributaries.

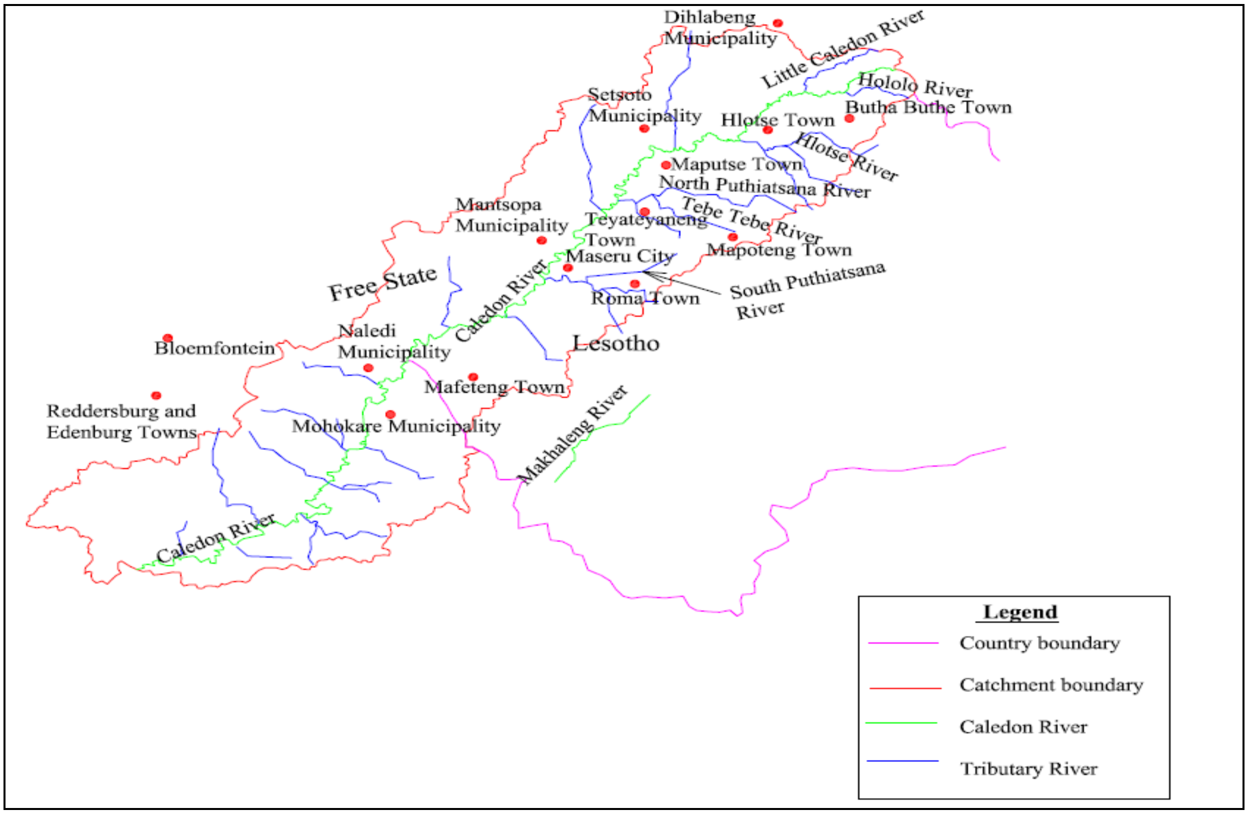


Figure 3.2: Description of areas in the study catchment (Sources: LLSPP, 1994; DWAF, 2012)

In the study catchment there are two large dams called Welbedacht and Metolong dams which are built across the Caledon River and South Puthiatsana River respectively. The Welbedacht Dam is a concrete barrage-type dam on the Caledon River which was designed and constructed by the DWASA. The dam has a catchment area of about 15 245 km^2 with an nMAR of approximately 1 210 Mm^3/a (during the period 1920 to 1987). The live storage capacity of the dam is 11.7 Mm^3 (DWAF, 2012). The Metolong Dam is 83 m high straight roller compacted concrete (RCC) gravity dam with a storage capacity of 63.7 Mm^3. The catchment area covers about 268 km^2 with a mean annual runoff of 66.7 Mm^3. It was built on the South Puthiasana River 35 km south east of Maseru. Construction began in 2010 and was completed in 2015 (Metolong Authority, 2009).

3.2.2 Climate

The climate of the Caledon catchment is characterised as hot and rainy in the summer. Summer in the Caledon catchment stretches from the month of October until April. January and February are the hottest months. The temperature varies from 31 °C in the lowlands to 18 °C in the mountainous areas. The winter climate is cold and dry. Winter begins in the month of May and lasts until September. Snowfall takes place during the winter season, especially in the highlands where the Caledon River Basin originates (TAMS Consultant, 1996). During this season, temperatures recorded in Lesotho vary from -7 °C in the lowlands to -18 °C in the highlands (TAMS Consultant, 1996; DWALS, 2004).

The average annual rainfall is 788 mm, varying from less than 300 mm in the western lowlands to 1600 mm in the north-eastern highlands of Lesotho. Intra-annual precipitation variation is high: 85% of the total is received during the months of October to April, with a peak in October and January (FAO, 2005). Very intense storms are frequent in this period, particularly in the lowlands, where as much as 15% of the annual rainfall may occur within 24 hours (LLBWSS, 2004). Figure 3.3 illustrates the historical average monthly rainfall recorded at the Phuthiatsana rainfall gauging station in the catchment and obtained from the Lesotho Meteorological Services (LMS) (LMS, 2014).

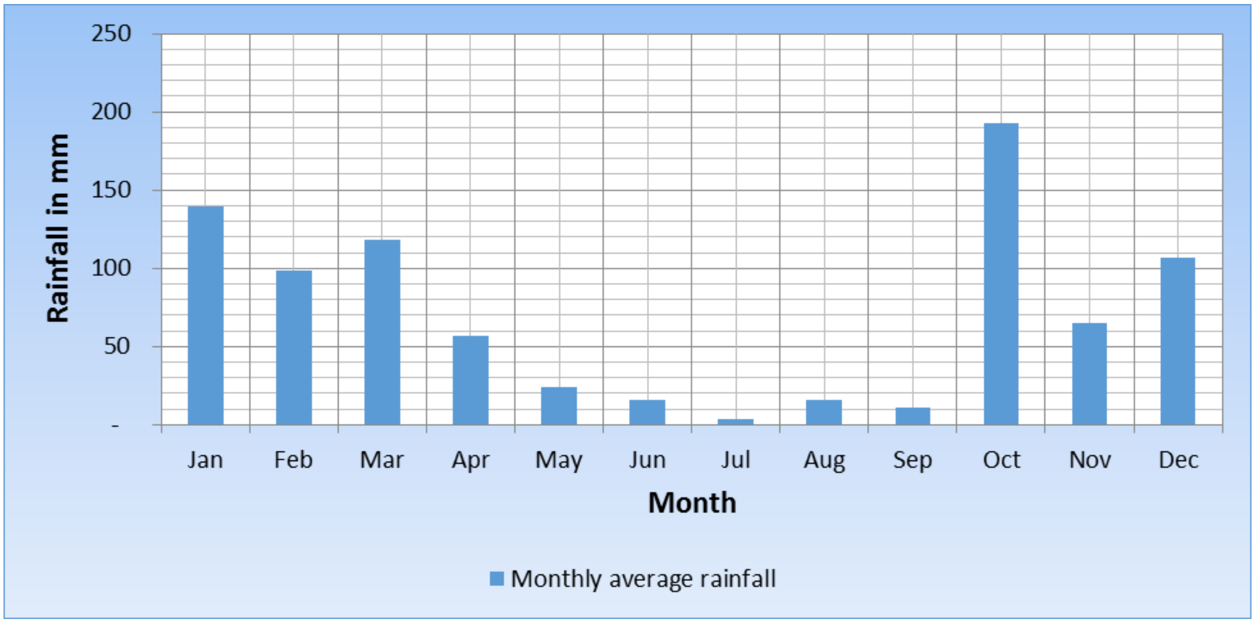


Figure 3.3: Monthly average rainfall recorded at Phuthiatsana station obtained from the Lesotho Meteorological Services (LMS)

3.2.3 Population

According to a 2011 census (StatsSA, 2011), in the Free State side of the catchment, there are five municipalities (Dihlabeng, Setsoto, Mantsopa, Naledi and Mohokare) with a total population of 1 208 121. The Manguang Municipality (Bloemfontein, Thaba Nchu and Botshabelo) and Reddersburg and Edenburg towns are situated outside of the study catchment (StatsSA, 2011). However, since the source of the water supply is from the Caledon River, they are included in this study. Based on the population census of Lesotho conducted in 2006, the population of the five districts on the Lesotho side of the catchment (Butha Buthe, Leribe, Berea, Maseru and Mafeteng) was 1 475 492, of which 37% live in urban areas and 63% are in rural areas (TAMS Consultant, 1996). The two sides of the catchment are considered to be some of the most densely populated areas in the two countries (StatsSA, 2011; TAMS Consultant, 1996).

3.3 WEAP21 Model Background

3.3.1 Overview

WEAP is structured as a set of five different "views": Schematic, Data, Results, Scenario Explorer and Notes (Figure 3.4). These views are listed as graphical icons on the View Bar located on the left side of the screen. Schematic is GIS tool for configuring the system by dragging and dropping to create and position. Adding ArcView or other standard GIS vector or raster images as background layers. It is an instant access to data and results for any node. Data view is used to build Model. It creates variables and relationships, enter assumptions and projections using mathematical expressions, and dynamically link to Excel. Notes are views where data and assumptions are documented. Results view displays detailed model outputs in the form of charts, tables and maps. Scenario Explorer is high-level view of data and results. The slider moves to change the value of the associated scenario data variable and WEAP recalculates so that the impact on user-selected key results are displayed.

The main menu at the top provides access to the most important functions of the program. A status bar is located at the bottom of the screen showing the current area name, current view, licensing information and other status information. The layout of the rest of the screen depends on which view is selected.

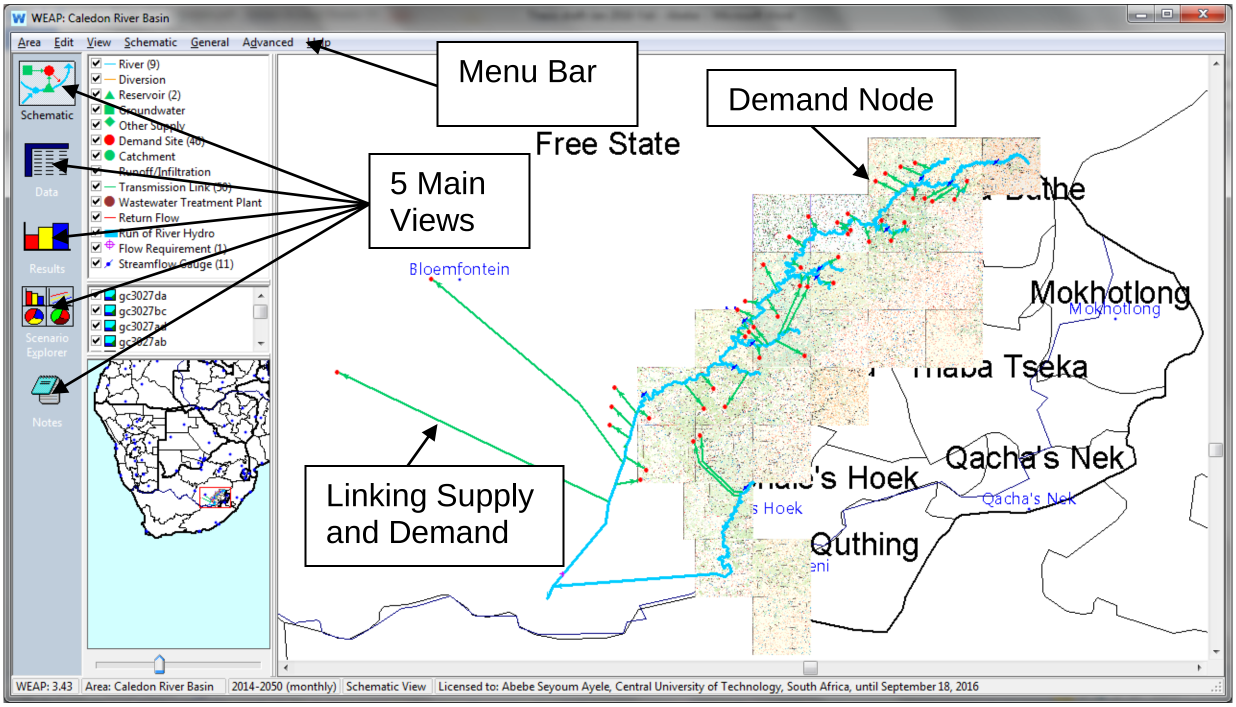
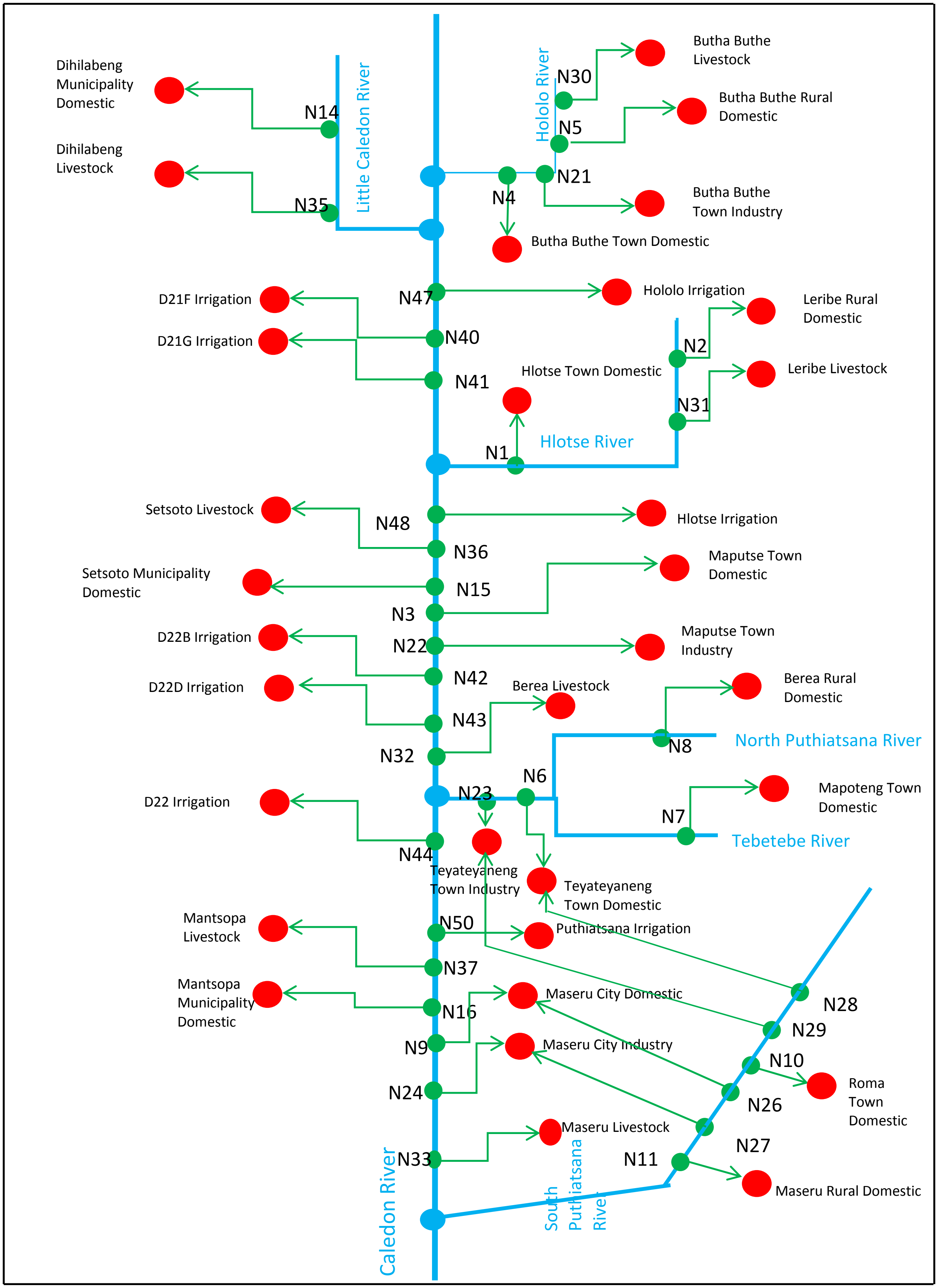


Figure 3.4: WEAP screen views, menu bar schematic view in the study catchment

3.3.2 WEAP21 Modelling Process

To allow for simulation of water balance and water allocation, the elements that comprise the water demand-supply system and their spatial relationships are characterised for the catchment under consideration. The starting point of the analysis is the development of catchment water demands. In WEAP modelling, the catchment comprises of 46 demand sites which were categorised into four use sectors: 20 domestic demand sites, 11 irrigation sites, 10 livestock sites and five industrial sites in both rural and urban areas (Figure 3.5). Each demand site in the model is represented by a node and linked to its nearby available river supply sources. The location of demand sites are configured within WEAP model based on the topo-maps obtained from Lesotho Land Administration Authority (LAA) in Maseru and Department of Water Affairs and Sanitation in Bloemfontein (DWAS). The environmental maintenance flow requirement (EFR) is not a water use sector. However, its impact on other water use sectors is evaluated depending on the volume allocated for EFR in the river and its priority level in the modelling process. The volume of water for EFR was set as a percentage of the Natural Mean Annual Runoff (nMAR) during the Water Reconciliation Strategy Study for Large Bulk Water Supply Systems by Aurecon, GHT Consulting Scientists and ILISO Consulting in 2012 (DWAF, 2012).

Figure 3.6 illustrates the WEAP model framework for the simulation of water supply and use in the Caledon catchment. The model input is represented in terms of its water sources (rivers) and demands (domestic, industrial, institutional, irrigation, livestock and environmental flow).


Dihilabeng Municipality Domestic
Dihilabeng Livestock
N14
N35
Little Caledon River
Hololo River
N30
N5
N21
N4
Butha Buthe Livestock
Butha Buthe Rural Domestic
Butha Buthe Town Industry
Butha Buthe Town Domestic
D21F Irrigation
D21G Irrigation
N47
N40
N41
Hololo Irrigation
Leribe Rural Domestic
N2
Leribe Livestock
N31
Hlotse Town Domestic
Hlotse River
N1
Setsoto Livestock
N48
N36
Hlotse Irrigation
Setsoto Municipality Domestic
N15
Maputse Town Domestic
N3
D22B Irrigation
N22
Maputse Town Industry
N42
D22D Irrigation
Berea Livestock
Berea Rural Domestic
N43
N32
N8
North Puthiatsana River
N6
D22 Irrigation
N23
Mapoteng Town Domestic
N7
Tebetebe River
N44
Teyateyaneng Town Industry
Teyateyaneng Town Domestic
Mantsopa Livestock
N50
Puthiatsana Irrigation
N37
Mantsopa Municipality Domestic
N16
Maseru City Domestic
N28
N29
N9
Maseru City Industry
N10
N24
N26
Roma Town Domestic
Maseru Livestock
N27
N33
N11
Maseru Rural Domestic
South Puthiatsana River
Caledon River

Continued....

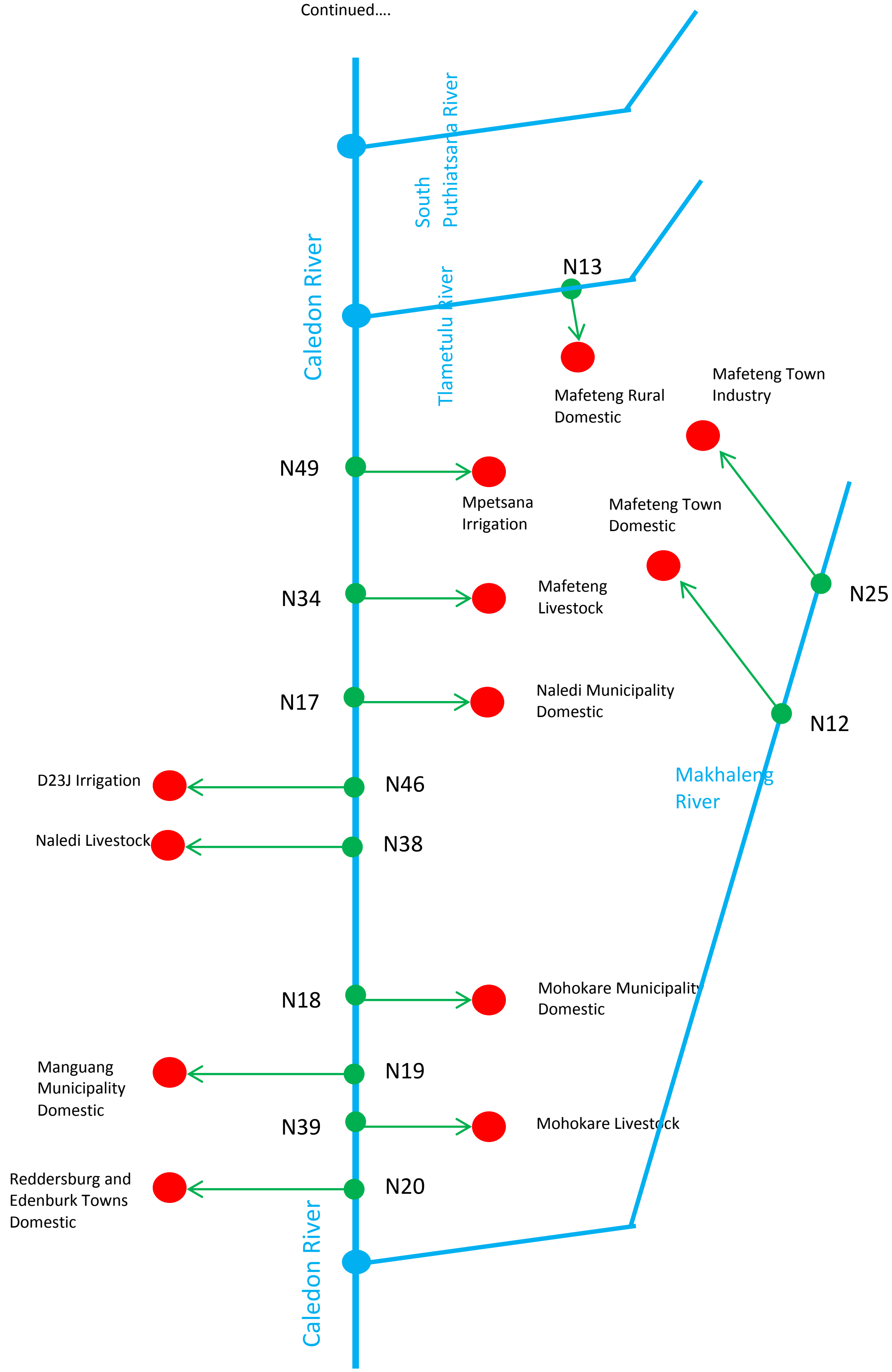


Figure 3.5: Schematic description of network in WEAP modelling process showing rivers, demand sites and nodes.

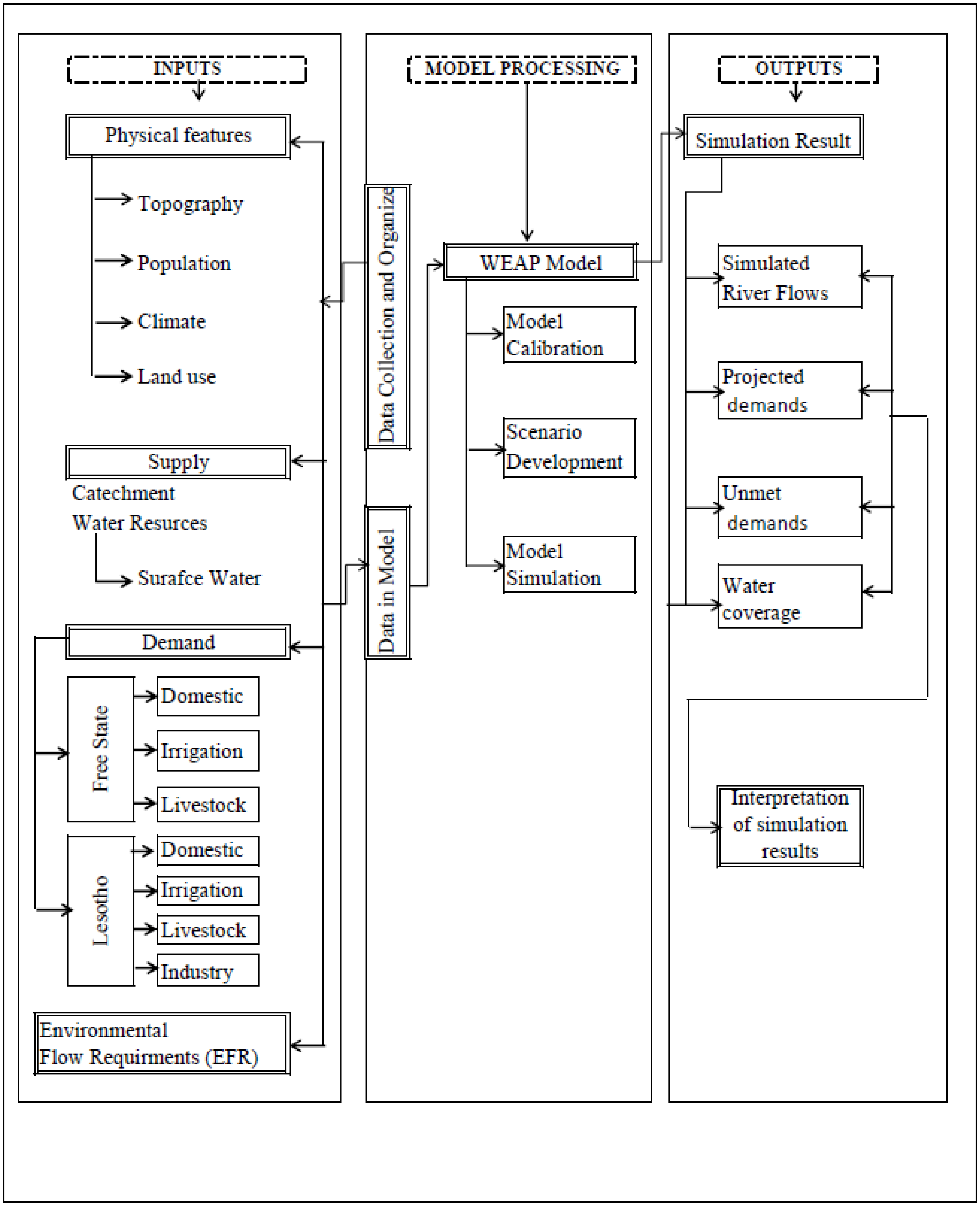


Figure 3.6: Modelling framework

The process of modelling and simulation using WEAP in the catchment makes use of the following steps (Levite et al., 2003):

1. Problem definition including time frame, spatial boundary, system components and configuration. This step involves setting area boundaries, mapping, problem identification and the collection of data. The required data is collected such as population, historical river flow, rainfall, catchment characteristics, present water supply, future development plan and standards and guidelines.

2. Establishing current accounts. The current accounts are viewed as a calibration step in the development of an application and they provide a snapshot of the actual water demand, pollution loads, resources and supplies for the system (Loon and Droogers, 2006). This forms the basis for the modelling process. In this study the current account is set at 2014.

3. Building scenarios based on future assumptions. Scenario development forms the core of the WEAP model since this allows for possible water resources management processes to be adopted from the results generated. The scenarios are used to address "what if" questions such as: What if the current population growth changes? What if industrialisation expands? What if the irrigation systems are developed in Lesotho, for example, if all irrigable lands use water from the Caledon River?

4. Evaluating the water balance and allocation with respect to scenarios. The results generated from running the model are used as a DSS for decision makers.

3.3.3 Data Requirements and Collection

The necessary data for this study were obtained in two ways: by visiting responsible government institutions on both sides of the catchment and from websites. The monthly streamflow of the Caledon River and its tributaries was obtained from the Department of Water Affairs and Sanitation (DWAS), Free State, and the Department of Water Affairs (DWALS), Maseru. The population census data were obtained from Statistics South Africa (StatsSA) in Bloemfontein and Bureau of Statistics in Maseru. Irrigation data were obtained from Municipalities Land Care and Agriculture offices and Water Use License Office, Free State, and the Department of Irrigation in the Ministry of Agriculture and Food Security, Maseru. The water supply design norms, criteria and guidelines were collected from the DWAS in the Free State and the Department of Rural Water Supply (DRWS) and the Water and Sewerage Company (WASCO) in Lesotho. The future development plans in industries and other water use sectors were obtained from the Lesotho National Development Corporation (LNDC). In addition, previous project documents about the Lesotho Lowland areas such as the Water Resources Management Policy and Strategies (TAMS Consultant, 1996), the Lesotho Lowlands Bulk Water Supply Studies (LLBWSS, 2004; LLBWSS, 2007), Metolong Dam and Water Supply Project (Lesotho Commissioner of Water, 2014) have been reviewed.

3.4 Input Data Preparation for WEAP Model

3.4.1 Population Projection

Two methods were applied to estimate population growth: the arithmetic growth method and expression builder methods. The arithmetic growth method was applied to estimate the population on the Lesotho side of the catchment between 2006 and 2011. This population projection was required since the last population census in Lesotho was conducted in 2006 (BoS, 2013). This method is commonly used for water development programmes in Lesotho (TAMS Consultant, 1996; LLBWSS, 2004; LLBWSS, 2007;

DRWS, 2002) and in South Africa (RDP, 2004). The equation for the arithmetic growth method is given below.

$$P = Po \times (1 + \rho)^{(T - To)} \quad \text{.......................................} \ (3.1)$$

Where

P = Projected population in number

Po = Baseline population in number

ρ = growth rate in percentage

T = Projected year

To = Baseline year

The Expression Builder is a "GrowthForm" function built into the WEAP model that helps project the population of the reference period (2015-2050). It is a general purpose tool to construct WEAP expressions by dragging and dropping the functions and WEAP branches into an editing box.

The input data in GrowthForm field within WEAP for projecting the population for reference period is the:

- Year of last census 2011;
- Population at 2011; and
- Estimated growth rates described in sections 3.4.1.1 and 3.4.1.2 for Lesotho and South Africa respectively.

3.4.1.1 Lesotho

The last population census in Lesotho was conducted in 2006 (BoS, 2006). Therefore, 2006 was taken as the baseline year to compute the population in 2011. The growth rates were adopted from the LLBWSS which were conducted in 2004 and 2007. The growth rates proposed by the LLBWSS were accepted by the Government of Lesotho and are applied for population forecasting in many water projects (DRWS, 2011/2015).

Table 3.1 below gives the population growth rates based on the LLBWSS approach. A number of factors (fertility, mortality, migration demographic factors, availability of services, development and settlements) have been taken into account in the development of these growth rates.

Table 3.1: Population growth rates based on the LLBWSS approach (LLBWSS, 2004/2007)

Sub-catchment	Growth rates (%)	
	Urban	Rural
Butha Buthe	2.65	0.71
Leribe	2.84	0.71
Berea	1.78	0.71
Maseru	2.41	0.96
Mafeteng	2.59	0.96

Districts such as Maseru, Berea and Leribe have two urban centres. Since these urban areas are situated in different locations and their domestic water supply is from nearby rivers, the population projection was calculated separately (BoS, 2013). Table 3.2 and 3.3 give the population of the urban and rural areas for 2006 and 2011.

Table 3.2: Urban population of the Lesotho sub-catchment (BoS Demographic Analytical Report, 2013)

Name of District	Name of Town	Urban population	
		2006	**2011**
Butha Buthe	Butha Buthe	24 047	27 407
Leribe	Hlotse	24 950	28 696
	Maputse	26 967	31 016
Berea	Teteyaneng	22 393	24 452
	Mapoteng	9 080	9 915
Maseru	Maseru City and Mazenod	294 901	324 407
	Roma	10 548	11 603
Mafeteng	Mafeteng	32 208	35 673
	Total	**445 094**	**490 214**

Table 3.3: Rural population of the Lesotho sub-catchment (BoS Demographic Analytical Report, 2013)

Name of District	Rural population	
	2006	**2011**
Butha Buthe	90 084	93 339
Leribe	239 942	248 613
Berea	218 784	226 690
Maseru	177 565	186 276
Mafeteng	159 995	167 844
Total	**886 370**	**922 762**

3.4.1.2 South Africa

South Africa has had three censuses since the first general elections in 1994 (StatsSA, 2011). The first census was conducted in 1996, the second one followed five years later (2001) while the most recent census was conducted in 2011 (StatsSA, 2011). The Caledon/Mohokare catchment falls under the municipalities of Dihlabeng, Setsoto, Mantsopa, Mohokare and Naledi in South Africa. Bloemfontein, the capital city of the Free State province, is not situated in this catchment. However, since its water source is the Caledon River, its population was estimated to calculate its future water demand. The growth rate of 2.5% was taken from the Reconstruction and Development Programme (RDP) Rural Water Supply Design Criteria Guidelines of the DWASA (RDP, 2004). The population projection for this catchment was determined for 2014 to 2050.

Table 3.4: Population of the Free State sub-catchment (StatsSA, 2011)

Sub-catchments	Population in 2011
Manguang (Bloemfontein, Thaba Nchu and Botshabelo)	747 431
Dihlabeng Municipality	128 704
Setsoto Municipality	112 597
Mantsopa Municipality	51 056
Naledi Municipality	24 314
Mohokare Municipality	34 146
Reddersburg and Edenburg Towns	12 627
Total	**1 208 127**

3.4.2 Livestock Population Projection

The livestock population data for South Africa and Lesotho was obtained from the United Nations Food and Agriculture Organisation (FAO) reports (FAO, 2005) and the Lesotho BoS (2012) and Table 3.5 present the total livestock population in the study catchment areas.

Table 3.5: Livestock population of the Free State and Lesotho sub-catchment area (FAO report, 2005; BoS, 2012)

Sub-catchments	Livestock
Free State	
Dihlabeng	16 668
Setsoto	5 533
Mantsopa	2 470
Naledi	1 265
Mohokare	1 188
Lesotho	
Butha-Buthe	171 470
Leribe	316 779
Berea	242 291
Maseru	524 653
Mafeteng	213 891

The FAO reported in 2005 that the average livestock population growth rate in South Africa was 0.2%. According to the same report, the annual growth rate in South Africa has decreased between 1980 and 2000 (FAO, 2005). As shown in Table 3.6, the cattle population appears to have remained the same between 1980 and 2000, the sheep and goat population decreased and the pig population increased.

Table 3.6: Livestock population growth rates in South Africa (FAO, 2005; Bos, 2012)

Livestock type	Growth rates (%)				
	South Africa		Lesotho		
	1980-1990	1990–2000	1980-1990	1990–2000	2000-2012
Cattle	-0.2	0.2	-1.3	0.7	0.7
Sheep and goats	0.3	-0.9	2	-3.9	4
Pigs	1.5	0.2	-2.1	-0.2	3

In Lesotho, the BoS (2012) report shows that the annual growth rate of the livestock population increased between 1980 and 2012.

Therefore, in this study the average value of 0.7%, 4% and 3% was used which is equal to 2.5% to project the livestock population for the referenced period within WEAP model.

3.4.3 Water Demand

The baseline population data obtained from StatsSA (2011) combines the rural and urban populations of the Free State municipalities. In Lesotho, the rural and urban communities are counted separately (BoS, 2012). Therefore, the rural and urban domestic water demands of the Free State municipalities are presented as one whereas the Lesotho sub-catchment rural and urban domestic water demands are treated separately.

Four water use sectors (domestic, industrial, irrigation and livestock) and the environmental flows are considered in this study.

3.4.3.1 Domestic Water Demand

The Department of Water Affairs and Forestry (DWAF) developed reconciliation strategies for the water supply for all towns in the central region of South Africa in 2011. The water supply reconciliation strategies were compiled to identify measures that are necessary to ensure the current and future water requirements of the towns in the central region of South Africa (DWASA, 2011).

The RDP rural water supply design criteria guideline of South Africa considers the domestic average annual daily demand (AADD) to be 60 litre/capita/day (ℓ/c/d) (DWAF, 2005). However, this figure has been revised as per the reconciliation strategies study for all towns in central region of South Africa conducted in 2011 (DWAF, 2011). The domestic water requirements in the Free State municipalities were calculated based on dwelling type category and the population category percentage. .

The RDP design criteria guideline considers certain assumptions in estimating industrial and institutional water demands and losses (RDP, 2005). These assumptions and the maximum peak factor are given in the table below for the various types of water uses and consumers.

Table 3.7: Water use rate assumptions in percentage of domestic average daily demand (AADD), Free State (RDP, 2005)

Water use for	Consumption rates
Domestic AADD	AADD in ℓ/c/d*
Bulk consumers (industries, schools, hospitals, etc.)	15% of domestic demand
Municipal usage (unmetered)	10% of domestic demand
Water treatment losses	10% of domestic demand
Water conveyance losses	10% of domestic demand
Maximum peak factor	1.5

* Amount of AADD is different for different municipalities depending up on dwelling type category.

In Lesotho the design guideline considers urban domestic use to be 80 ℓ/c/d (WASA, 1996; WASCO, 2012). Because of the unavailability of data regarding the dwelling types and the population percentage for each category in Maseru and other district towns, the 80 ℓ/c/d is applicable for all urban areas. This is given in Table 3.8. The design guideline considers the percentage of domestic usage, usage by institutions including schools, hospitals, offices, churches, colleges, etc., public water points (municipal usage) and losses including those incurred in water treatment and conveyance. The losses are calculated at 25% of the total demand (AADD, bulk and municipal water usage) (WASCO, 2012).

Table 3.8: Urban water use rate assumptions, Lesotho (WASA design criteria and guidelines, 1996)

Water use for	Consumption rates
Domestic AADD	80 ℓ/c/d
Institutional water demand (schools, hospitals, offices, churches, colleges, etc)	15% of domestic demand
Municipal water usage	10% of domestic demand
Total Demand	100 ℓ/c/d
Losses	25% of total demand
Maximum peak factor	1.5

The water use rate for rural areas in Lesotho is adopted from the Design Guidelines and Standards Manual (DRWS, 2005). The assumptions are shown in Table 3.9.

Table 3.9: Rural water use rate assumptions, Lesotho (DRWS, 2005)

Water use for	Consumption rates
Domestic AADD	30 ℓ/c/d
Institutional water demand	10% of domestic demand
Losses	20% of domestic demand
Maximum peak factor	1.5

3.4.3.2 Industrial Water Demand

In South Africa and Lesotho different approaches are applied in calculating the industrial water requirement. In South Africa, the DWASA considers a 15% share of domestic water demand for industrial water demand (RDP, 2005). Therefore, the industrial water demand is included in the domestic water demand in case of South Africa.

In Lesotho, a projected proportion of future water demand for industrial demand has been projected by the LNDC which is the government institution in charge of the implementation of the country's industrial development policies (LNDC, 2012). The corporation has allocated plots of land for manufacturing and processing industries in each industrial zone of the towns up to 2035, as shown in Table 3.10. Towns such as Maseru, Maputse and Teyateyaneng have developed 19%, 15% and 10% of the allocated industrial areas up to 2014 respectively (LNDC, 2000). Therefore, their water demands were considered in the year selected for the current account. In Butha Buthe and Mafeteng, the implementation programmes started from 2015 according to the LNDC (2000) plan. The LLBWSS (2007) has studied the water demand of such development areas by considering the daily water consumption rate of $60m^3$/day/hectare (m^3/d/ha). This means the total required quantities of water have been computed based on the estimated total built area of industries.

Table 3.10: Industrial areas allocation in Lesotho (LNDC, 2012 annual report; LLBWSS, 2007)

Description of areas		Years					
		2003-2014	2015	2020	2025	2030	2035
Butha Buthe	Total allocated area in hectares	0.00	112.0	112.0	112.0	112.0	112.0
	Development area in percentage		20	30	50	75	100
	Total development area in hectares	0.00	22.4	33.6	56.0	84.0	112.0
Maputse	Total allocated area in hectares	87.60	87.60	87.60	87.60	87.60	87.60
	Development area in percentage	15	20	30	50	75	100
	Total development area in hectares	13.14	17.52	26.28	43.80	65.70	87.60
Teyateyaneng	Total allocated area in hectares	25.00	25.00	25.00	25.00	25.00	25.00
	Development area in percentage	10	20	30	50	75	100
	Total development area in hectares	2.5	5.00	7.50	12.50	18.75	25.00
Maseru	Total allocated area in hectares	198.5	198.50	198.50	198.50	198.50	198.50
	Development area in percentage	19	20	30	50	75	100
	Total development area in hectares	37.8	39.70	59.55	99.25	148.88	198.50
Mafeteng	Total allocated area in hectares	25.00	25.00	25.00	25.00	25.00	25.00
	Development area in percentage		20	30	50	75	100
	Total development area in hectares		5.00	7.50	12.50	18.75	25.00

3.4.3.3 Livestock Water Demand

Arranz and McCartney (2007) use a water consumption rate of 42 ℓ/c/d to compute the water demand requirement of livestock in the Olifants catchment. The Caledon and Olifants catchment are found in the same climatic zone with similar seasonal weather patterns. Therefore, it is assumed that there is no significant difference between the two bio-diversities and agricultural practices and this study will use the same daily water consumption rate of 42 ℓ/c/d (Arranz and McCartney, 2007).

3.4.3.4 Irrigation Water Demand

The irrigation water demand is one of the key assumptions in scenario development when evaluating the impact of future water use in the study catchment. The water demand varies inter-annually, depending on the type of crops grown and evapotranspiration. Maize and vegetables are chosen as a representative crop for the study area because these are the principal crops grown in the study catchment (Turner, 2003). The seasonal climatic regimes (dry and wet) are considered as main factors in monthly water consumption variations. Maize is cultivated from January to April and vegetables are cultivated from December to May (DAFF, 2013).

In some demand sites, such as industrial sites, water use may remain constant throughout the year, while other demands may vary considerably from month to month. If demand does not vary, all months are assumed to use the same amount, according to the number of days in the month. For example, the default annual share for January is 31/365=8.49%, whereas February is 28/365=7.67%. Otherwise, the percentage of annual water used in each month is entered in to WEAP model (Sieber and Purkey, 2015). The percentage in each month is determined using CROPWAT 8 (www.fao.org). Table 3.11 presents the percentage of irrigation water requirement in each month for maize.

Table 3.11: Monthly share of annual irrigation water requirement used in WEAP model.

Month	Jan	Feb	Mar	Apr	May	Jun	Jul	Aug	Sep	Oct	Nov	Dec
Percent	10%	31%	30%	14%	8%	0%	0%	0%	0%	0%	0%	7%

In the Free State, the quaternary catchments consist of irrigated lands which are operated by both licensed and non-licensed water users. This study considered only water used by licensed water users due to the unavailability of data on non-licensed water users. The total irrigated land by licensed water users in the Free State side of the catchment is 5 164.08 ha (DWAF, 2015). The sources of the water supply are rivers, boreholes, dams and springs. The major sources of water supply for irrigation are dams and rivers, followed by piped water distribution systems. In this study, rivers and springs are considered water supply sources, whereas dams and boreholes are not considered due to the unavailability of data. The total water requirements for all irrigated lands include losses in the canal, absorption and percolation.

The total irrigable land on the Lesotho side of the catchment is 14 351 ha (MoAFS, 2000). The distribution of the area in the sub-catchments is presented in Table 4.11. At present, irrigation practices have not been developed in this part of the catchment. A "reference" scenario is established to evaluate the impact of possible future irrigation developments in the catchment on the region's water balance. The scenario is based on the assumption that the irrigable lands will be developed near the banks of the main river and tributaries and most irrigable lands are situated where they can be supplied from the river courses with the aid of gravity. The annual water consumption per hectare is adopted from the average water consumption rate applied in the Free State since both sub-catchments are adjacent and have similar agro-ecological zones. The water consumption per hectare includes all losses, percolation and absorption.

3.4.4 Monthly Water Demands

Monthly average demands are the requirements of water by the different sectors in each month. Theoretically, the monthly water requirements vary considerably from month to month, depending on different factors such as the number of days in a month, seasonal climatic conditions, etc. However, since there is no recorded data for the catchment area that reflects the historical patterns of monthly domestic demands, values were calculated depending on the number of days in each month. For example, the default annual share for January is 31/365 = 8.49%, whereas February is 28/365 = 7.67%. Therefore, it is assumed that months with the same number of days will have similar water demands. For irrigation, the demands vary not only due to the number of days in a month but also the availability of rain during that specific month.

3.4.5 River Flow

The river system management and water allocation practices are simulated using historical naturalised streamflow sequences to represent basin hydrology (Wurbs, 2004). The historical streamflow data (m^3/sec) of the Caledon River Basin was obtained from the DWAF in Bloemfontein and the DWALS in Maseru. Both departments have river flow gauging stations installed in the main river and tributaries to monitor the flow regime on daily, monthly and annual time steps. Sources of streamflow data include studies such as the LLBWSS (DWALS, 2004; DWALS, 2007) and the Metolong Dam and Water Supply Project (Metolong Authority, 2003) as well as the Water Resources Management, Policy and Strategies (DWALS, 1996) document.

The gauging stations are shown in Figure 3.7 and the mean monthly flows of the stations are presented in Table 3.12.

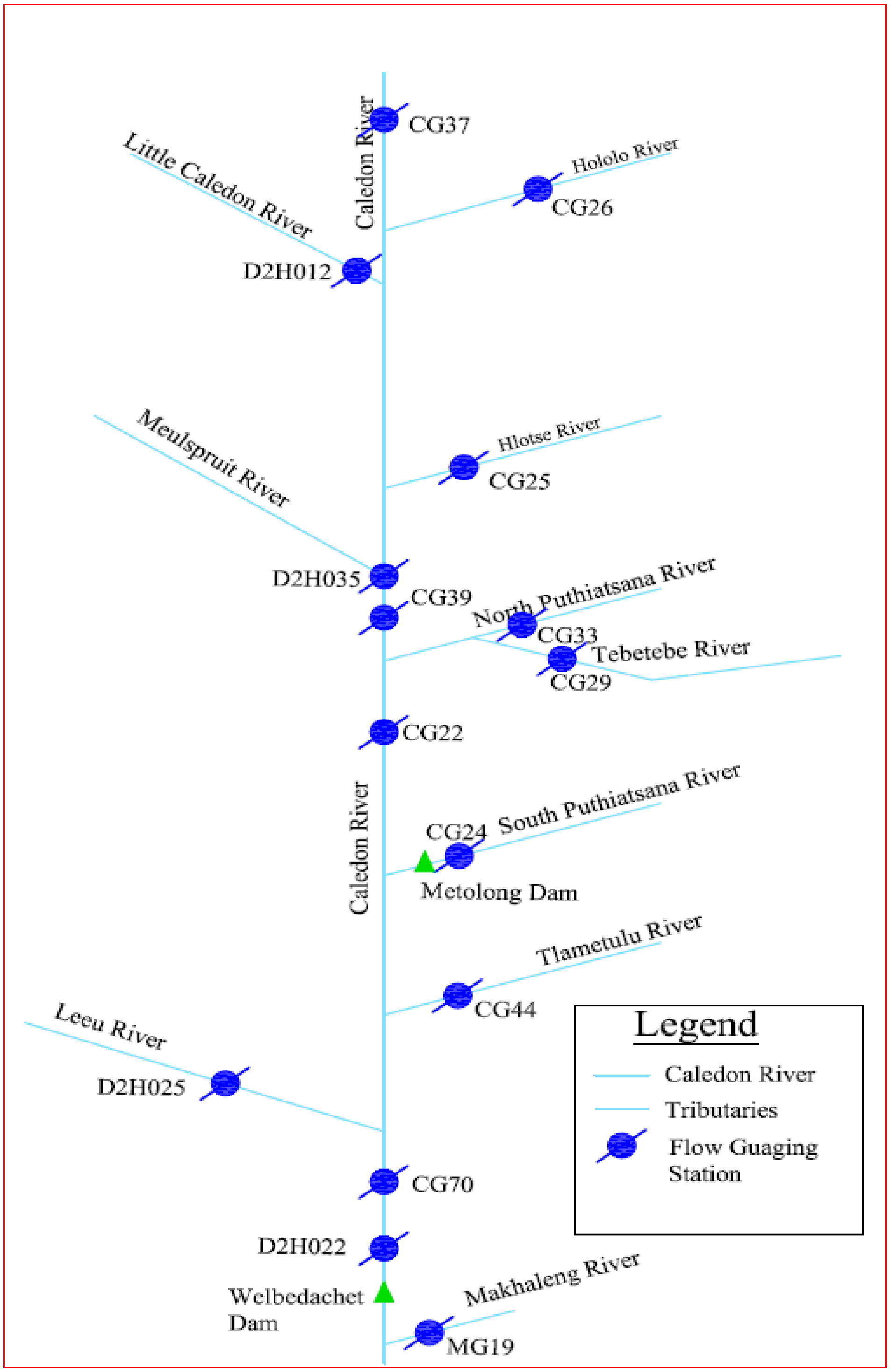


Figure 3.7: Schematic description of the Caledon River and its tributaries.

Table 3.12: Mean monthly river flow (m^3/sec), (Sources: Stream discharge data report updated to 2013, DWALS, and Streams discharge data report updated to 2014, DWASA)

Rivers	Month											
	Jan	Feb	Mar	Apr	May	Jun	Jul	Aug	Sep	Oct	Nov	Dec
Caledon River (CG37)	2.62	3.33	2.79	1.95	1.31	0.68	0.36	0.48	0.74	1.7	2.64	2.53
Little Caledon River (D2H012)	3.51	3.67	2.93	1.92	1.41	1.12	0.88	0.92	1.23	2.19	3.51	3.63
South Phuthiatsana River (CG24)	8.51	11.07	12.5	5.47	2.91	2.02	0.99	1.39	1.42	2.77	4.88	5.8
Hlotse River (CG25)	10.86	10.36	6.44	8.63	2.5	1.68	1.14	1.82	2.7	6.25	10.38	11.31
Hololo River (CG26)	5.9	6.12	4.89	2.99	1.03	0.66	0.47	0.97	1.48	2.72	5.79	5.54
Tlametlu River (CG44)	12.8	11.57	14.37	1.82	0.28	0.13	0.1	1.61	1.40	3.45	7.34	3.82
North Phuthiatsana River (CG33)	5.77	4.79	5.90	3.05	1.24	0.81	0.54	0.70	0.99	2.23	4.15	4.07
Tebe Tebe River (CG29)	1.07	0.72	0.40	0.61	0.28	0.23	0.1	0.17	0.08	0.23	0.27	0.74
Makhaleng River(MG19)	5.90	6.90	5.90	4.20	2.10	1.00	0.6	0.80	0.90	2.60	4.50	4.50

3.5 Demand Priorities and Supply Preferences

In WEAP21, priority values (1 to 99) are used to classify demands, with 1 being the highest priority value and 99 the lowest (Arranz and McCartney, 2007). Many demand sites can share the same priority. If priorities are the same, shortages will be shared equally (Arranz and McCartney, 2007). In this study, the domestic demands of municipalities in the Free State and Lesotho (urban), industrial demands in Lesotho, irrigation demands and EFRs were given a priority value of 1 whereas livestock was given a priority value of 2. Using supply preferences, WEAP determines the allocation order to follow when allotting the water supply (www.weap21.org). All urban domestic demands supplied from rivers have a supply preference value of 1 but, since rural domestic users in Lesotho are supplied from local sources such as springs, ponds and boreholes, the supply preference from the Caledon River and tributaries is given a priority value of 2. The study assumed that the livestock sector also has alternative water sources in rural areas and therefore withdrawal from the rivers is given a supply priority value of 2. The irrigation sector in the Free State is assigned a supply priority of 2. This is because other alternative sources such as boreholes, springs and ponds are also used (DWAF, 2015). In Lesotho, from view of the topography the irrigation sites are close to the Caledon River and can be supplied with gravity system. Therefore, there will be possibility that the irrigable lands get water from the Caledon River and its tributaries and hence the supply preference was given a priority value of 1.

3.6 Calibration of the WEAP Model

Calibration is the adjustment of model parameters such as roughness, hydraulic structures coefficients, etc., so that the model reproduces the observed prototype data at an acceptable accuracy (Brunner, 2008). The WEAP model calibration involves the quantitative evaluation of the hydrologic response of the Caledon River Basin and its tributaries with the aim of fitting the simulated data to the observed flow data obtained from gauging stations. The WEAP model has a hydrological component called “soil moisture method” which requires parameters (such as irrigation thresholds and loss rate in transmission links, hydraulic conductivity and wetted length and aquifer storage at equilibrium and specific yield) to calibrate and validate the historical river flow data. However, due to the unavailability of data, the fitness of the observed flow data with the model result was generally checked using two general approaches as described below.

The two general approaches for assessing the fitness of the observed flow with simulated flows are the objective function and subjective criteria (Ahmad, Hosein and Masoud, 2007). The objective function used in the calibration was a percentage error in the average annual flow. Otherwise, only subjective criteria can be used which is based on a visual comparison of the simulation results with the observed flow data (Ahmad, 2007). Objective assessment is based on developing measures of errors using statistical parameters to evaluate the model predictions. These are mean error (ME), mean square error (MSE) and the model coefficient of efficiency (EF) (Ahmad, 2007). The MSE measures the average of the squares of the errors, that is, the difference between the simulated and observed flow values. The EF is called the Nash-Sutcliffe coefficient and is used to assess the predictive power of hydrological models (Krause et al., 2005). It is a dimensionless and scaled version of the MSE for which the values range between 0 and 1 and it gives a much clearer evaluation of the model results and performance (Tesfaye, 2014). An efficiency value of 1 corresponds to a perfect match between the modelled discharge and the observed data. An efficiency value of 0 indicates that the model predictions are as accurate as the mean of the observed data (Tesfaye, 2014).

The ME, MSE and EF are defined by equations (3.3), (3.4) and (3.5) respectively.

$(E_Q) = (Q_m) - (Q_o)$ ………………………………………… (3.2)

$$ME = \sum_{i=1}^{n} \frac{(Q_m(i) - Q_o(i))}{n} = \sum_{i=0}^{n} \frac{EQ(i)}{n} \quad \text{…………………… (3.3)}$$

$$MSE = \sum_{i=1}^{n} \frac{(Q_m(i) - Q_o(i))}{n^2} = \sum_{i=0}^{n} \frac{EQ(i)}{n^2} \quad \text{…………………. (3.4)}$$

$$EF = \left[1 - \frac{MSE}{S_{Q_o}^2}\right] \quad \text{…………………………………………… (3.5)}$$

Where:

E_Q = Difference between simulated and observed flow

Qo = observed flow

Qm = simulated flow

ME = Mean Error

MSE = Mean Squared Error

EF = Model Efficiency Coefficient

n = number of data

s = variance

3.7 Scenario Development

A scenario can be defined as a plausible description of how the future may develop based on a coherent and internally consistent set of assumptions about key relationships and driving forces (Arranz and McCartney, 2007). Scenarios are self-consistent storylines of how a future system might evolve over time in a particular socio-economic setting and under a particular set of policy and technological conditions (Sieber and Purkey, 2015). Using the WEAP model, scenarios can be built and then compared to assess water requirements, costs and environmental impacts. All scenarios start from a common year for which the current accounts data is established.

The water demands are influenced by both varied demand and supply. Varied demands can be as a result of different factors such as changes in population growth, changes in land use policy, industrialisation, etc. Supply is affected by variation in natural climate (stream flow, rainfall, etc.) (Mounir et al., 2011).

How future systems will be altered over time as a result of socio-economic development and other factors are considered in building a scenario. This study develops scenarios based on the assumptions that will have an impact on the water balance of the catchment. These factors are population growth and the expansion of irrigation activities in the catchment. Currently there are no irrigation activities on Lesotho side of the catchment. This situation will change in the future as the population grows and economic development takes place. The irrigable land is situated alongside the Caledon River where the water is gravity-fed. Another factor to consider is the water flow volume allocated for the EFR which has a significant impact on upstream users. The volume was set during a strategic water reconciliation study for the Greater Bloemfontein area. In order to address a broad range of "what if" questions, three scenarios are created and their possible impacts on the water balance evaluated. Scenario 1 considers an increase in population growth rate. Scenario 2 considers an increase in irrigation activities in Lesotho. Scenario 3 deals with the implementation of an EFR on the Caledon River. Each scenario is discussed in more detail below.

3.7.1 Scenario 1: Increase in Population Growth Rate

The current population growth rates are presented in section 3.4.1. According to the RDP Rural Water Supply Design Criteria Guidelines of the DWASA, growth rates are at 2.5% and 3% for local municipalities and metropolitan cities respectively (RDP, 2004). In Lesotho, growth rates are different for urban and rural areas which are each affected by different demographic factors as presented in Table 3.1. Currently, the region is badly affected by HIV/AIDS and hence the mortality rate is significantly high. However, government action to reduce the prevalence of HIV/AIDS by developing awareness among the population will improve citizen health and consequently the rate of mortality will be reduced. Therefore, an increased population growth rate is expected in the future (BoS, 2013). This study considers population growth rates of 4% for Bloemfontein, 3% for the local municipalities of the Free State, 3% for Maseru and the district towns of Lesotho and 2% for rural areas in Lesotho. Table 3.13 shows the growth rates for reference scenario and high population growth scenario for the relevant areas in the catchment site.

Table 3.13: Population growth rate assumptions (Sources: BoS, StatSA and DWASA)

Description of areas	Reference scenario	High population growth scenario	
	2014-2050	2014-2019	2020-2050
Maseru urban population growth rate	2.41%	2.41%	3%
Butha Bute urban population growth rate	2.65%	2.65%	3%
Leribe urban population growth rate	2.84%	2.84%	3%
Berea urban population growth rate	1.78%	1.78%	2.5%
Mafteng urban population growth rate	2.59%	2.59%	3%
Free State municipalities growth rate	2.5%	2.5%	3%
Manguang municipality population growth rate	3%	3%	4%
Lesotho North rural population growth rate	0.71%	0.71%	2%
Lesotho South rural population growth rate	0.96%	0.96%	2%

3.7.2 Scenario 2: Increase in Irrigation Activities in Lesotho

Currently, the irrigation activities in Lesotho are not well developed. The total irrigable land in Lesotho alongside of the Caledon River is 14 351 ha (MoAFS, 2000). According to the National Irrigation Policy of Lesotho reported by the Ministry of Agriculture and Food Security (MoAFS), donor support is necessary before the development of irrigation activities in the area can occur but such funding is anticipated in future (MoAFS, 2002). The National Irrigation provided a framework for practitioners and investors in the Lesotho's irrigation sub-sector. The strategy covers a 20-year planning horizon, starting in year 2002 (MoAFS, 2002). Taking this strategy plan in to consideration this study assumed that 2020 a year for irrigation activities will be started in Lesotho side of the catchment.

3.7.3 Scenario 3: Application of EFRs

The environmental (in-stream) flow refers to the flow regime in a river that ensures conservation of a river ecosystem (Speed et al., 2013). It is the minimum monthly flow required along a river to meet water quality, fish and wildlife, navigation, recreation, downstream and other requirements (Sieber and Purkey, 2015). Depending on its demand priority, an EFR will be satisfied before, after or at the same time as other demands on the river. In South Africa, the EFR is considered a water right by the NWA and must be satisfied before any water is used for other purposes (Government of South Africa, 1998).

The DWAF (2012) of South Africa selected two EFR sites on the Caledon River based on the Water Reconciliation Strategy Study for the Bulk Water Supply Systems: Greater Bloemfontein Area. The sites are named EFR C5 and EFR C6 and are located in the quaternary catchments Q21A and Q24J of the upper and lower Caledon, respectively. The reconciliation study provided a percentage of the nMAR and volumes for varied flow conditions for both EFR sites (DWAF, 2012). According to the study, the environmental maintenance flow required at C5 is 13.8% of nMAR which is equal to

7.85 Mm^3 and at C6 it is 8.8% of nMAR which is equal to 118.62 Mm^3 (DWAF, 2012). EFR C6 is located close to the outlet of the WEAP model, as shown below in Figure 3.8, and is used to evaluate the impact of the EFR implementation at this site on water resources and upstream demands. Monthly flow requirements of 8.8% are determined for low, medium and high flow periods from flow gauging stations at CG70. This gauging station is in close proximity to the EFR C6 site (DWAF, 2012).

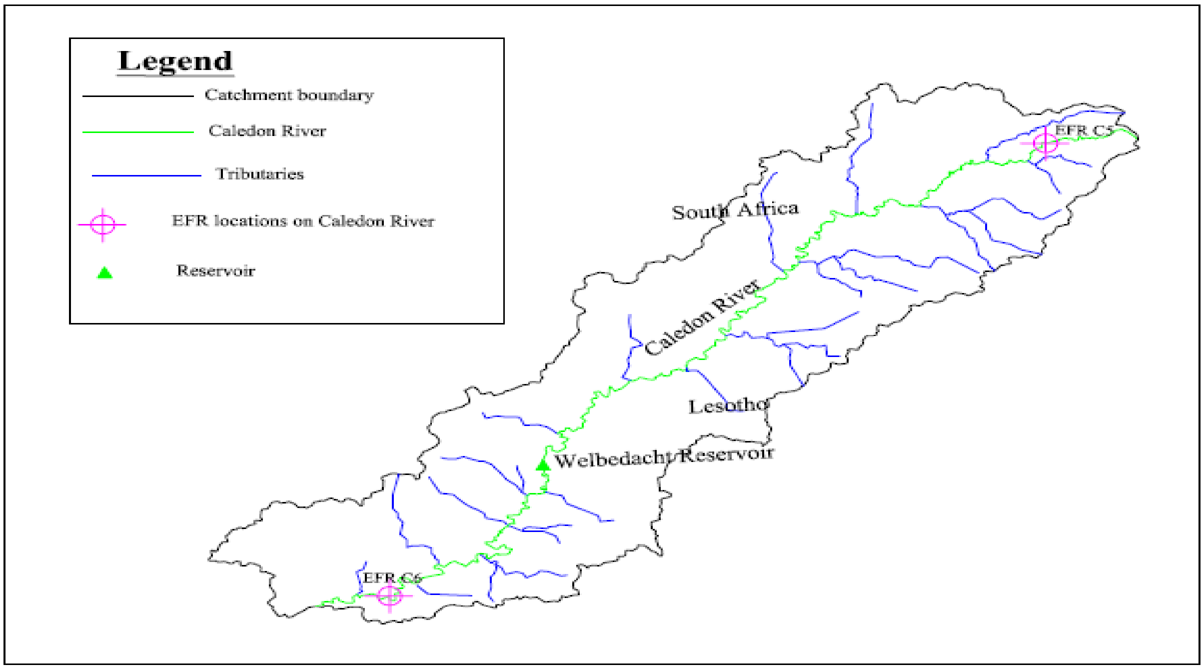


Figure 3.8: Location of EFR C5 and C6 in the Caledon River Basin (Source: Water Reconciliation Strategy Study for the Large Bulk Water Supply Systems, DWAF, 2012)

The structure of the scenarios is represented according to the current accounts (2014), reference scenarios (2015-2050), high population growth scenario (2015-2050), increased Lesotho irrigation scenario (2015-2025) and the EFR at C6. The current account refers to the base year of the model. A "reference" scenario is established and inherits all activity levels from the current accounts. The high population growth scenario and the Lesotho irrigation scenario are inherited from the reference scenario to evaluate the effects of the increased population and irrigation activities after 2020 on changes in water demand. The addition of EFRs at C6 is also inherited from the reference scenario and created to evaluate the unmet water demands and water demands coverage on upstream water demand sites. Figure 3.9 shows the structure of the scenario development within the WEAP model.

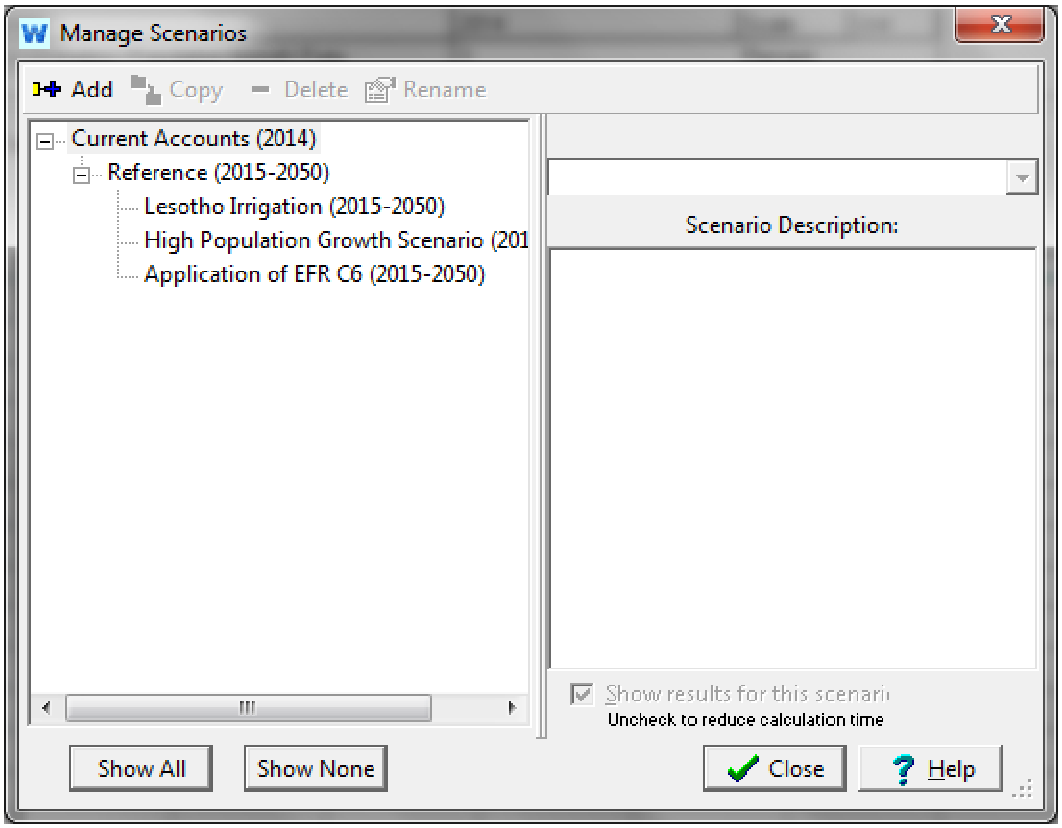


Figure 3.9: Scenario development within the WEAP model

3.8 Reservoir Operation Rules

Two large reservoirs are considered under the reference scenario to evaluate the effects of the application of operation rules on supplies to water users. These are the Welbedacht and Metolong Dams on the Caledon and South Puthiatsana Rivers respectively.

The operation criteria of reservoirs determine how much water is available in the current time step to be released for downstream demand and EFR (Yates et al., 2005). If the priority value assigned to fill water in a reservoir is less than the downstream demands or EFRs, the WEAP21 model will allow for a release of only as much of the available storage as is needed to satisfy the demand and EFRs while taking into consideration releases from the rivers or other sources (Yates et al., 2005). In this study, both the Welbedacht and Metolong reservoirs are set to a priority level of 99. The priority of 99 (the lowest possible priority value) means that the reservoirs will fill only after all other demands have been satisfied. The application of reservoir operation rules affects water supply to downstream users. According to user guide for WEAP 2015, the operation rules divide the reservoirs into water level-related zones as illustrated below in Figure 3.10. The water lying above the full supply level is in the Flood Control Zone and cannot be stored. In the next zone, the Conservation Zone, water is used as required to meet demand. In the next zone down, the Buffer Zone, some restrictions are applied so that the water is not used too quickly (Sieber and Purkey, 2015). Below the "dead storage level" in the Inactive Zone it is not possible to use the water other than to satisfy evaporation and seepage losses from the reservoir (Sieber and Purkey, 2015).

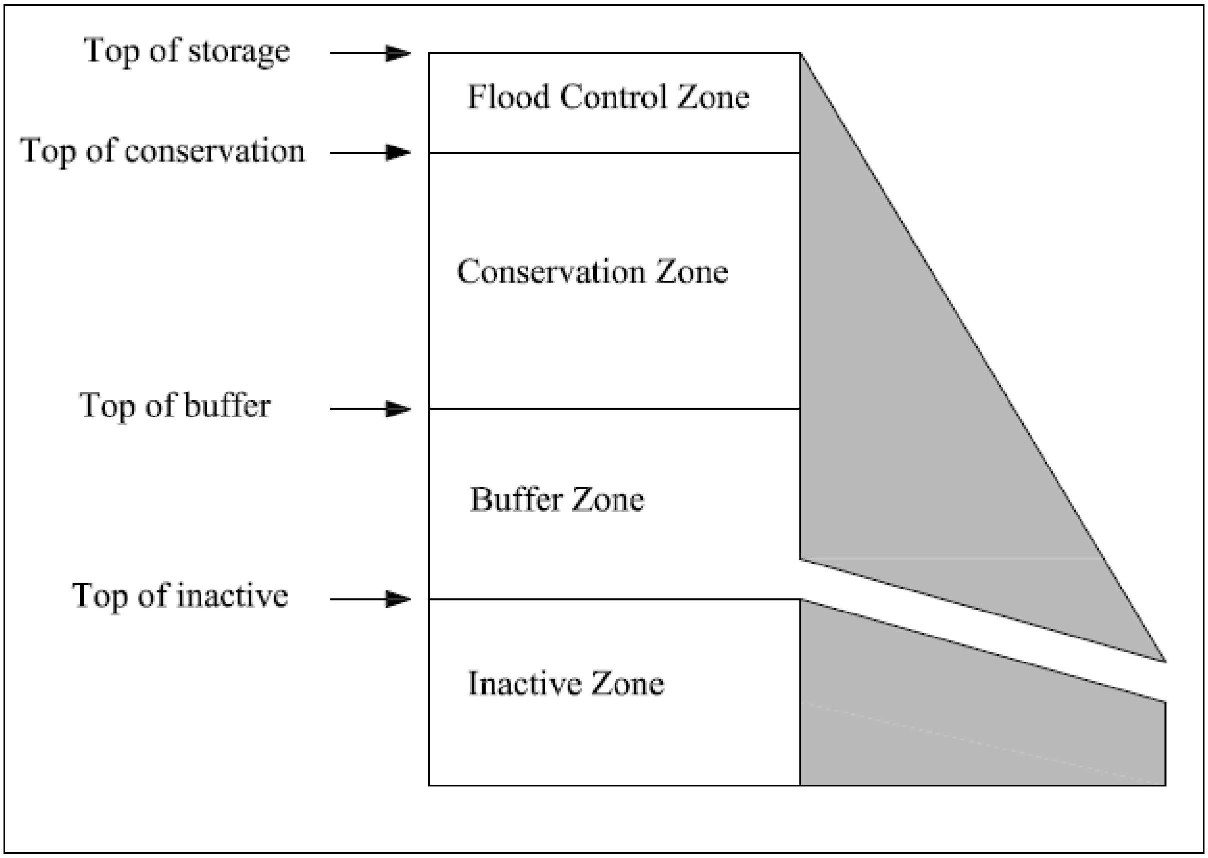


Figure 3.10: Reservoir storage zones (Source: User Guide for WEAP 2015)

The amount available to be released from the reservoir (Sr), is the full amount in the conservation (Sc) and flood control zones (Sf) and a fraction (defined by bc) of the amount in the buffer zone (Sb) (Yates et al., 2005). Equation 3.7 below shows the calculation for the amount available to be released from the reservoir.

$$Sr = Sc + Sf + (bc \times Sb) \quad \text{(3.7)}$$

Where:

- Sr = total amount for release from reservoir storage
- Sc = conservation storage
- Sf = flood storage
- Sb = buffer storage

bc = buffer coefficient

To define reservoir zones in the WEAP model, the volumes corresponding to the top of each zone are entered. The WEAP model uses the buffer coefficient (bc) to slow down releases when the storage level falls into the buffer zone. When this occurs, the monthly release cannot exceed the volume of water in the buffer zone multiplied by this coefficient. In other words, the buffer coefficient is the fraction of the water in the buffer zone available each month for release (Sieber and Purkey, 2015).

CHAPTER 4: RESULTS AND DISCUSSION

4.1 Introduction

The WEAP model was set up for water demands with the baseline year of 2014 and was run up to 2050. The scenario analysis approach was used in order to assess the Caledon River Basin water balance and its water allocation situation for the projected period from 2014 up to 2050. The analysis was based on three main scenarios. Under each scenario, the projected water demand was computed and the unmet demands were analysed. The WEAP model's suitability for evaluating the water balance of the river basin was also assessed.

4.2 Computing Water Use Rate

4.2.1 Domestic Water Use Rate

Free State

The domestic water requirements of the Free State municipalities were calculated based on the dwelling type category and the percentage of the population in the category as developed by DWASA. Since the dwelling type differs from town to town, the average daily domestic water requirements also differ as presented in Tables 4.1, 4.2, 4.3 and 4.4.

Table 4.1 presents updated average water consumption per water use category in ℓ/c/d ranging from from 1 to 8 for different dwelling type. Table 4.2 presents the percentage (%) of the population per water use category for the relevant municipal areas. Table 4.3 presents calculated values of domestic water use (AADD) rate in ℓ/c/d for each municipality. It is a sum of total water requirements based on the percentage of available dwelling type. Table 4.4 presents calculated values of Average, Maximum and total average daily demands in ℓ/c/d for each municipality.

Table 4.1: Updated average water consumption per water use category in ℓ/c/d (DWAF, 2011a-m)

Category	Dwelling type		Average water consumption in ℓ/c/d
1	Flats		226
2	Clusters		255
3	Single residential	Low income	101
4		Medium income	189
5		High income	304
6		Very high income	442
7	Informal	RDP level	40
8		No services	12

Table 4.2: Percentage (%) of the population per water use category for the relevant municipal areas (DWAF, 2011a-m)

Category	Setsoto Municipality			Dihlabeng Municipality					Mantsopa Municipality				Naledi Municipality
	Ficksburg	Clocolan	Marquard	Bethlehem	Clarens	Fouriesburg	Paul Roux	Rosendal	Hobhouse	Ladybrand	Thaba Patshoa	Tweespruit	Van Stadensrus and Wepener
1	0.70	0.51	0.30	2.00	0.70	1.50	0.30	0.00	0.30	0.70	0.00	0.00	0.00
2	0.60	0.51	0.20	1.70	0.50	0.50	0.00	0.00	0.00	1.00	0.00	0.50	0.70
3	38.80	28.12	43.40	51.80	60.80	53.00	41.70	41.00	60.40	50.90	94.20	69.30	77.10
4	7.40	3.61	5.90	13.1	10.1	4.20	4.50	3.60	5.50	10.2	5.80	7.70	3.10
5	2.20	0.45	0.80	3.50	2.70	0.70	0.20	0.40	0.00	3.30	0.00	0.50	0.70
6	0.00	0.10	0.00	0.10	0.00	0.00	0.00	0.00	0.00	0.10	0.00	0.00	0.00
7	50.40	66.70	49.40	25.50	23.10	36.90	49.00	50.50	33.80	33.80	0.00	21.90	18.30
8	0.00	0.00	0.00	2.30	2.00	3.30	4.40	4.50	0.00	0.00	0.00	0.00	0.10

The average daily water use rate and maximum daily demand was computed as follows:

Average water use rate = AADD + bulk consumers + Municipal usage + Losses

The maximum daily water requirement was computed as follows:

Maximum daily water requirement = 1.5 x Average water use (DWAF, 2011a-m, RDP, 2005)

Table 4.3: Average annual daily demand in ℓ/c/d (DWAF, 2011a-m)

Municipality	Towns	Domestic water demand (AADD) in ℓ/c/d	Average daily demand in ℓ/c/d	Maximum day demand in ℓ/c/d	Average total daily demand of Municipality in ℓ/c/d
Setsoto	Ficksburg	83.13	120.54	180.81	165.05
	Clocolan	66.17	95.95	143.92	
	Marquard	78.36	113.62	170.43	
Dihlabeng	Bethlehem	107.49	155.86	233.79	186.86
	Clarens	101.04	146.51	219.76	
	Fouriesburg	83.42	120.96	181.44	
	Paul Roux	72.04	104.46	156.69	
	Rosendal	70.17	101.75	152.62	
Mantsopa	Hobhouse	85.6	124.12	186.18	210.22
	Ladybrand	98.81	143.27	214.91	
	Thaba Patshoa	106.1	153.85	230.77	
	Tweespruit	96.1	139.35	209.02	
Naledi	Van Stadensrus	94.98	137.72	206.58	206.58
	Wepener	94.98	137.72	206.58	

The Greater Bloemfontein Water supply system provides the majority of potable water requirements to Bloemfontein, Thaba Nchu and Botshabelo as well as the smaller towns of Wepener, Dewetsdorp, Reddersburg, Edenburg and Excelsior, which are also dependent to varying degrees on local water sources (DWAF, 2012). The source of the water supply is the Welbedacht Dam and the Knellpoort off-channel storage dam.

The 2011 water requirement of Manguang, for its population of 747 431, was 83 Mm^3 per annum (Mm^3/a) (DWAF, 2012). Therefore, the average total daily water requirement per capita per day would be 304.24 ℓ.

Reddersburg and Edenburg are small towns and situated outside the Caledon catchment. However, both towns receive water from the Greater Bloemfontein supply system (DWAF, 2012). The total population in 2011 was 12 627 (StatsSA, 2011) and the water requirement was 1.247 Mm^3/a (DWAF, 2012). Therefore, the average daily water requirement per capita per day is 270.56 ℓ. Table 4.4 presents total average daily demands in ℓ/c/d for each municipality.

Table 4.4: Average daily demand on the water supply system of Greater Bloemfontein

Water Users	Average daily demand in ℓ/c/d
Manguang (Bloemfontein, Thaba Nchu and Botshabelo)	304.24
Reddersburg and Edenburg	270.56
Mohokare Municipality	270.56

It should be noted that the population and water consumption of Excelsior are considered part of Manotsopa Municipality and the population and water consumption of Wepener and Dewetsdorp are considered part of Naledi Municipality. In summary, the municipalities' daily water consumption rates of the Caledon catchment in South Africa are presented in Table 4.5.

Table 4.5: Summary of daily and annual water consumption rates in Free State Municipalities

Water users	Average daily demand in ℓ/c/d	Annual water use rate in m^3/capita
Manguang (Bloemfontein, Thaba Nchu and Botshabelo)	304.24	118.35
Setsoto	165.05	60.24
Dihlabeng	186.86	68.20
Mantsopa	210.22	76.73
Naledi	206.58	75.40
Mohokare	206.58	75.40
Reddersburg and Edenburg	270.56	98.75

Lesotho

The AADD for urban areas is considered to be 80 ℓ/c/d (WASA, 1996). Therefore, the maximum daily demands are computed as follows:

Average water use rate = AADD + bulk consumers + municipal usage = 100 ℓ/c/d

Losses = 25 ℓ/c/d

Maximum daily water requirement = 1.5 x (average water use) = 187.5 ℓ/c/d (WASA, 1996).

Table 4.6 presents calculated urban use rates in ℓ/c/d based on the design guideline developed by WASA.

Table 4.6: Lesotho urban water use rates (Source: Design Guidelines for Planning of the Capital Program of the Water Sector project, WASA, 1996)

Towns	Domestic water demand in ℓ/c/d	Average daily demand in ℓ/c/d	Maximum day demand in ℓ/c/d
Butha Buthe	80	125	187.5
Hlotse	80	125	187.5
Maputse	80	125	187.5
Teteyaneng	80	125	187.5
Maseru	80	125	187.5
Mafeteng	80	125	187.5

Similarly, the water use rates for rural areas were calculated as shown below.

The water use rate is expressed as the average water use rate = [AADD + Institutional Water demand + Losses] = 58.5 ℓ/c/d

Maximum daily water requirement = 1.5 x average water use rate

The total daily water demand is the product of the water use rate and the population.

Table 4.7 presents calculated urban use rates in ℓ/c/d based on the design guideline developed by DRWS.

Table 4.7: Lesotho rural water use rates (Source: Rural Water Supply Design Guidelines and Standards Manual, DRWS, 2002)

Sub-catchments	Domestic water Demand (AADD) in ℓ/c/d	Average daily demand in ℓ/c/d	Maximum Day Demand in ℓ/c/d
Butha Buthe	30	58.50	87.75
Leribe	30	58.50	87.75
Berea	30	58.50	87.75
Maseru	30	58.50	87.75
Mafeteng	30	58.50	87.75

The annual water use rates for the urban and rural population in Lesotho are summarised in Table 4.8.

Table 4.8: Summary of daily and annual water consumption rates in Lesotho

Water users' area	Average daily demand in ℓ/c/d	Annual water use rate in m^3/c
Urban	187.5	68.44
Rural	87.75	32.03

4.2.2 Industrial Water Use Rate

In South Africa, the DWASA considers a 15% share of domestic water demand for industrial water demand (RDP, 2005), as described in section 3.6.2. Therefore, the industrial water demand is included in the domestic water demand.

In Lesotho, the industrial water demand is calculated based on the total inbuilt area of factories or industries. A study conducted by the LLBWSS (2007) considered the daily water consumption rate to be 60 m^3/day/ha. This consumption rate was used to compute the annual industrial water use rate of 21 900 m^3/d/ha in WEAP. In the annual activity level, the total developed areas are inserted in yearly time series for the reference period.

4.2.3 Livestock Water Use Rate

The annual water use rate is computed as the product of the daily water use rate and the number of days in a year. The daily water use rate considered is 42 ℓ/c/d (Arranz and McCartney, 2007).

Therefore, the annual water use rate is calculated as follows:

Annual water use rate = (0.042 m^3/c/d) x 365 = 15.33 m^3/c/a

4.2.3 Irrigation Water Use Rate

As mentioned in section 3.4.3.4, the study considers the irrigated lands operated by licensed water users only for Free State. The total irrigated land by licensed water users in the Free State side of the catchment is 5 164.08 ha (DWAF, 2015). According to DWAF the licensed water users use rivers and springs to irrigate. Dams and groundwater are also other sources of supply. However, in this study only supplies from rivers and springs are considered as mentioned in section 3.4.3.4. The annual water use rate for each quaternary catchment in meter cube per hectare per annum (m^3/ha/a) used in WEAP is calculated as the total water use divided by the total area of irrigated land under consideration. The quaternary catchments in the Caledon catchment are represented by drainage region designated as D21F, D21G, D22B, etc. (DWAF, 2015). The total irrigable lands and the annual water requirement per hectare for the Free State side of the catchment area are presented in Table 4.9.

Table 4.9: Irrigable land in the Free State Caledon sub-catchment by licensed water users (DWAF, 2015)

Quaternary catchments	Area (ha)	Annual registered volume of water to use for irrigation (m^3)		Total water Use (m^3/a)	Annual water use ($m^3/ha/a$)
		River	Spring		
D21F	802.43	1 600 900		1 600 900	1 995.06
D21G	138.50	420 836		420 836	3 038.53
D22B	504.70	3 449 781		3 449 781	6 835.31
D22D	980.15	2 979 949		2 979 949	3 040.30
D22G	934.00	1 164 760	586 395	1 751 155	1 874.90
D23H	392.50	12 000	272 000	284 000	723.57
D23J	565.90	1 984 288	42 000	2 026 288	3 580.65
Total	**5 164.08**	**11 612 514**	**900 395**	**12 512 909**	

Table 4.10 presents the total irrigable land and the annual water requirement per hectare for the Lesotho side of the catchment.

Table 4.10: Irrigable land in the Lesotho Caledon sub-catchments (MoAFS, 2000)

Sub-catchment	Area (ha)	Annual water use per hectares ($m^3/ha/a$)
Hololo (Butha Buthe)	711	1 995.06
Hlotse (Leribe)	6 252	3 038.53
Phutiatsana (Berea, Maseru)	5 820	3 040.30
Mpetsana (Mafeteng)	1 568	3 580.65
Total	**14 351**	

4.2.4 Environmental Flow Requirement (EFR)

The location of EFR sites and the volume of water allocated in the Caledon River Basin have been discussed in section 3.7.3. The allocated volume of water for the EFR was determined to be 8.8% of nMAR. The nMAR recorded at gauging station CG70 was chosen to determine the mean monthly flow at EFR site C6 as this station is in close proximity to the EFR site C6 (DWAF, 2012). Table 4.11 shows the historic mean monthly flow recorded at CG70 and the percentage of nMAR allocated for the EFR.

Table 4.11: Mean monthly flow at gauging station CG70 and EFR in m^3/sec (Sources: Streams Discharge Data Report updated to 2013, DWALS, 2015: Water Reconciliation Strategy Study for the Large Bulk Water Supply Systems, 2012, DWAF).

Description	Jan	Feb	Mar	Apr	May	Jun	Jul	Aug	Sep	Oct	Nov	Dec
Monthly flow at CG70 (m^3/sec)	54.85	57.70	55.29	38.11	30.92	21.06	17.28	22.60	16.53	38.77	47.75	55.13
8.8% of monthly flow for EFR (m^3/sec)	4.83	5.08	4.87	3.35	2.72	1.85	1.52	1.99	1.45	3.41	4.20	4.85

4.3 Water Demand in the Caledon Catchment

WEAP calculated the annual domestic water demands during the current year (2014) for both urban and rural areas in the catchment. The result shows that domestic is the largest water use sector which comprises of 76.74% of total water demands (247.94Mm^3).

Table 4.12 presents the WEAP modelling result of annual domestic water demands during the current year in Free State and Lesotho. The total annual water demand is 190.27 Mm^3 of which Free State has 123Mm^3 and Lesotho 66.56Mm^3. In Free State, Manguang municipalities are major water users followed by Dihlabeng and Sesotho Local municipalities. Reddersburg and Edenburg towns are the least users. In Lesotho, Maseru city is the major user followed by rural areas such as Leribe and Berea.

Table 4.12: Population and domestic water demands in the study catchment area during the current account

Sub-catchment	Municipality/District	Population	Water use rate ($m^3/c/a$)	Annual water demand (Mm^3)
Free State	Manguang Municipalities	816 738	118.34	96.65
	Dihlabeng Local Municipalities	138 600	68.20	9.45
	Sesotho Local Municipalities	121 255	60.24	7.30
	Mantsopa local Municipalities	54 982	76.73	4.22
	Naledi Local Municipalities	26 184	75.40	1.97
	Mohokare Local Municipalities	36 772	75.40	2.77
	Reddersburg and Edenburg	13 598	98.75	1.34
Sub Total		**1 208 129**		**123.70**
Lesotho rural	Butha Buthe	95 341	32.03	3.05
	Leribe	253 946	32.03	8.13
	Berea	231 553	32.03	7.42
	Maseru	191 692	32.03	6.14
	Mafeteng	172 724	32.03	5.53
Sub Total		**945 256**		**30.26**
Lesotho urban	Butha Buthe Town	29 644	68.44	2.03
	Hlotse Town	31 211	68.44	2.14
	Maputse Town	33 734	68.44	2.31
	Teyateyaneng Town	25 781	68.44	1.76
	Mapoteng Town	10 454	68.44	0.72
	Maseru City	348 431	68.44	23.85
	Roma Town	12 463	68.44	0.85
	Mafeteng Town	38 518	68.44	2.64
Sub Total		**530 236**		**36.30**
Total (rural + urban)		**1 475 492**		**66.56**
Total (Free State + Lesotho)		**2 683 621**		**190.27**

The irrigation and livestock sectors were accounted for in rural demand sectors for both sub-catchments. The annual water demand is 27.70Mm^3 which comprises of 11.17% of total water demands (247.94Mm^3). In comparing sub-catchments, since Lesotho has large number of livestock population the annual water demand exhibited higher as compared with Free State. The livestock water demands for the Free State and Lesotho sides of the catchment during the current year (2014) are presented in Table 4.13.

Table 4.13: Livestock population in the study catchment area and their water demands during the current account

Sub-catchment	Area	Livestock Population	Water use rate ($m^3/c/a$)	Annual Water demands (Mm^3)
Free State	Dihlabeng Local Municipality	6 019	15.33	0.09
	Setsoto Local Municipality	5 567	15.33	0.09
	Mantsopa Local Municipality	2 485	15.33	0.04
	Naledi Local Municipality	1 273	15.33	0.02
	Mohokare Local Municipality	1 809	15.33	0.03
	Sub Total	**17 153**		**0.26**
Lesotho	Butha Buthe	208 920	15.33	3.20
	Leribe	385 964	15.33	5.92
	Berea	295 208	15.33	4.53
	Maseru	639 239	15.33	9.80
	Mafeteng	260 605	15.33	4.00
	Sub Total	**1 789 936**		**27.44**
	Total (Free State + Lesotho)	**1 807 089**		**27.70**

There is no irrigation activity on the Lesotho side of the catchment currently and therefore no water demand was modelled using WEAP for the sector in this part of sub-catchment. Irrigation is expected to start after 2020 and this has also been modelled in the reference scenario. Irrigation sector is the second highest water consumer which comprises of 11.60% of total water demand (247.94Mm^3). The irrigation water demands during the current year are presented for the Free State in Table 4.14

Table 4.14: Irrigation water requirements in the study catchment area during the current account

Sub-catchment	Quaternary catchment	Area (ha)	Water use rate (m^3/ha/a)	Annual Water demands (Mm^3)
Free State	D21F	802.43	1 995.06	1.62
	D21G	138.50	3 038.53	0.43
	D22B	504.70	6 835.31	3.48
	D22D	980.15	3 040.30	3.01
	D22G	934.00	1 874.90	17.90
	D23H	392.50	723.57	0.29
	D23J	565.90	3 580.65	2.05
Total		**5 164.08**		**28.77**

Industries are treated under urban water demands and were computed along with the domestic water demand in a combined per capita use in the case of the Free State. In Lesotho, the industrial demand was considered separately and the Lesotho lowlands bulk water supply study in 2007 study determined the water requirements per allocated industrial areas as presented in section 3. The industrial water demands in Lesotho during the current year are presented in Table 4.15.

Table 4.15: Industrial water demands in the study catchment area during the current account

Sub-catchment	Industrial areas in	Allocated area (ha)	Water use rate (m^3/ha/a)	Annual Water demands (Mm^3)
Lesotho	Butha Buthe	0.00	0.00	0.00
	Maputse	13.14	21 900	0.29
	Teyateyaneng	2.50	21 900	0.05
	Maseru	37.8	21 900	0.83
	Mafeteng	2.00	21 900	0.04
Total		**55.44**		**1.21**

Table 4.16 presents the summary of annual water demand during the current year in sector wise in the study catchment. Free State has total demands of 152.73Mm^3

(61.60% of total demand) of which domestic sector is the major water consumer comprised demand of 81% followed by irrigation 18.84%. Lesotho has total demands of 95.21Mm^3 which comprised of 38.40% of total demand. In this sub-catchment also domestic sector is the major user and followed by livestock.

Table 4.16: Total water demands in the study catchment area in Mm^3 during the current account

Sub-catchment	Rural			Urban		Total
	Domestic	Livestock	Irrigation	Domestic	Industrial	
Free State	-	0.26	28.77	123.70	-	152.73
Lesotho	30.26	27.44	-	36.30	1.21	95.21
Total	**30.26**	**27.70**	**28.77**	**160.00**	**1.21**	**247.94**

4.4 Water Resources Availability

The total annual flow of the Caledon River Basin amounts to 1 347.95 Mm^3 at its downstream end before it joins the Orange-Senqu River (DWAF, 2012). At the most upstream point of the catchment (CG37 flow gauging station), its annual flow is 55.21 Mm^3 (DWALS, 2015). Tributaries located in the upstream catchment (within the Lesotho boarder) contribute 776.61 Mm^3 of water in total. This does not include small streams flowing directly into the Caledon River (DWALS, 2007). Makhaleng River has an annual flow of 104.16 Mm^3 at the MG19 flow gauging station. It is a source of water supply for Mafeteng town domestic and industrial requirements (WASCO, 2012). Since the river is situated outside the study catchment area, the withdrawal from this river to other demand sites that are situated outside the catchment were not simulated in the WEAP modelling process.

Figure 4.1 presents the monthly flow of the Caledon River at CG22 and its tributaries. High flow conditions occur during the period between November and March and low flow conditions occur from April to October. It can be seen from the figure that the minimum flow occurs in the month of July and peak flows occur from January to February.

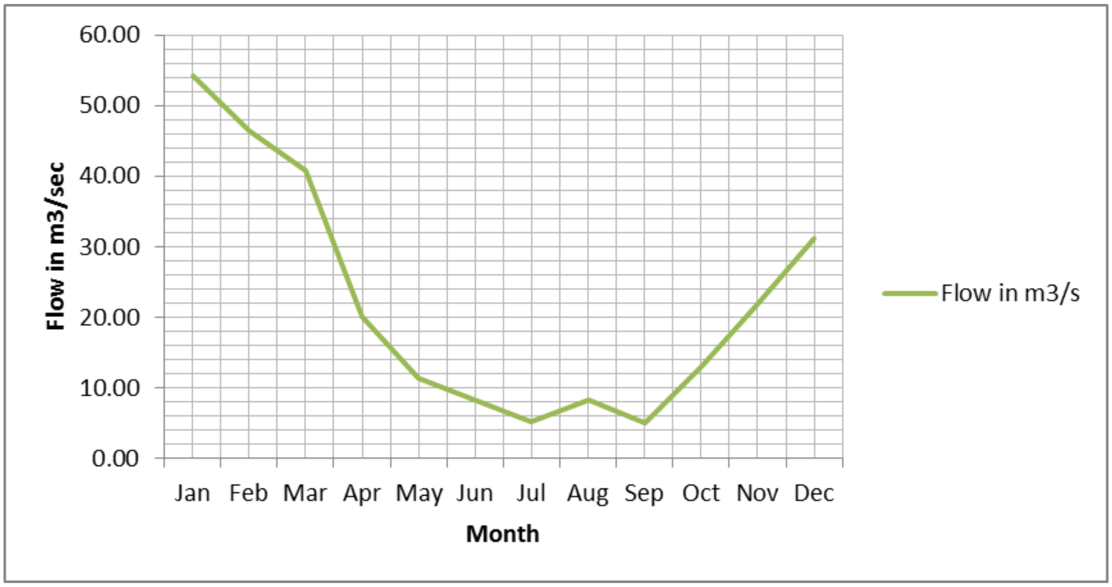


Figure 4.1: Caledon River monthly flow patterns (DWALS, 2015)

4.5 Measures of Water Availability and Reliability

A flow-duration curve of the Caledon and its tributaries were modelled using WEAP on a water per year basis according to data obtained from the flow gauging stations. When the flows are arranged according to frequency of occurrence and a flow-duration curve is plotted, the resulting curve shows the integrated effect of the various factors that affect runoff, and indicates how much flow is available for abstraction and EFR, based on the time equal to or exceeding the dependable flow.

Figure 4.2 shows the flow duration curves of the rivers in the study catchment which indicates the availability of water on the time equal to or exceeding the dependable flow.

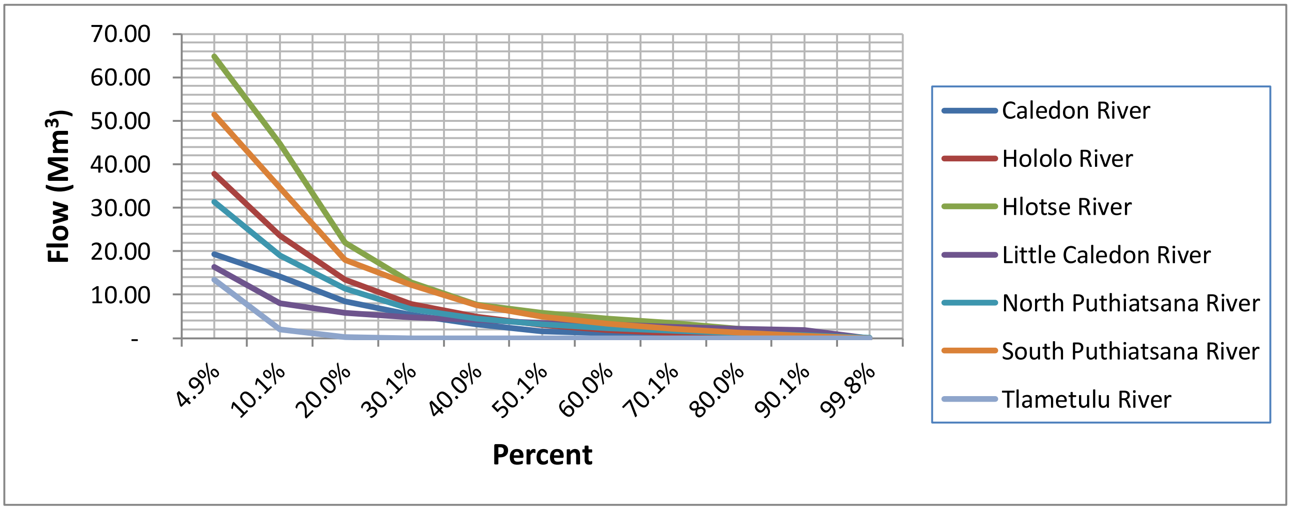


Figure 4.2: Flow duration curves of the rivers in the study catchment area (based on streams discharge data report of DWASA and DWALS)

4.6 Model Performance

The WEAP model essentially performs a mass balance of flow sequentially down a river system, making allowance for abstractions and inflows (Arranz and McCartney,2007). The WEAP model was tested on a monthly and annual time step basis. The model performance was evaluated using the statistical parameters such as mean error (ME), mean square error (MSE) and model coefficient of efficiency (EF), as described in section 3.10. The model compares stream flows recorded at gauging stations CG26 (1970 – 1983), CG25 (1986 – 2000) and D2H012 (1930 – 1961) to the observed flow at nearest upstream node. For example simulated flow at Node 4 (Figure 3.5) with the observed flow at CG25 of Hololo River gives EF 0.99. Comparing observed and simulated streamflow is one means to assess if the model is representing the system accurately. Table 4.17 presents statistical analysis for Hololo, Hlotse and Little Caledon Rivers. The results show that the simulated flows match the observed values very well with EF values of 0.99, 0.96 and 0.96 for the Hololo, Hlotse and Little Caledon Rivers, respectively.

Table 4.17: Statistical analysis of observed and simulated flows of the main tributaries

Rivers	Statistical parameters			
	Mean Qo (Mm^3)	Standard deviation (STDEV)	MSE $(Mm)^6$	EF
Hololo River (CG26)	7.39	312.88	4.06	0.99
Hlotse River (CG25)	16.78	1,292.49	57.42	0.96
Little Caledon River (D2H012)	6.26	91.30	3.26	0.96

The scatter plot diagrams provided in Figure 4.3, 4.4 and 4.5 for the mean monthly time step basis illustrate the very good correlation between the simulated and observed stream flow values for the major tributaries of the Caledon River. In these figures, the simulated and observed stream flow values demonstrate a very close tendency to the best fit line.

Figure 4.3 shows the mean monthly observed and simulated flow at CG26 of the Hololo River.

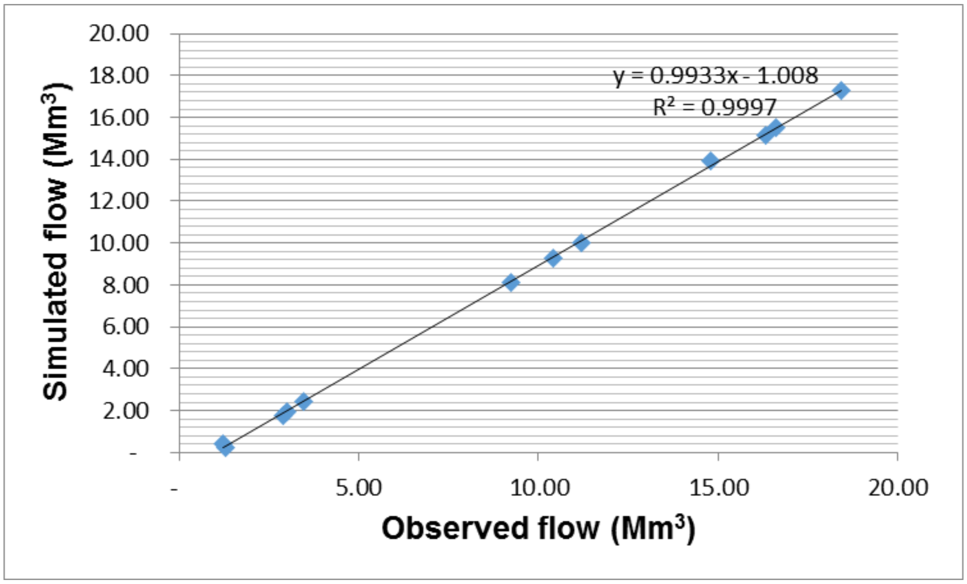


Figure 4.3: Scatter plot diagram of mean monthly observed and simulated flow at CG26 of the Hololo River

The mean monthly observed and simulated flow at CG25 of the Hlotse River is illustrated in Figure 4.4.

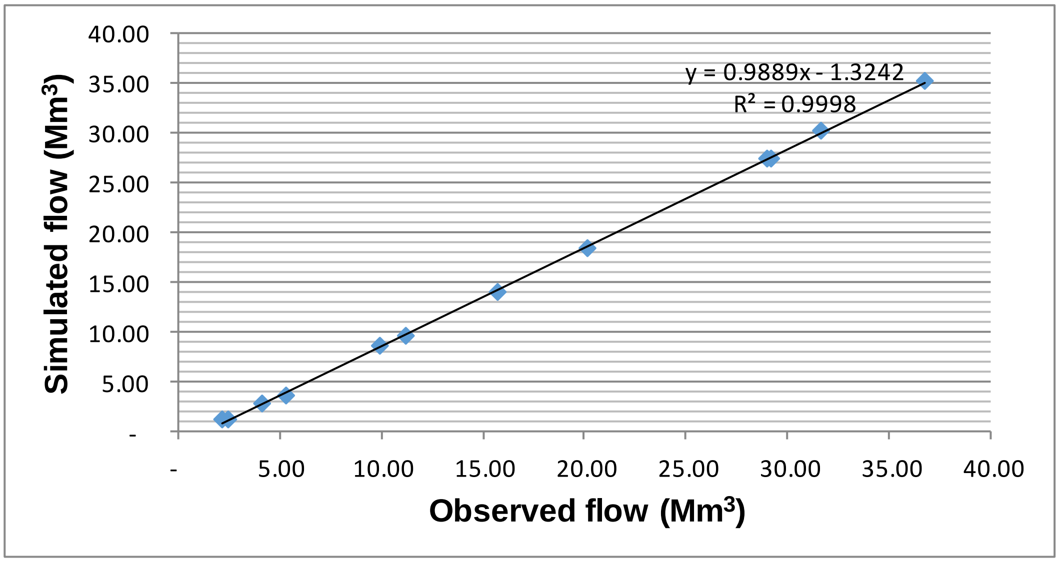


Figure 4.4: Scatter plot diagram of mean monthly observed and simulated flow at CG25 of the Hlotse River

The mean monthly observed and simulated flow at D2H012 of the Little Caledon River is shown in Figure 4.5.

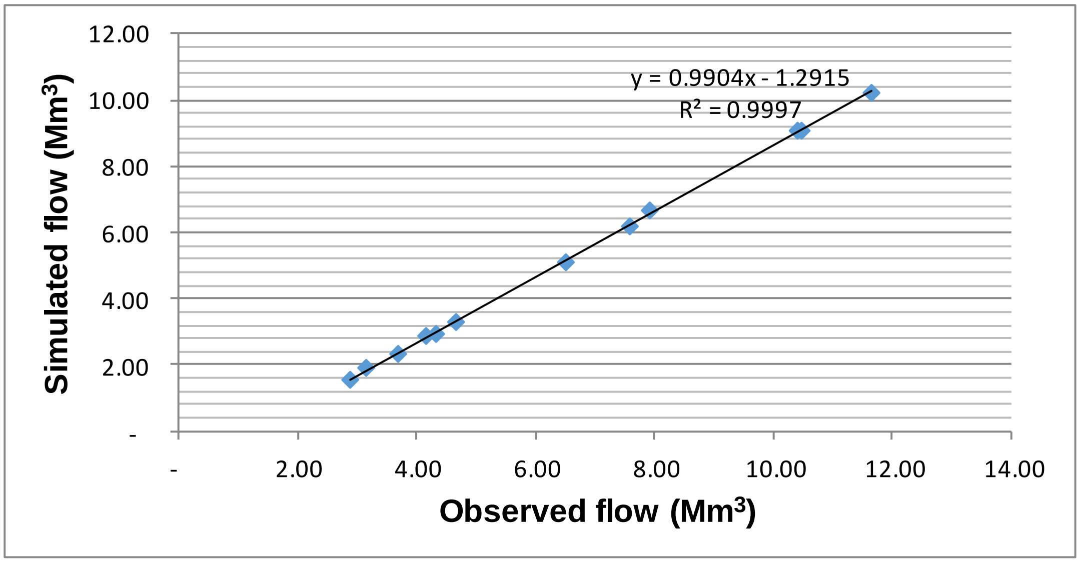


Figure 4.5: Scatter plot diagram of mean monthly observed and simulated flow at D2H012 of the Little Caledon River

Time series plots were created to show that the trend in the simulated monthly flows closely follows the measured data for each of the four tributaries. These time series are shown in Figures 4.6 to 4.8. The observed flows at gauged stations cover for the period between 1970 and 1983.

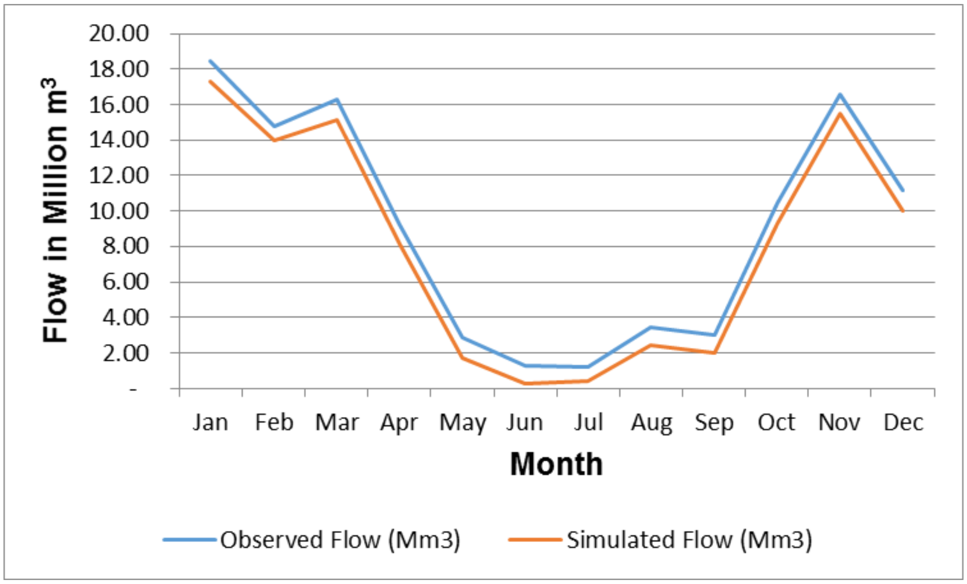


Figure 4.6: Comparison between observed and simulated flows of the Hololo River (CG26)

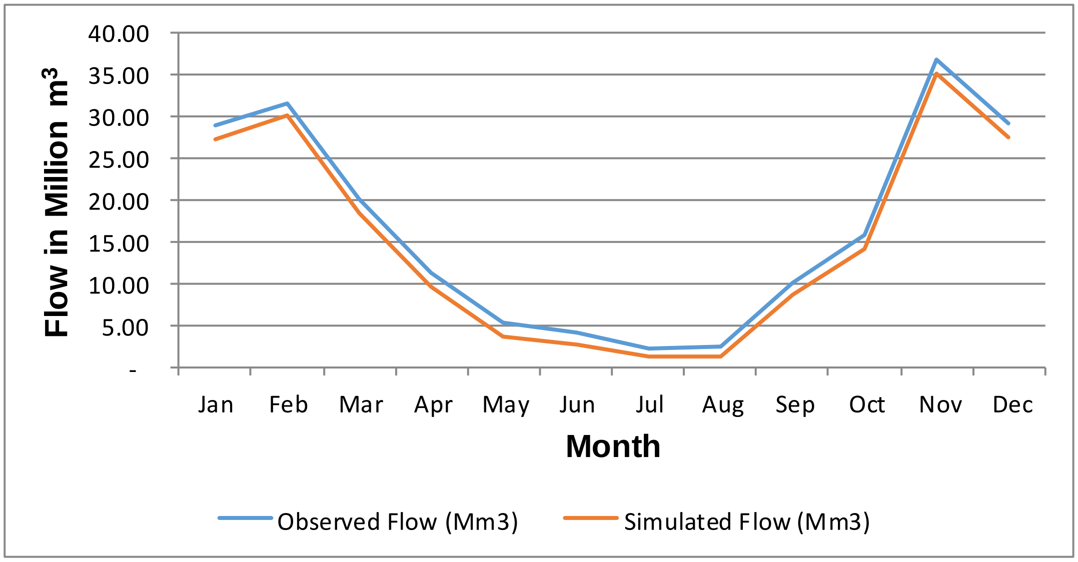


Figure 4.7: Comparison between observed and simulated flows of the Hlotse River (CG25).

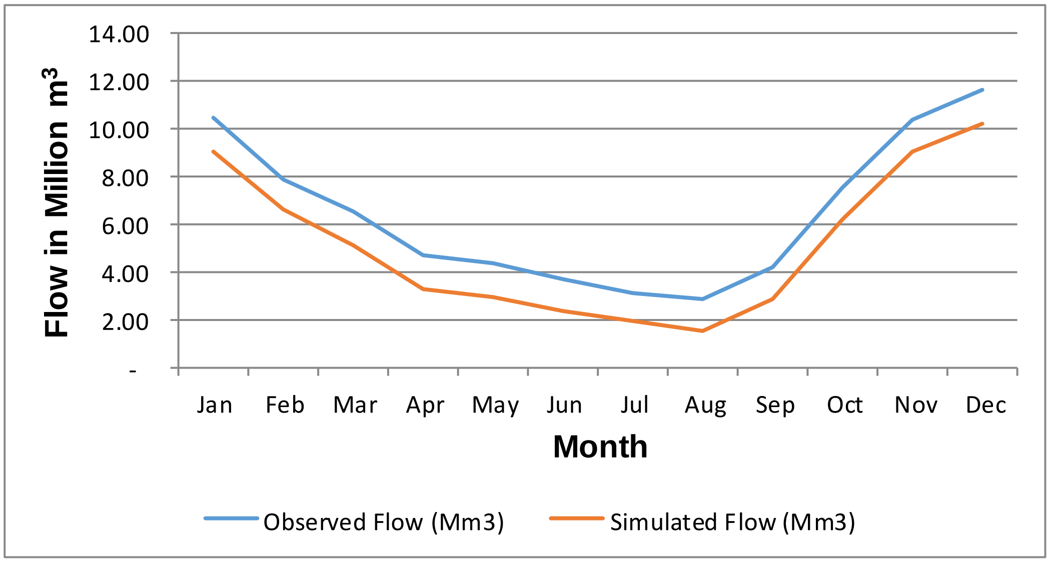


Figure 4.8: Comparison between observed and simulated flows of the Little Caledon River (D2H012).

4.7 Population Projection and Future Water Demands

4.7.1. Population Projection

The WEAP model wasused to project the population for both sides of the Caledon catchment for the reference years (2015-2050). WEAP has a built-in function called “GrowthForm”. Tables 4.18 and 4.19 present the projected populations under reference and high population growth scenarios, respectively.

Table 4.18: Projected population under reference scenario for Caledon catchment areas, 2015-2050 – WEAP model results

Sub-catchment	Area	Years				
		2015	2020	2030	2040	2050
Lesotho Rural	Berea	233 197	241 594	259 305	278 316	298 720
	Butha Buthe	96 018	99 476	106 768	114 596	122 997
	Leribe	255 749	264 958	284 383	305 231	327 608
	Mafeteng	174 383	182 915	201 253	221 430	243 630
	Maseru	193 533	203 002	223 354	245 747	270 384
	Total	**952 880**	**991 945**	**1 075 063**	**1 165 320**	**1 263 339**
Lesotho Urban	Butha Buthe Town	30 430	34 681	45 049	58 516	76 008
	Hlotse Town	32 097	36 922	48 854	64 643	85 535
	Mafeteng Town	39 516	44 905	57 989	74 885	96 705
	Mapoteng Town	10 640	11 621	13 864	16 539	19 730
	Maputse Town	34 692	39 907	52 804	69 869	92 450
	Maseru City	356 829	401 950	510 029	647 171	821 188
	Roma Town	12 764	14 378	18 244	23 149	29 374
	Teyateyaneng Town	26 240	28 660	34 190	40 787	48 658
	Total	**543 208**	**613 024**	**781 023**	**995 559**	**1 269 648**
Free State	Dihlabeng Municipality	142 065	160 734	205 753	263 381	337 150
	Manguang Municipality	841 240	975 228	1 310 625	1 761 370	2 367 134
	Mantsopa Municipality	56 356	63 762	81 621	104 481	133 745
	Mohokare Municipality	37 691	42 644	54 588	69 877	89 448
	Naledi Municipality	26 838	30 365	38 870	49 756	63 692
	Reddersburg and Edenburg Towns	13 938	15 769	20 186	25 840	33 077
	Setsoto Municipality	124 286	140 618	180 003	230 419	294 956
	Total	**1 242 414**	**1 429 120**	**1 891 645**	**2 505 125**	**3 319 203**

Table 4.19: Projected population under high population growth scenario for Caledon catchment areas, 2015-2050 – WEAP model results

Sub-catchment	Area	Years				
		2015	2020	2030	2040	2050
Lesotho Rural	Berea	233 197	270 916	330 245	402 566	490 726
	Butha Buthe	96 018	111 549	135 977	165 756	202 055
	Leribe	255 749	297 116	362 182	441 498	538 184
	Mafeteng	174 383	200 589	244 517	298 065	363 339
	Maseru	193 533	222 617	271 369	330 797	403 240
	Total	**952 880**	**1 102 786**	**1 344 290**	**1 638 682**	**1 997 544**
Lesotho Urban	Butha Buthe Town	30 430	35 760	48 058	64 586	86 799
	Hlotse Town	32 097	37 442	50 319	67 624	90 881
	Mafeteng Town	39 516	46 546	62 555	84 068	112 981
	Mapoteng Town	10 640	12 382	15 851	20 290	25 973
	Maputse Town	34 692	40 469	54 387	73 091	98 229
	Maseru City	356 829	423 278	568 850	764 486	1 027 406
	Roma Town	12 764	15 141	20 348	27 346	36 750
	Teyateyaneng Town	26 240	30 537	39 090	50 039	64 054
	Total	**543 208**	**641 555**	**859 456**	**1 151 531**	**1 543 072**
Free State	Dihlabeng Municipality	142 065	167 930	225 683	303 299	407 609
	Manguang Municipality	841 240	1 063 827	1 574 724	2 330 977	3 450 415
	Mantsopa Municipality	56 356	66 616	89 527	120 317	161 696
	Mohokare Municipality	37 691	44 553	59 875	80 467	108 141
	Naledi Municipality	26 838	31 724	42 635	57 298	77 003
	Reddersburg and Edenburg Towns	13 938	16 475	22 142	29 756	39 990
	Setsoto Municipality	124 286	146 914	197 440	265 342	356 598
	Total	**1 242 414**	**1 538 039**	**2 212 026**	**3 187 456**	**4 601 452**

4.7.2 Future Water Demand

The future water demands are influenced mainly by population increases and economic activities in the catchment including industry and irrigation sector expansion. In comparing scenarios, the water demand increases more over time under a high population growth scenario than the reference and increased Lesotho irrigation scenarios. The projected demands all users under each scenario are shown in Appendix A. In 2015 the annual water demand was 254.12 Mm^3 in all scenarios. Under the high population growth scenario the demand will increase to 301.73 Mm^3, 409.45 Mm^3, 557.40 Mm^3 and 763.16 Mm^3 in 2020, 2030, 2040 and 2050 respectively. Under the irrigation scenario it will increase to 328.50 Mm^3, 404.48 Mm^3, 500.52 Mm^3 and 623.12 Mm^3 in 2020, 2030, 2040 and 2050 respectively (WEAP model result). Figure 4.11 shows the projected water demands under the reference, high population growth and irrigation scenarios.

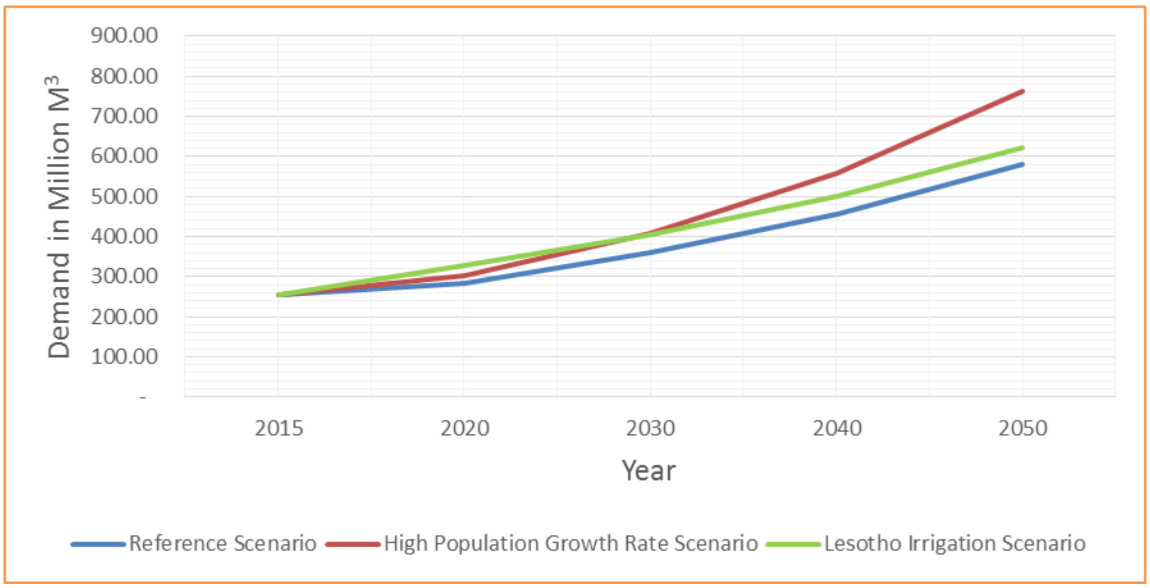


Figure 4.9 Water demand projection under reference, high population growth rate and increased Lesotho irrigation scenarios, 2015-2050.

Considering the sectoral aspects of water demand, domestic water demand dominates. Under the reference scenario the domestic demand comprises 78%, 79%, 81%, 82% and 83% of the total demands (254.12 Mm^3, 284.33 Mm^3, 360.31 Mm^3, 456.35 Mm^3 and 578.96 Mm^3) in 2015, 2020, 2030, 2040 and 2050 respectively. The livestock and irrigation sectors comprise the remaining portion of water demand. Under the high population growth scenario, domestic water demand increases substantially after 2020 compared to the reference scenario. It accounts for 80%, 83%, 85% and 87% of total water demands (301.73 Mm^3, 409.45 Mm^3, 557.40 Mm^3 and 763.16 Mm^3) in 2020, 2030, 2040 and 2050 respectively. Under the increased irrigation scenario, since irrigation activities are expected to start on the Lesotho side of the catchment in 2020, the average percentage comprising domestic water demand decreased to 74% of the total water demand (WEAP model result). Figures 4.10, 4.11 and 4.12 show the projected water demands of the different sectors under the reference, high population growth and irrigation scenarios.

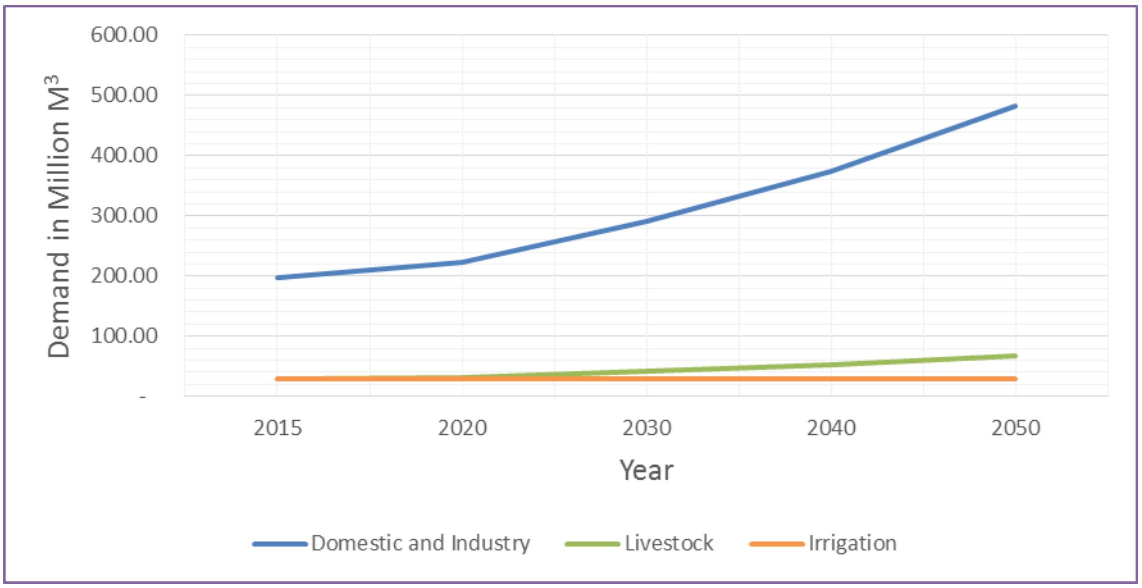


Figure 4.10: Water demand projection under reference scenario, 2015-2050

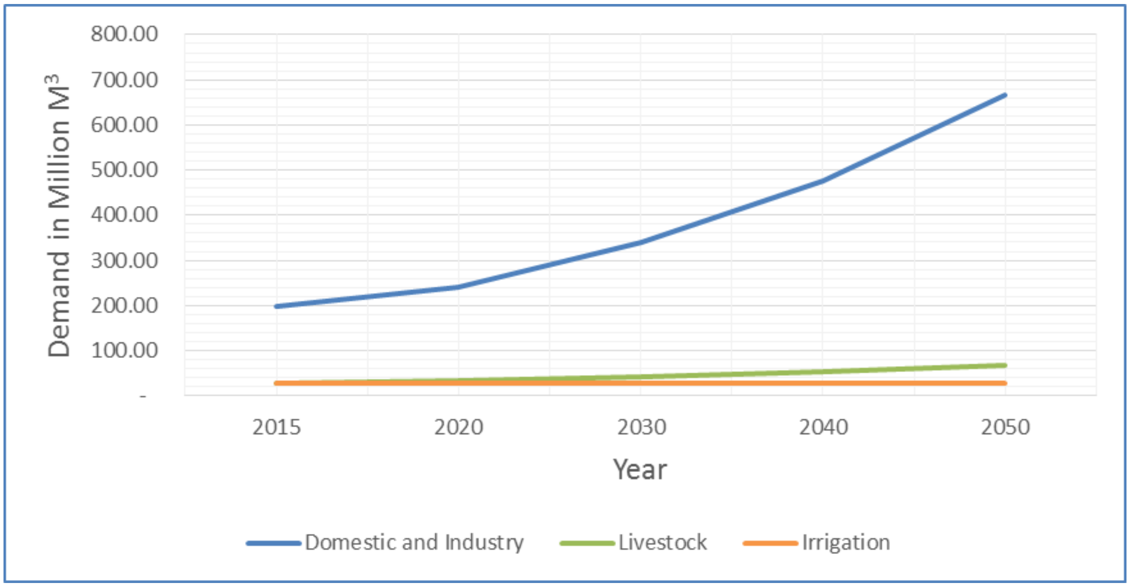


Figure 4.11: Water demand projection under high population growth scenario, 2015-2050

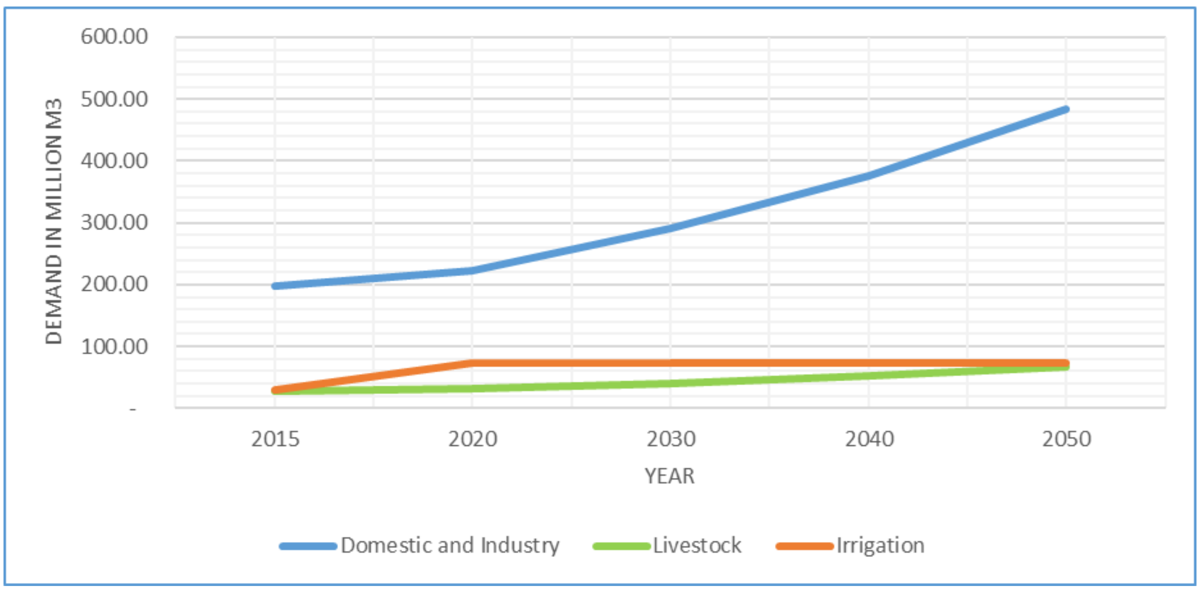


Figure 4.12: Water demand projection under Lesotho irrigation increase scenario, 2015-2050.

4.8 Unmet Demands

In this section the amount of demands site's requirement that is not met under each scenario is discussed. Unmet demand is the amount of water required but not supplied from the source. It is useful to know the magnitude of the water shortage (Sieber and Purkey, 2015).

The unmet demand occurs due to the amount of water used by other sectors and the amount allocated to EFRs. The WEAP model results show that a high population growth increases the water shortage for all water use sectors in the catchment. Under a high population growth scenario, the unmet demand occurred from May to October whereas under the reference, EFR and increased irrigation scenarios the unmet demand occurred only from June to September. The annual unmet demand is increased substantially after 2020 in a high population growth scenario when the population growth rates are altered (Appendix B). The water demand for irrigation is covered or no unmet demands are registered in all years. This is because active irrigation activities happen from December to May when enough water is available from the rivers. Table 4.20 presents the total projected unmet demand registered for 2015 to 2050.

Table 4.20: Annual unmet demand in Mm^3 under all scenarios and for all demand sites, 2015-2050

Scenario	Year				
	2015	**2020**	**2030**	**2040**	**2050**
High population growth scenario	0.36	0.69	4.02	33.91	121.22
Implementation of EFR at C6	0.36	0.40	2.83	16.41	63.36
Irrigation activities in Lesotho	0.36	0.40	2.83	6.85	46.09
Reference	0.36	0.40	2.83	6.85	42.59

Under the high population growth scenario, the total unmet demands occurring in 2015, 2020, 2030, 2040 and 2050 are 0.36 Mm^3, 0.69 Mm^3, 4.02 Mm^3, 33.91 Mm^3 and

121.22 Mm^3 respectively. The most affected sector is the domestic, followed by livestock. For example, the unmet domestic demand comprises 72% of the total unmet demand in 2020 and 77% of total unmet demand in 2050. In the same years, the unmet livestock demand comprises 28% (2020) and 21% (2050) of the total unmet demand. The demand from the irrigation sector is covered in all years. Table 4.21 presents the unmet demand registered for the various sectors under a high population growth scenario.

Table 4.21: Annual unmet demand in Mm^3 of sectors under a high population growth scenario, 2015-2050

Sector	Year				
	2015	**2020**	**2030**	**2040**	**2050**
Domestic	0.36	0.50	1.04	18.04	93.98
Industry	-	-	0.01	0.40	1.36
Livestock	-	0.19	2.97	15.47	25.88
Irrigation	0.00	0.00	0.00	0.00	0.00
Total	**0.36**	**0.69**	**4.02**	**33.91**	**121.22**

Under the implementation of the EFR scenario, the total unmet demand in 2015, 2020, 2030, 2040 and 2050 are 0.36 Mm^3, 0.40 Mm^3, 5.15 Mm^3, 26.02 Mm^3 and 84.51 Mm^3 respectively. In this scenario, the most affected sector is domestic, followed by livestock. Irrigation is the least affected sector. Table 4.22 presents the unmet demands for the EFR scenario.

Table 4.22: Annual unmet demand in Mm^3 for sectors under the EFR scenario, 2015-2050

Sector	Year				
	2015	**2020**	**2030**	**2040**	**2050**
Domestic	0.36	0.40	2.83	16.23	62.44
Industry	-	-	-	0.18	0.92
Livestock	-	-	2.33	9.61	21.15
Irrigation	0.00	0.00	0.00	0.00	0.00
Total	**0.36**	**0.40**	**5.15**	**26.02**	**84.51**

With an increase in irrigation activities in Lesotho, the total unmet demands in 2015, 2020, 2030, 2040 and 2050 are 0.36 Mm^3, 0.40 Mm^3, 2.83 Mm^3, 6.85 Mm^3 and 46.09 Mm^3 respectively. In this scenario domestic demand is also the most affected sector compared to other sectors. The demands for the irrigation and industry sectors were covered in all years. Table 4.23 shows the unmet demands of the various sectors under the increased irrigation scenario.

Table 4.23: Annual unmet demands in Mm^3 of sectors in irrigation added scenario, 2015-2050

Sector	Year				
	2015	**2020**	**2030**	**2040**	**2050**
Domestic	0.36	0.40	0.50	1.49	23.49
Industry	-	-	-	0.05	0.51
Livestock	-	-	2.33	5.30	22.09
Irrigation	0.00	0.00	0.00	0.00	0.00
Total	**0.36**	**0.40**	**2.83**	**6.85**	**46.09**

4.9 Water Resources and Demand Analysis

In this section the water resource and demand relationships are analysed. The years 2025 and 2050 were chosen to evaluate the water balance as they fall in the middle and at the end of the reference period. The relationships were analysed under two water use scenarios: high population growth and increased irrigation. The following section illustrates the results of the water balance analysis of the main Caledon River and its tributaries.

4.9.1 Little Caledon

The Little Caledon River (D2H012) joins the main river (the Caledon River) at the upper part of the Caledon catchment. It originates from the Free State side of the catchment. The annual flow of the Little Caledon is estimated at 70.49 Mm^3 (DWASA, 2015). The water users of this river are the Dihlabeng municipalities (node 14) and Dihlabeng livestock (node 35) (Figure 3.5). Figure 4.13 and Figure 4.14 illustrate the supply and demand results under the high population growth and intensified irrigation scenarios in 2025 and 2050. As can be noted from the two figures, the supply is higher than the demand in all months. Even during a low flow period, the available flow meets the demands.

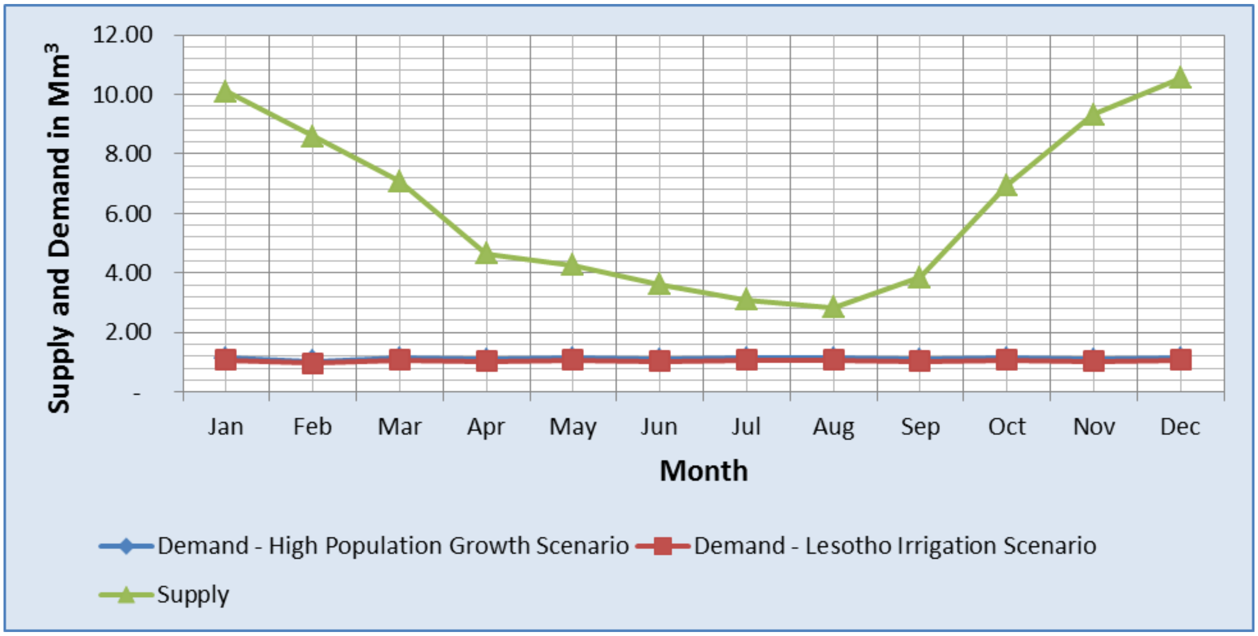


Figure 4.13: Water balance in the Little Caledon River in 2025

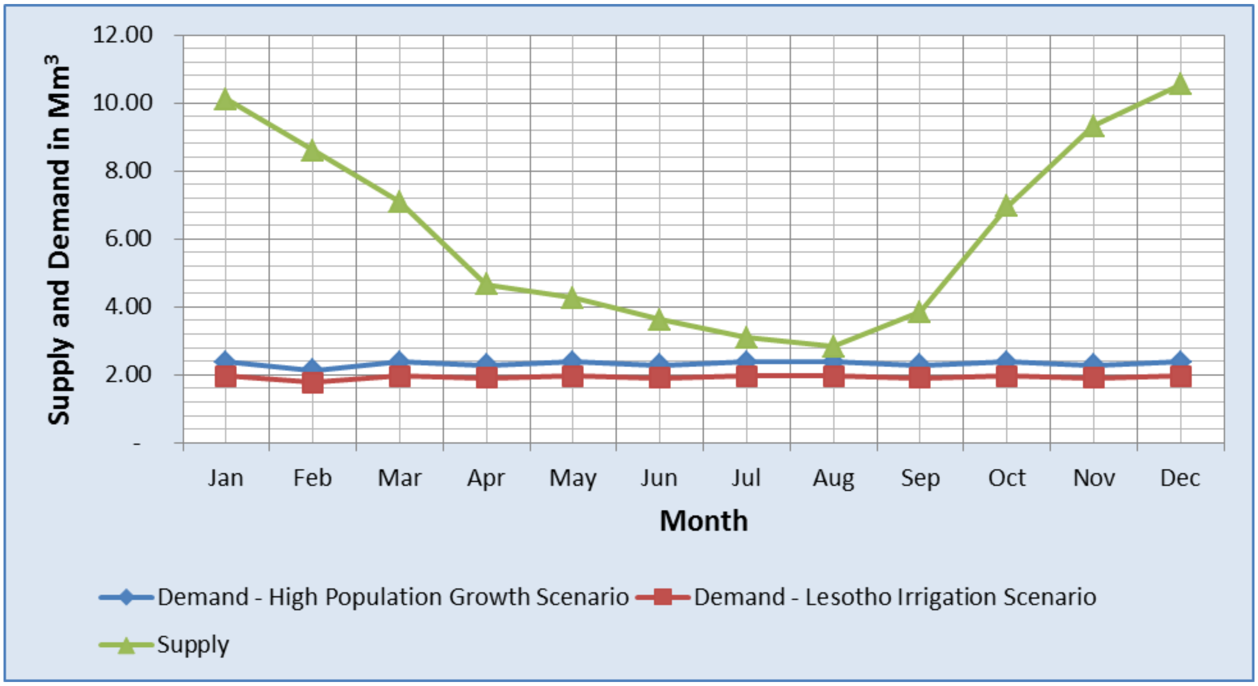


Figure 4.14: Water balance in the Little Caledon River in 2050

4.9.2 Hololo River

Hololo River originates in the Lesotho highlands and has an annual flow of 100.77 Mm^3. Hololo River also joins the Caledon River at the upper part of the Caledon catchment. The water users of this river are the Butha Buthe industrial (node 21), Butha Buthe livestock (node 30), Butha Buthe rural domestic (node 5) and Butha Buthe urban domestic (node 4) sectors (Figure 3.5). The annual total water requirements of these sectors under the high population growth and increased irrigation scenarios in 2025 are 12.21 Mm^3 and 11.43 Mm^3 respectively. In 2050 for the high population growth scenario, the total annual demand is 22.66 Mm^3. However, during June and July the available river flow is less than the requirements and, as a result, the demands are not satisfied for both scenarios indicating a potential water shortage. Figures 4.15 and 4.16 present the relationship between supply and demand for the irrigation and high population scenarios in 2025 and 2050.

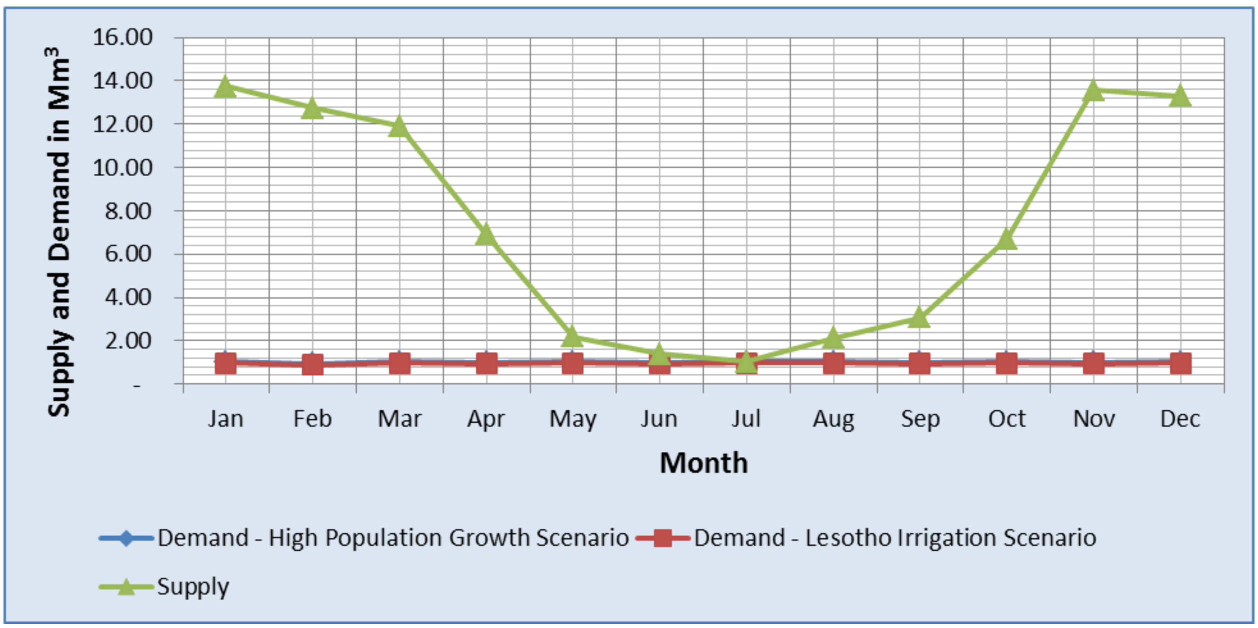


Figure 4.15: Water balance in Hololo River in 2025

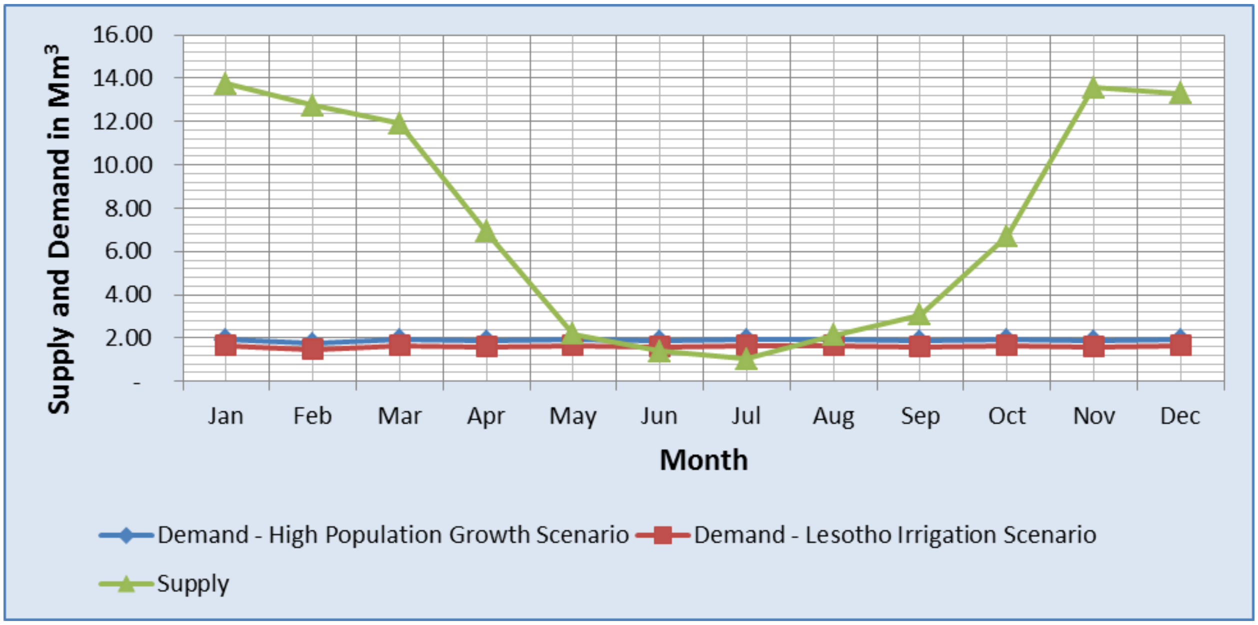


Figure 4.16: Water balance in the Hololo River in 2050

4.9.3 Hlotse River

The annual flow of Hlotse River is 193.67 Mm^3 and it also joins the Caledon River at the upper part of the Caledon catchment. It originates in the Lesotho part of the catchment. The water users of this river are the Hlotse town domestic (node 1), Leribe livestock (node 31) and Leribe rural domestic (node 30) sectors. The annual total water requirements of these sectors under a high population growth and intensified irrigation scenario in 2025 are 21.24 Mm^3 and 19.46 Mm^3 respectively. In 2050 the demand increases to 37.85 Mm^3 and 30.74 Mm^3 respectively. Figure 4.17 and 4.18 illustrate the relationship between supply and demand under the irrigation and high population scenarios. As can be observed from Figure 4.18, the river flow does not meet the demand under the high population scenario in July 2050.

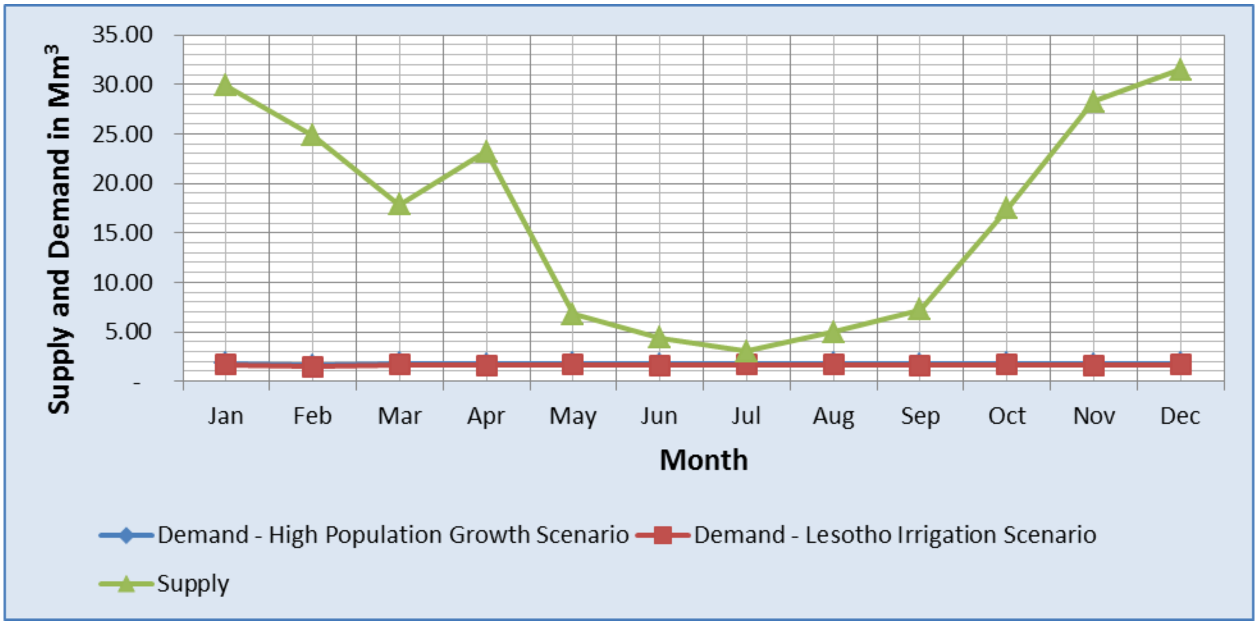


Figure 4.17: Water balance in the Hlotse River in 2025

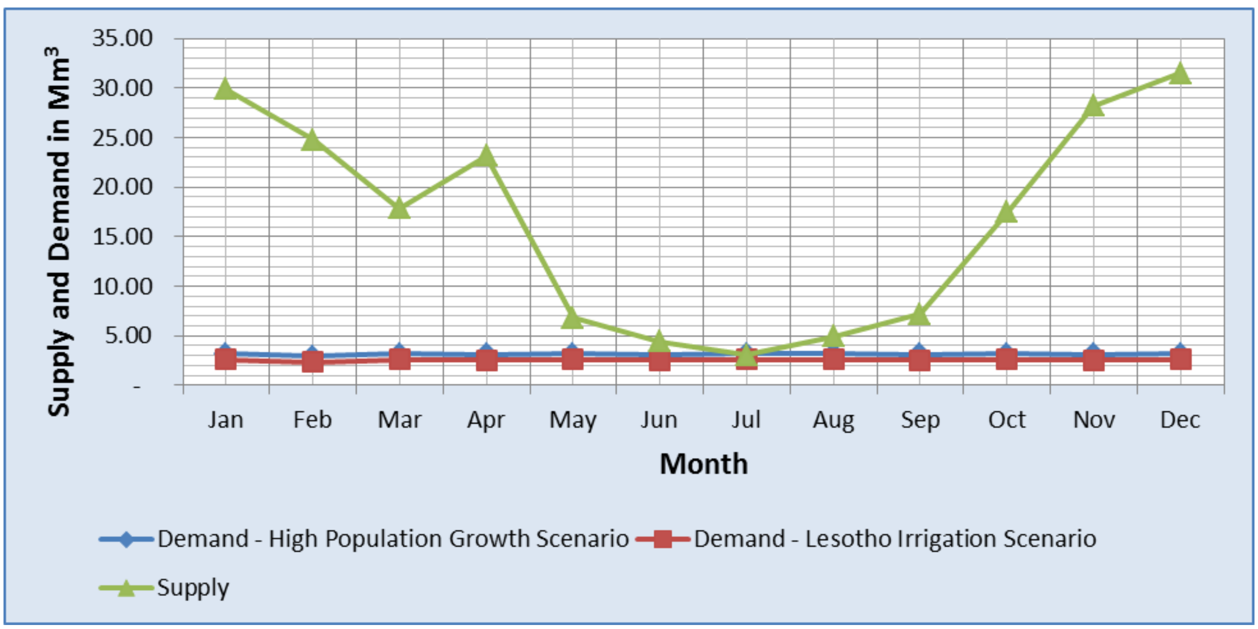


Figure 4.18: Water balance in the Hlotse River in 2050

4.9.4 North Phuthiatsana and Tebe Tebe Rivers

The North Phuthiatsana and Tebe Tebe Rivers originate from the Lesotho side of the catchment and they join together before reaching the Caledon River. The annual flow of both rivers was recorded as 102.54 Mm^3. The water users of this river are the Berea rural domestic (node 8), Mapoteng town (node 7), Teteyaneng industrial (node 23) and Teyateyaneng town domestic (node 6) sectors (Figure 3.5). The annual water requirements of these water users, under high population growth and increased irrigation scenarios, in 2025 are 13.18 Mm^3 and 11.30 Mm^3 respectively and in 2050 this demand increases to 22.43 Mm^3 and 14.80 Mm^3. Figures 4.19 and 4.20 present the relationship between supply and demand for the irrigation and high population scenarios in 2025 and 2050. As shown in Figure 4.20, in July 2050 the flow diminishes and is lower than the requirement resulting in a potential water shortage under the high population growth scenario.

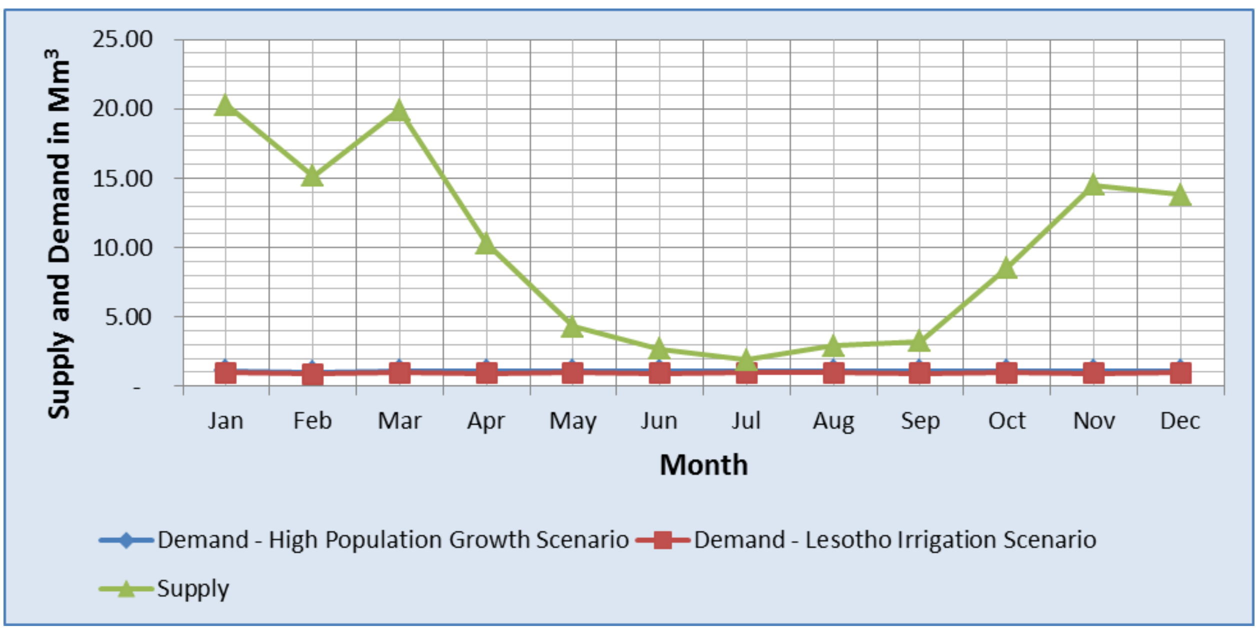


Figure 4.19: Water balance in the North Puthiatsana River in 2025

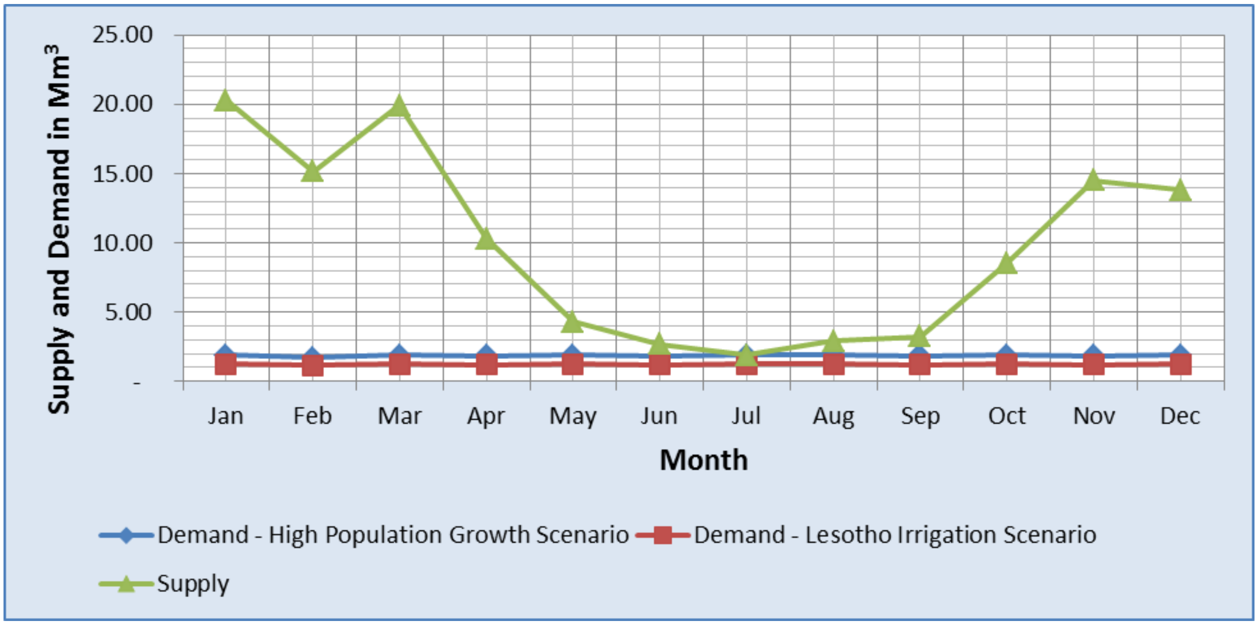


Figure 4.20: Water balance in the North Puthiatsana River in 2050

4.9.5 South Phuthiatsana River

The South Puthiatsana River is a major tributary of the Caledon River Basin in the lower part of the Caledon catchment. It originates from the Lesotho side of the catchment. Its annual flow is 155.91 Mm^3. Currently, a reservoir called Metolong Dam, which was built in the middle reaches of the South Phuthiatsana River, is operational. The main purpose of the dam is to meet the future water supply of Maseru and the neighbouring towns such as Mazenod, Roma and Teyateyaneng up to the year 2020. The results show that the coverage increases and unmet demands decrease with the addition of this dam. For example, in 2050 the annual total unmet demands will be 42.59 Mm^3 and 105.79 Mm^3 with and without Metolong Dam respectively.

The water users from this river are the Maseru city domestic (node 26), Roma town domestic (node 10), Teyateyaneng town domestic (node 28), Maseru rural domestic (node 11), Maseru city industry (node 27) and Teyateyaneng town industry (node 29) sectors (Figure 3.5). The river is considered as having a priority supply preference value of 2 for domestic and industrial supplies of Maseru city and Teyateyaneng town since these towns obtain water primarily from the Caledon River. The results show that in 2025 the demands will not be meet in July, August and September under the high population growth scenario and in July under the increased irrigation scenario. In 2050 a water shortage will occur from May to October in the case of the high population growth scenario. Under the increased irrigation scenario, water shortages will occur from June to September in 2050. Figures 4.21 and 4.22 present the supply-demand relationship for the South Puthiatsana River in 2025 and 2050.

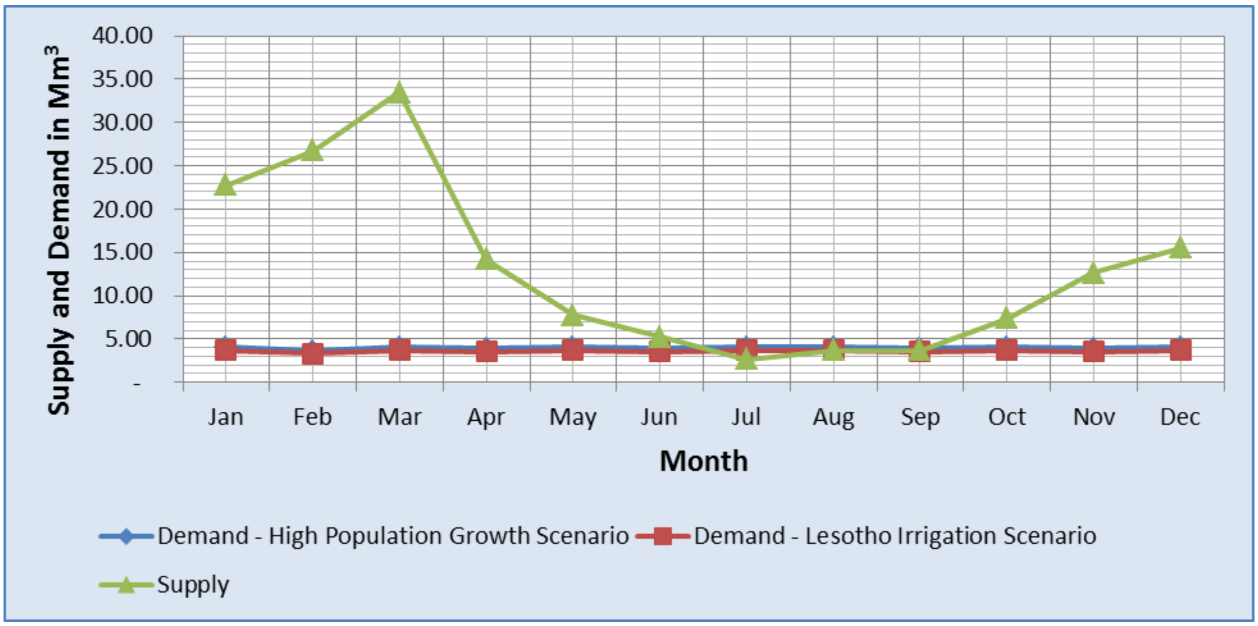


Figure 4.21: Water balance in the South Puthiatsana River in 2025

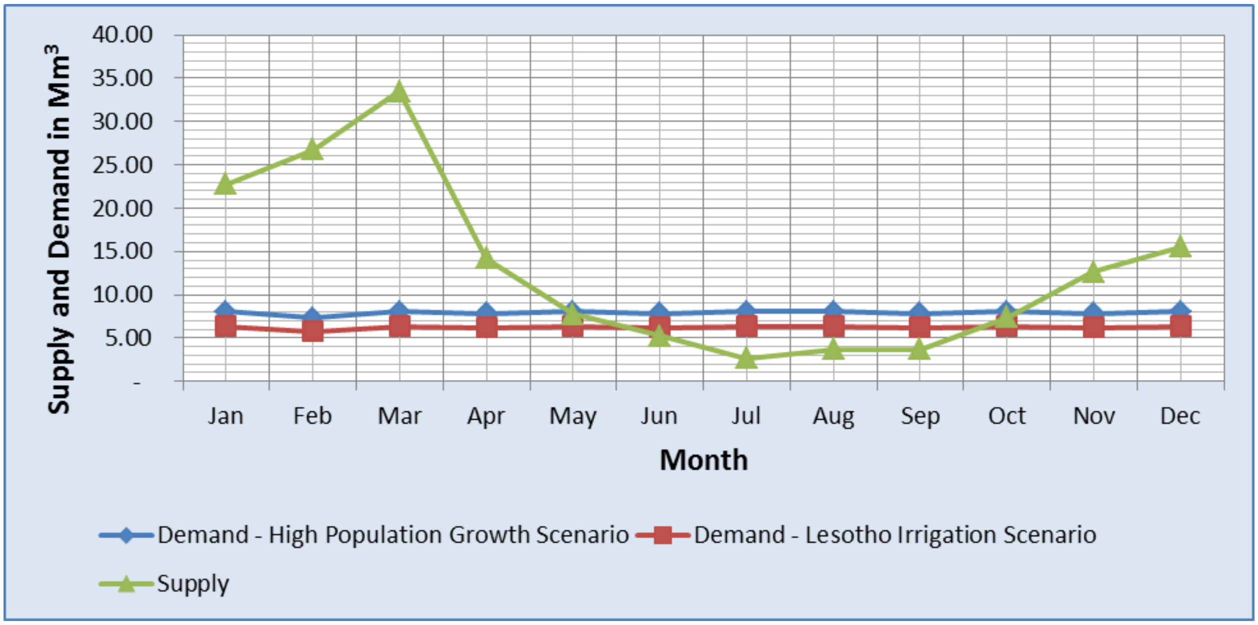


Figure 4.22: Water balance in the South Puthiatsana River in 2050

4.9.6 Caledon River

The mean annual flow of the Caledon River (which is the main river in this study) recorded at its origin (CG37) is 55.21 Mm^3. The rivers such as the Little Caledon, Hololo, Hlotse, Grootspriut, Mopeli, North Puthiatsana, South Puthiatsan, Talemtulu and Leeu are major tributaries of the Caledon River. According to the DWASA, nearly 70% of the total surface runoff flowing through the Upper Caledon under natural conditions originates from Lesotho and 30% from the Free State in South Africa. The Caledon's mean annual flow is 1 347.95 Mm^3 at the lower end of the river before it joins the Orange-Senqu River. Its tributaries in the upstream catchment (within the border of Lesotho) contribute a total of 776.61 Mm^3 to the river flow. The Caledon River is a source of water supply for 28 demand sites (Figure 3.5). Under the high population growth scenario, the total annual demand in 2025 is 270.83 Mm^3 and in 2050 it is 616.97 Mm^3 which is 77% and 80% of total water demand respectively. Under the irrigation scenario for the same years the demands are 291.82 Mm^3 and 509.42 Mm^3, respectively. Figures 4.23 and 4.24 present the supply and demand in 2025 and 2050. It can be noted that the available supplies do not satisfy the demands during low flow periods, especially from May to September. During this period the highest unmet demands were registered in the area.

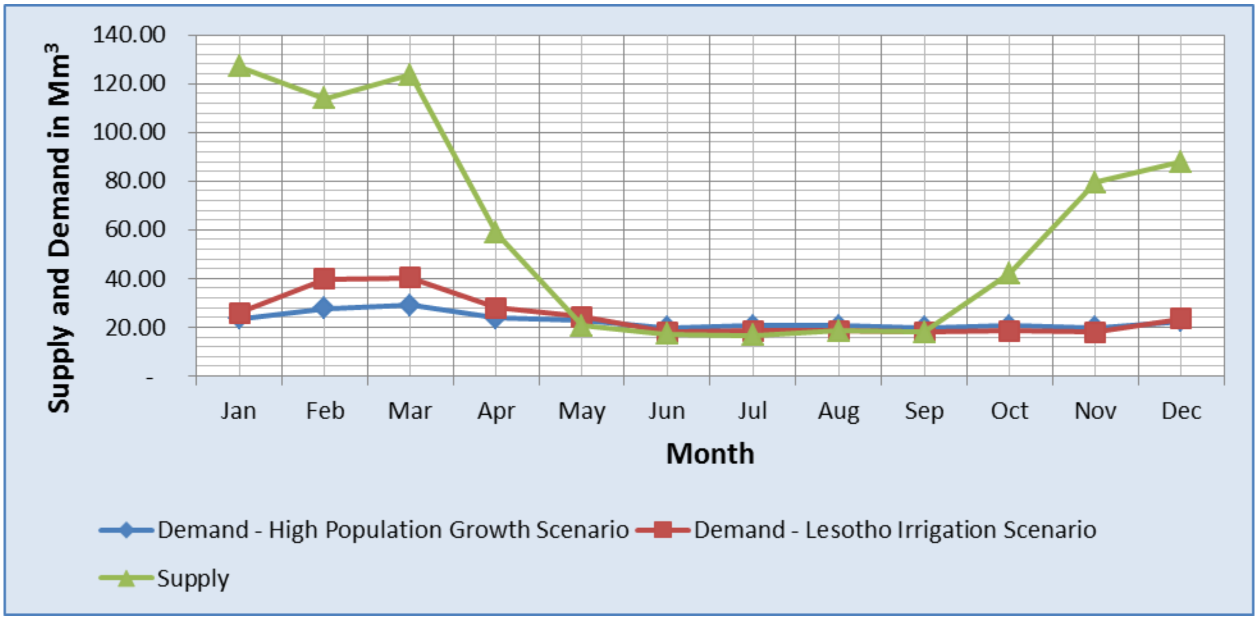


Figure 4.23: Water balance in Caledon River in 2025

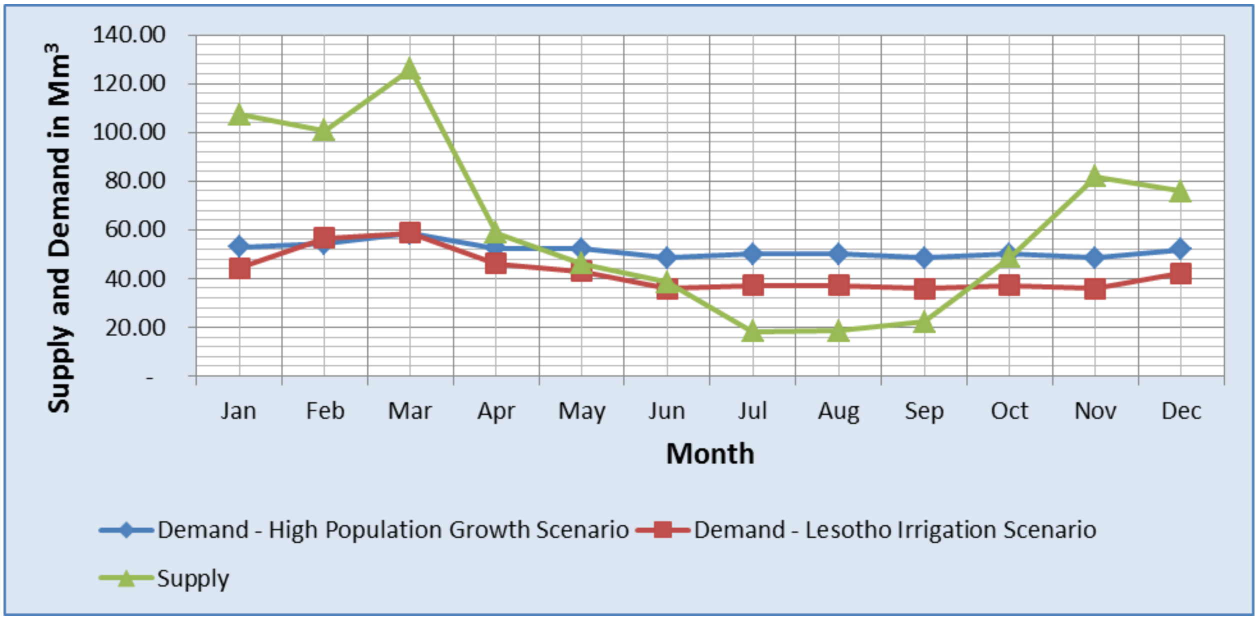


Figure 4.24: Water balance in the Caledon River in 2050

CHAPTER 5: CONCLUSIONS AND RECOMMENDATIONS

5.1 Introduction

The Caledon River Basin is a source of water for different water use sectors such as the domestic, irrigation, livestock and industry sectors in the Free State of South Africa and Lesotho. It contributes also a significant volume of water to downstream in forming the Orange River. Analysing its water balance using WEAP model helps decision makers in future managing the natural variability of water availability, and frequent or unexpected water shortfalls. The future water demands have been evaluated under certain scenarios and these are: high population growth, increased irrigation activity in Lesotho and the implementation of EFRs. A rising population and increasing water demands in urban and rural areas in conjunction with increased irrigation and industry activity and the implementation of an EFR will greatly intensify the need for careful water resource management. The reference period in the assessment of the impacts of increased water demands in the Caledon catchment is from 2015 up to 2050.

5.2 Discussion

The purpose of this study was to analyse the water balance of the Caledon River Basin, to determine the present water allocation for domestic, industrial and environmental demands, and to predict future water demands and allocation based on different development scenarios using the Water Evaluation and Planning System version 21 (WEAP21) as a Decision Support System (DSS) tool.

The modelling results show that the tributaries of the Caledon River have a better capacity to satisfy the water demands compared to the main river under normal climatic conditions regardless of the fact that the tributaries supply fewer water consumers. A comparison of the high population growth scenario with the reference scenario shows that most tributaries will not be under water stress conditions in all months of the years until 2050. An analysis of the Hololo and Puthiatsana Rivers flows shows that the supply meets the demand even in low flow periods. In the case of the Caledon River, the present conditions indicate that it is facing water scarcity periodically and is unable to meet the demands. The downstream users, including Maseru city and Bloemfontein, which are the major consumers of the Caledon River, are affected by water scarcity during the low flow periods, especially from July to September.

The water balance of the Caledon River Basin was analysed on the basis of projected water demands and a recorded data series of the discharge of the Caledon River and its tributaries. The analysis shows that the flow becomes minimal in June, July and August and is at its maximum in February and March. During the low flow period, high unmet demands are registered, especially for the main river where the majority of water users are located. In view of the flow variability, two programmes have been implemented in order for the Caledon River to tackle these challenges. The first one is the 1986 agreements and treaties made between the Republic of South Africa and the Kingdom of Lesotho to release an additional flow of water from the Lesotho highlands into the Caledon River. The release amounts to 5 Mm^3 of water delivered from the Muela low level outlet valves into the Hololo River system, which eventually flows down the Caledon to Maseru and other downstream towns (LHWP, 1986). The second programme was minimising the dependency on the Caledon River supply to Maseru city and Teyateyaneng town for domestic and industrial water demands by implementing a supply system from the South Puthiatsana River. Construction of the Metolong reservoir was the main step in the implementation of this programme from which other nearby small towns such as Roma, Mazenod, Mohale's Hoek and rural areas are benefiting. The purpose of the Water Reconciliation Strategy Study, which was undertaken in 2012 by the DWAF of South Africa, in cooperation with Bloem Water (BW) was to develop various possible future water balance scenarios up to 2035 and to design strategies to tackle the scarcity in Manguang municipalities and smaller towns such as Wepener, Dewetsdorp, Reddersburg, Edenburg and Excelsior.

The WEAP model optimizes water use in the catchment using an iterative linear programming algorithm, the objective of which the water delivered to demand sites, according to a set of user-defined priorities. All demand sites are assigned a priority between 1 and 99, where 1 is the highest priority and 99 is the lowest. When water is limited, the model restricts water allocation to demand sites with water priority. Based on this priori definition of priority, in terms of demand, the domestic, industry and irrigation sectors are given a priority value of 1 whereas livestock is given a priority value of 2. The EFR is given a priority value of 1. In terms of supply preference, water supply from the nearby rivers is assigned a priority value of 1 for all domestic and industry sectors and 2 for irrigation and livestock sectors.

Under the high population growth scenario, the Caledon River faces scarcity and becomes a water-stressed river. Under the irrigation added scenario, scarcity is considerably high compared to the reference scenario. As a consequence of the implementation of the EFR, since the flow was allocated as a percentage of the nMAR and the volume is high which ensures a substantial base flow, there will be more water flowing in the river but less water available to meet the anticipated user demands. Therefore, the unmet demands are high if the EFRs are fully implemented.

Population growth, the expansion of irrigation activities and EFRs put considerable pressure on the water resources of the Caledon River catchment and the simulation results show that this may lead to an increase in water scarcity. The WEAP modelling exercises indicate unmet demands in the years up to 2050 for all water demand sectors, namely, domestic, livestock, irrigation, industry and EFR.

5.3 Conclusion

The findings of the study show that the WEAP model enabled analyses water balance of the rivers. More accurate simulation of water allocation and demand management is possible if other unaccounted sources of water such as groundwater, springs and local dams, and losses and return flows are incorporated.

The results of the projects using the modelling framework indicates the projected demands will not fully be met, and the water supply coverage will becoming lessen and lessen overtime. Increasing water demands due to increased population and urbanization, and implementation of EFR are the driving forces in creating the scarcity in the catchment. Implementation of EFR ensures more water flowing in the rivers, but less water available to meet direct human demands and water shortages in the upstream users will increase.

5.4 Recommendations

The study provided useful information on future water resource management and planning in the Caledon catchment. It also indicates that exploiting river water alone is not reliable to satisfy the increased demands in the future. Hence, it is necessary to take into account groundwater reserves that are or could be exploited.

The main recommendations stemming from the study are described below.

1. A water balance analysis of the Caledon catchment up to the year 2050 was conducted and it is recommended that the results be used to assist in water resource decision making and planning by the decision makers in future.
2. Water allocation planning should be applied on the basis of water resource availability and demand priorities. For optimal water allocation in the Caledon catchment, in addition to the considerations taken in this study, the integration of additional data on groundwater, reservoirs and catchment characteristics is also required. Further research on these topics is thus recommended.
3. Further to the previous point, in order to minimise uncertainty on the potential water resource availability of the Caledon catchment and increase water availability, it is necessary to take into account groundwater reserves that are or could be exploited. Modelling exercises for reservoirs together with other water bodies in the catchment will increase the reliability of the results.

4. When unmet water demand increases, water supply coverage will decrease. This is an indication that dependence on surface water resources alone is not sufficient to satisfy the demands. Thus, exploiting groundwater, the reuse of wastewater and building storage reservoirs should be part of the solutions for long-term water use sustainability.
5. Finally, the study recommends that future research concentrate on the inclusion of data not taken into account in this study such as the hydraulic parameters of groundwater, groundwater storage, snowmelt, return flows and other factors relevant to the Caledon catchment area so as to provide more accurate and improved results.

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APPENDIXES

Appendix A: Annual Water Demand Projection

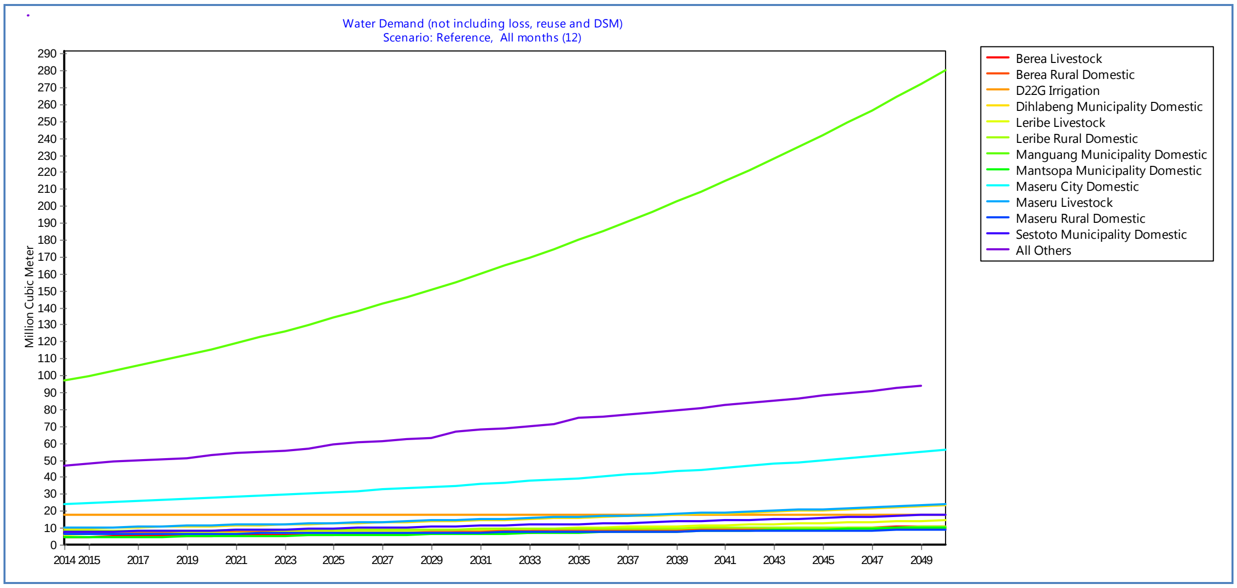

Figure A1: Water demand projection under reference scenario (WEAP model result)

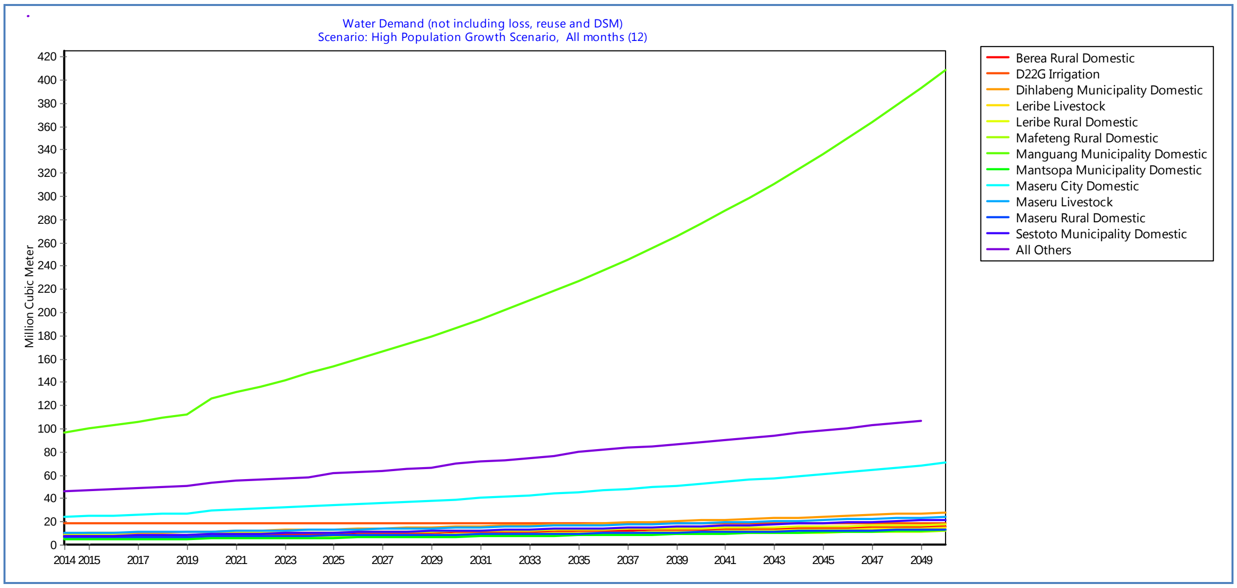

Figure A2: Water demand projection under high population growth scenario (WEAP model result)

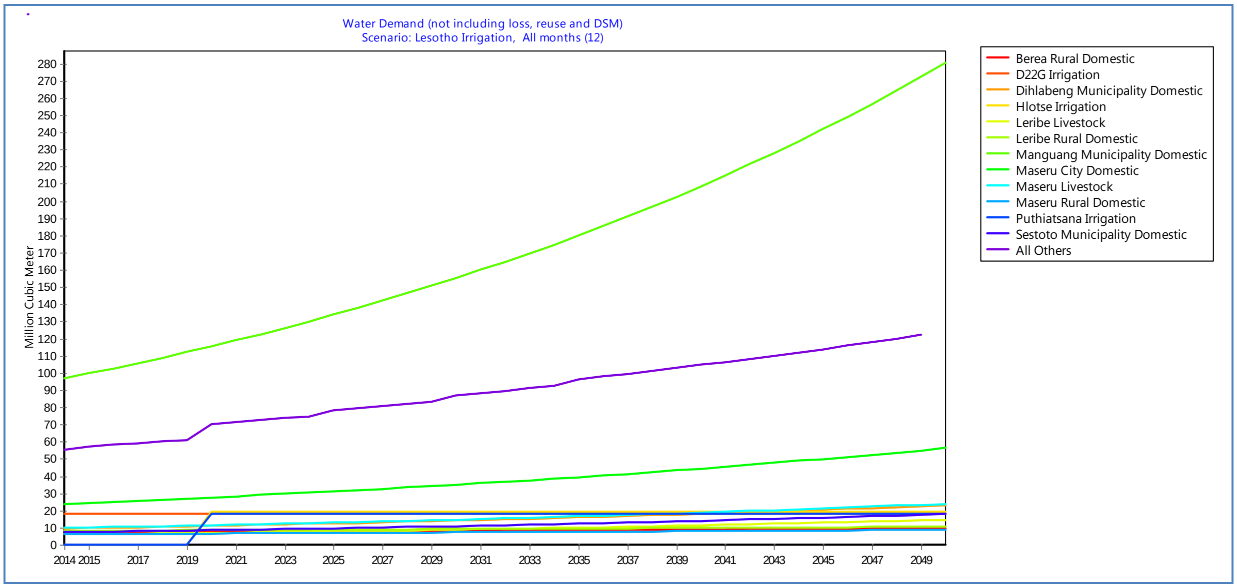

Figure A3: Water demand projection under irrigation added scenario (WEAP model result)

Appendix B: Annual Unmet Water Demand

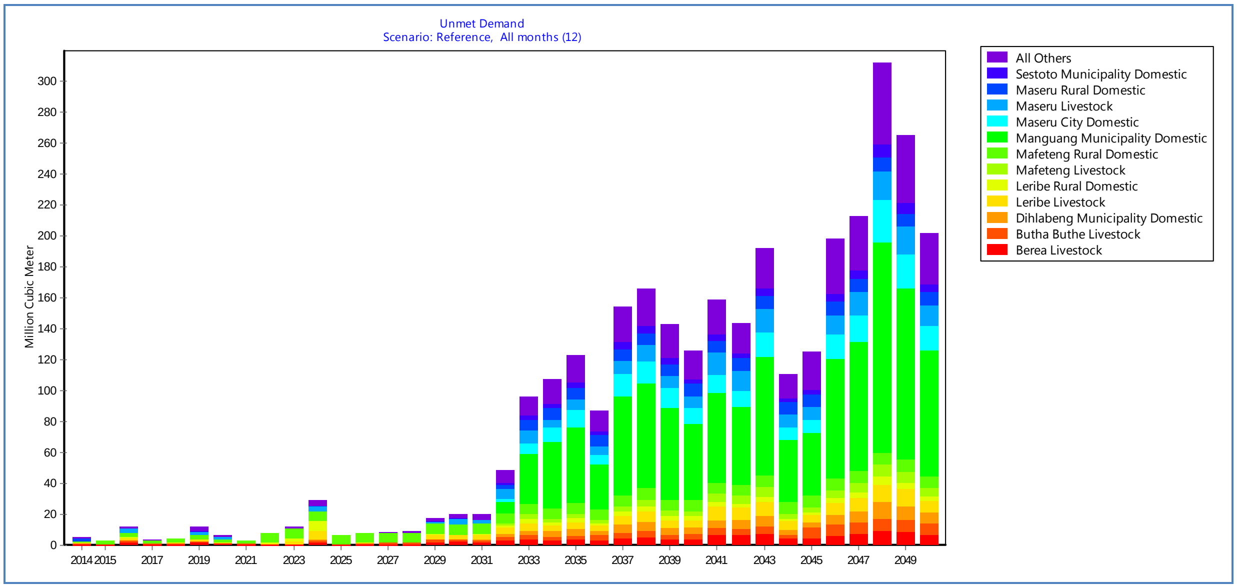

Figure B1: Unmet demands in all years under the reference scenario (WEAP model result)

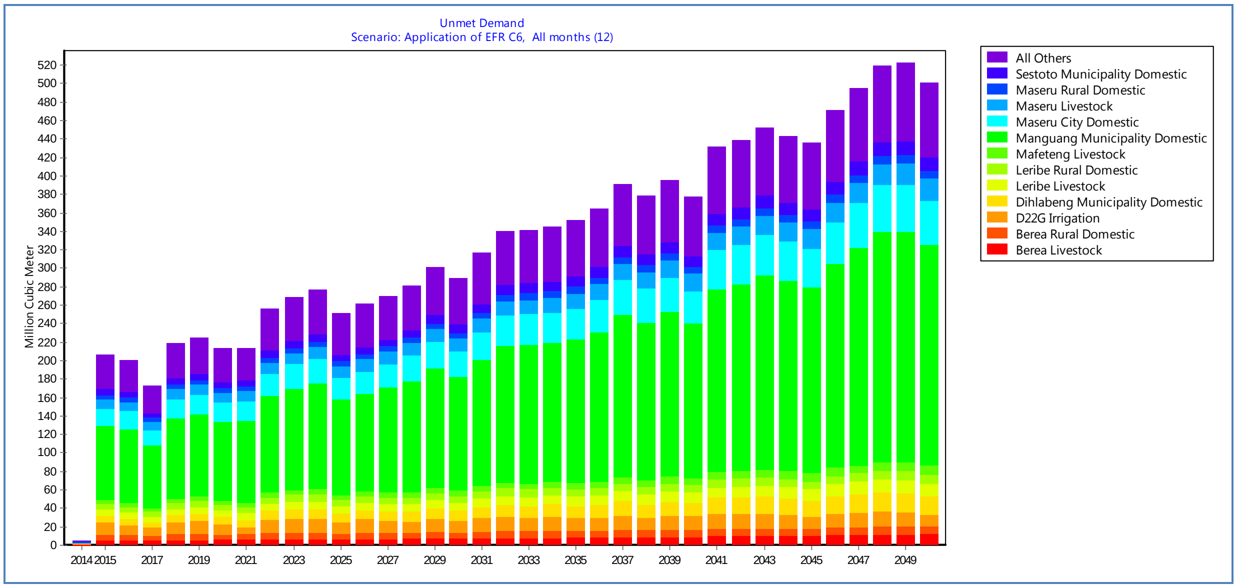

Figure B2: Unmet demands in all years when an EFR is added at C6 (WEAP model result)

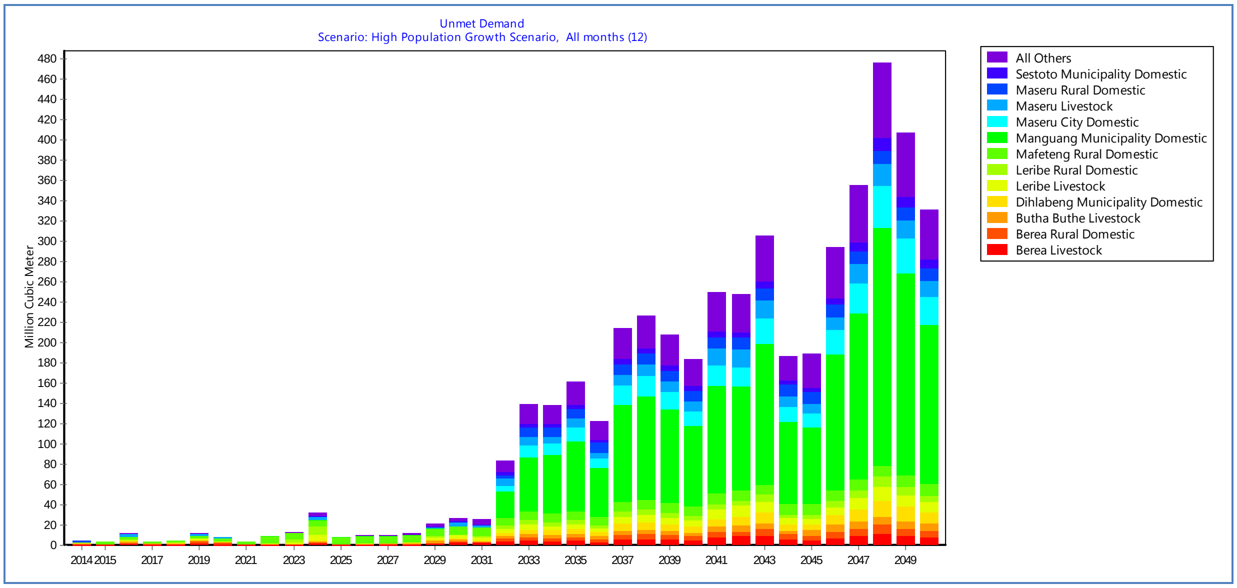

Figure B3: Unmet demands in all years under a high population growth scenario (WEAP model result)

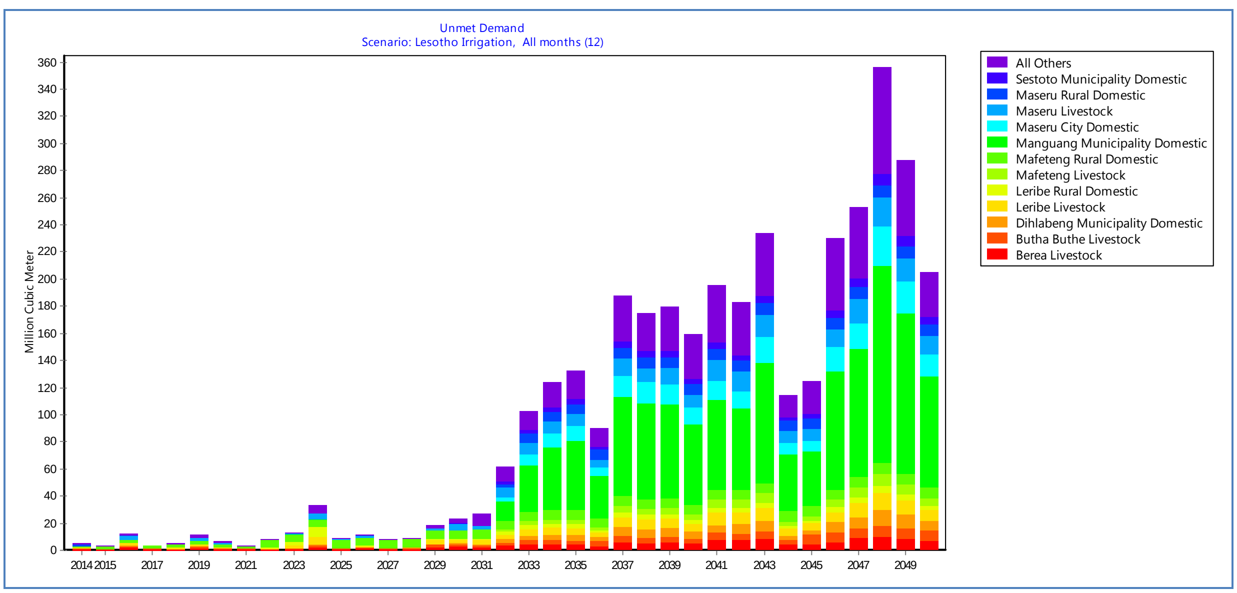

Figure B4: Unmet demands in all years under the irrigation added scenario (WEAP model result)