Master's thesis

NTNU
Norwegian University of Science and Technology
Faculty of Engineering
Department of Civil and Environmental Engineering

Helga Løset Skodjereite

Evaluating water allocation within the water-energy-food nexus in the lowlands of Lesotho

A case study of Hlotse river basin

Master's thesis in Civil and Environmental Engineering
Supervisor: Tor Haakon Bakken
Co-supervisor: Leif Lillehammer

June 2021

NTNU
Norwegian University of
Science and Technology

Helga Løset Skodjereite

Evaluating water allocation within the water-energy-food nexus in the lowlands of Lesotho

A case study of Hlotse river basin

Master's thesis in Civil and Environmental Engineering
Supervisor: Tor Haakon Bakken
Co-supervisor: Leif Lillehammer
June 2021

Norwegian University of Science and Technology
Faculty of Engineering
Department of Civil and Environmental Engineering

NTNU
Norwegian University of Science and Technology

Abstract

Water is one of the most important natural resources of Lesotho, located in Southern Africa. The relative abundance of water in the highlands of Lesotho compared to its surrounding areas constitutes the particularly strategic value of the water resources of Lesotho. The Lesotho Highlands Water Development Project, LHWP, forms the basis for water resource management in Lesotho through water export to South Africa and hydropower generation. Water-related challenges are prominent in the lowlands of Lesotho, where most of the population resides, and water availability is highly variable due to seasonal variations and lack of infrastructure developments. Careful and efficient management of water resources is viewed as a key to economic growth and sustainable development in Lesotho to secure, among other things, water availability for human consumption, agricultural production, and renewable energy generation.

The main objective of this study is to analyse the trade-offs of different water management strategies within the water-energy-food nexus in Hlotse river, located in the lowlands of Lesotho, and their likely impacts downstream in Caledon river. The objective is addressed by setting up a hydrological and water allocation model for the river basin using the software tool Water Evaluation and Planning System (WEAP). Scenarios for both planned and desired future developments of potable water supply and irrigation expansion are defined and explored in the model. The effects of regulation measures considering water transfers from Katse dam in the highlands into Hlotse river and reservoir regulation for hydropower production in Hlotse river are evaluated.

Significant water shortages are found, mainly from April to October, for planned and desired future developments of potable water supply and irrigation expansion relying on direct river abstractions in Hlotse river. The findings confirm that runoff in Hlotse river and Caledon river is largely exposed so seasonal variations both within and between years. This demonstrates a need for regulation measures to secure stable water supply, where the need for regulation to meet demands is not constant. The model simulations indicates that significant altering of the runoff in Hlotse river will give marginal effects further downstream in Caledon river. Simulation of water transfer volumes into Hlotse river within the existing framework for the LHWP of 3.75 MCM annually are insufficient to meet future demands in Hlotse river. This demonstrates a need for planning and refining the operational rules from the LHWP, facilitating flexible water transfers for various climatic conditions to meet the demands for water supply in the lowlands. This will require further assessments of the possible effect on the security of water supply to South Africa and the associated Treaty. Hydropower production simulated in WEAP for the proposed hydropower plant in Hlotse river, Hlotse HPP, is significantly lower than what is projected and found to constitute only 41% of the projected production for the proposed project. The results show that the proposed Hlotse HPP reservoirs can provide positive benefits and water security for downstream users if releases from the proposed reservoirs are adapted.

The uncertainties associated with the modelling in this study demonstrate that collection and processing of data, both in quantity and quality, and implementation of these into existing tools and plans is necessary for such models to function as an effective tool. However, the results demonstrate the usefulness of the WEAP model by combining a hydrological model with water allocation, where the model is found well-functioning for its purpose as an assisting tool and supplement for decision-making in water resource management.

Samandrag

Vatn er ein av dei viktigaste naturressursane i Lesotho, eit land i det Sørlige Afrika. Samanlikna med områda omkring har høglandet av Lesotho relativ overflod av vatn. Dette gjer at vassressursane i Lesotho er av spesielt strategisk verdi. Lesotho Highlands Development Project, LHWP, dannar grunnlaget for vannressursforvaltning i Lesotho gjennom eksport av vatn til Sør-Afrika og vannkraftproduksjon. I låglandet av Lesotho er det derimot store vass-relaterte utfordringar. Størsteparten av befolkninga er busett der og tilgang på vatn er svært variabel på grunn av sesongvariasjonar og mangel på infrastruktur. Det er behov for vassforsyning til menneskeleg forbruk, jordbruksproduksjon og til produksjon av fornybar energi. Effektiv og skånsom forvaltning av vassressursane er vurdert som svært viktig for økonomisk vekst og berekraftig utvikling i Lesotho.

Elva Hlotse ligger den nordvestlige delen av låglandet i Lesotho. Formålet med denne studien er å analysere ulike strategiar for vannressursforvatning og sjå på korleis dei kan påverke samanhengen mellom vatn, energi og matproduksjon i elva Hlotse. Eventuell påverkning nedstraums i vassdraget i elva Caledon er også vurdert. Oppgåva er løyst ved hjelp av eit modelleringsverktøy i programvaren Water Evaluation and Planning System (WEAP). Ulike scenario for planlagd og ønska framtidig utvikling innanfor forsyning av drikkevatn og vatning til jordbruk er definert og utforska i modellen. Det er også sett på effekt av reguleringstiltak som omfattar overføring av vatn til elva Hlotse frå dammen Katse. Vannkraftproduksjon og kraftverksregulering med magasiner i elva Hlotse er også vurdert.

Resultata frå denne studien viser betydelig mangel, i hovudsak frå april til oktober, for framtidig drikkevannsforsyning og vatning til jordbruk dersom forsyninga skal basere seg på direkte uttak av tilgjengelig vatn i elva Hlotse. Simuleringane bekrefter at vassføringa i elva Hlotse og Caledon er svært avhengig av sesongmessige variasjonar både gjennom året og mellom ulike år. Dette demonstrerer at det er behov for reguleringstiltak for å sikre stabil vassforsyning, og at reguleringsbehovet for å møte krava ikkje er konstant. Modellsimuleringane indikerer at betydelege endringar i avrenning i elva Hlotse vil gi marginale effekter nedstrøms i vassdraget i elva Caledon. Simulering av vassoverføring til elva Hlotse frå dammen Katse i høglandet med volum innanfor eksisterande rammer i traktaten for LHWP på 3.75 MCM i året er ikkje tilstrekkelig for å møte framtidige behov for utvikling i elva Hlotse. Dette demonstrerer eit behov for planlegging og vurdering av driftsmønsteret for overføring til låglandet frå LHWP. Vidare er det behov for fleksibel overføring under ulike klimatiske forhold for å møte framtidige utviklingsbehov. Det er behov for å gjere vidare vurderingar på effekten av leveringssikkerheten av vassforsyning til Sør Afrika og den tilhøyrande traktaten. Vannkraftproduksjonen simulert i WEAP for det foreslåtte kraftverket i elva Hlotse, Hlotse HPP, er betydelig lågare enn anslått og funne til å utgjere kun 41% av forventa produksjon for det foreslåtte prosjektet. Resulta viser at magasina planlagt for Hlotse HPP kan gi positive fordelar og betre forsyningssikkerhet for nedstraums interesser, forutsett at utsleppa frå magasina blir justert for dette.

Usikkerhetene knytta til modelleringa i denne studien viser at innsamling og behandling av data, både i mengde og kvalitet, og implementering av desse i eksisterande verktøy og planer er nødvendig for at slike modellar skal fungere som et effektivt verktøy. Resultata viser nytta av WEAP-modellen ved å kombinere ein hydrologisk modell med allokering av vatn til ulike formål. Modellen er vurdert til å fungere godt for sitt formål, som et supplerande hjelpemiddel for beslutningstaking innanfor vannressursforvaltning.

Preface

This thesis is submitted in partial fulfilment of the requirements for a Master of Science in Civil and Environmental Engineering at the Norwegian University of Science and Technology. The study has been performed between January and June 2021 with supervision of Professor Tor Haakon Bakken. The thesis is carried out in close cooperation with Multiconsult, with Leif Lillehammer as co-supervisor. The thesis is seen as a complementary analysis to the ongoing project Environmental Flow Assessment and Water Quality Modelling within the Lesotho Lowlands Water Development Phase II (LLWDP II).

The process of writing this thesis has been both rewarding and challenging. The problem formulation for the study is a topic of current interest and has required an interdisciplinary approach, which was one of my motivations for choosing this task. The process has required application of knowledge and tools previously introduced during the course of study at NTNU and providing me experience with new tools such as QGIS and the modelling tool WEAP. The cooperation with Multiconsult and their international partners has provided knowledge and insight into the forward-thinking E-Flow methodology DRIFT, although it has not been applied directly in this thesis.

The COVID-19 virus has posed some additional challenges for this study, including the postponed start of the project to which this study is connected and no opportunity for field visits and study area investigation. However, I have experienced both the rewarding aspects and the challenges of working with an international project, which is often quite different from what is traditionally the case here in Norway.

My greatest thanks to my supervisor Tor Haakon Bakken for giving me this opportunity to study this topic of interest and the support you have provided throughout this process. My greatest thanks also to Leif Lillehammer in Multiconsult and Ron Passchier in Deltares, for your engagement and support in this study. I appreciate your generosity while sharing your expertise, experiences and letting students gain insight and experience working with international projects.

I want to thank my family for their support and patience in this process. A special thanks and my greatest gratitude to Hege, my godmother, who has encouraged me in the writing process and provided me invaluable support in completing this assignment. I am eternally grateful for your commitment to the thesis, our discussions, and the feedback you have provided.

Trondheim, 15.06.2021

Helga Løset Skodjereite

Helga Løset Skodjereite

Table of Contents

List of Figures

List of Tables

List of Abbreviations

DC	Deep Conductivity
DRWS	Department of Rural Water Supply
DWA	Department of Water Affairs
DWC	Deep Water Capacity
ET	Evapotranspiration
FAO	Food and Agriculture Organization of the United Nations
HGF	Hydro Generation Factor
HPP	Hydro Power Plant
IRR	Irrigation
Kc	Crop Coefficient
LEAP	Low Emissions Analysis Platform
LHDA	Lesotho Highlands Development Authority
LHWP	Lesotho Highlands Water Project
LLWSS	Lesotho Lowlands Water Supply Scheme
LLWDP II	Lesotho Lowlands Water Development Phase II
MAR	Mean Annual Runoff
NSE	Nash-Sutcliffe Efficiency
PBIAS	Percent Bias
PET	Potential Evapotranspiration
PEST	Parameter Estimation Tool
PFD	Preferred Flow Direction
RRF	Runoff Resistance Factor
RSA	Republic of South Africa
RZC	Root Zone Conductivity
SEI	Stockholm Environment Institute
SREP	Scaling up Renewable Energy Programme
SWC	Soil Water Capacity
WARMS	Water Authorization and Registration Management System
WASCO	Water Sewage Company
WEAP	Water Evaluation and Planning system
WRM	Water Resource Management
WS	Water Supply

1 Introduction

1.1 Background

Water encompasses all aspects of life on earth and is a necessity for human existence. About 2.5% of all available water on earth is freshwater (Šiklomanov & Rodda, 2003). The fact that freshwater resources are irregularly distributed in both time and space constitutes a significant challenge for larger parts of the world due to both scarcity and abundance of water. Altering of freshwater resources through diversions and impoundments of river systems has been, and will be, necessary to meet human needs for various purposes (Nilsson, 2005). As a result, many rivers are exposed to pressure on biodiversity and essential ecosystem services (Grill et al., 2019). The combination of human interventions and climate change is projected to alter the water cycle dynamics (Haddeland et al., 2014). Projections of future developments such as population growth, economic development, increased consumption, land-use changes, and urbanisation have led to an increased concern about pressure on global water resources (Olsson, 2015). Many river basins face water-related challenges that threaten security, and the number of water-related conflicts across the globe appears to be growing (Greick et al, 2020). An integrated approach to water resource management is necessary to ensure efficient use of freshwater resources, maintain the health of ecosystems, and avoid water-related conflicts (UN-Water, 2008).

The core of water resource management is about planning, developing, and managing water resources. Water plays a central role, both directly and indirectly, for a majority of the Sustainable Development Goals, promoting the challenge of efficient water resource management to achieve sustainable outcomes (Albrecht et al., 2017; United Nations, 2015). The nexus approach has gained increasing attention globally, addressing the interlinkages between different sectors to support a transition to sustainability (Hoff, 2011). Water, energy, and food resources are needed to sustain livelihoods. Demand for these resources is increasing, and the so-called water-energy-food nexus concerns understanding and managing the complex interaction between these sectors (FAO, 2014). Water resource management can be assisted using model simulations to understand the dynamics of available water resources, capture interlinkages within different sectors and predict future outcomes. With this area of interest, this study addresses the application of such a model for a case study in Lesotho, located in Southern Africa.

Water is one of the most important natural resources of Lesotho. The relative abundance of water in the highlands of Lesotho compared to its surrounding areas constitutes a particularly strategic value of the water resources of Lesotho. The Lesotho Highlands Water Development Project, LHWP, forms the basis for water resource management in Lesotho through water export to South Africa and hydropower generation. Water-related challenges are prominent in the lowlands of Lesotho, where most of the population resides, and water availability is highly variable due to seasonal variations and lack of infrastructure developments. Careful and efficient water resource management is viewed as a key to economic growth and sustainable development for the country in the National Strategic Development Plan (GoL, 2018).

The Hlotse river is a tributary to Caledon river, located in the lowlands of Lesotho. Increased water abstractions from the Hlotse river is planned to secure potable water supply for the area. Augmenting flows from the LHWP in the Lesotho highlands into Hlotse river is planned to secure a stable water supply in the Hlotse river, severely affected by seasonal variations. This is the triggering cause for the project of Environmental Flow Assessment and Water Quality Modelling within the Lesotho Lowlands Water Development Project Phase II (LLWDP II) to be conducted out by Multiconsult and their partners during 2021. This thesis is defined as a supplementary analysis for this project with a larger perspective on water resource management for the study area, with a focus on the interactions between water, energy, and food. The thesis will reveal different management options for the study area to secure the availability of water for human consumption, agricultural production while at the same time seeking opportunities for renewable energy production.

1.2 Objectives

The main objective of this study is to analyse the trade-offs of different water management strategies within the water-energy-food nexus in Hlotse river and their likely impacts downstream. To cover this objective, the following research questions are defined;

- What are the effects of water allocation and available water resources for different possible sector developments, such as potable water supply and irrigation, along Hlotse river and downstream in Caledon river?
- What are the possible effects of different water regulation measures, such as reservoirs for hydropower production and water transfers, for different future water users in Hlotse river?
- How is the hydrological and water allocation model WEAP suitable for the evaluation of these questions?

The questions are adressed by following a procedure of data collection and configuration of a hydrologial and water allocation model WEAP. Based on this, scenarios for future developments are defined and explored. The complete task description for the thesis is included as supplementary material in Appendix A.

The study is focused and delimited on the practical water allocation by use of model application as a tool for water resource management. The scenarios explored in the study are developed by use of existing development plans proposed in the study area. With this as a basis, no separate assessments are made to maximise the potential of hydropower production for the area, nor the water supply or agricultural production. The study is limited to evaluate the water allocation between sectors and does not consider the economic aspects in detail for the different scenarios. Some considerations are given for the managemental aspects in relation to the existing framework for water transfers in Lesotho. Apart from this, the institutional and political aspects of water resource management in Lesotho is not discussed in detail and is an important delimitation of the study.

2 Theory and description of study area

The Kingdom of Lesotho is a mountainous country located in Southern Africa. Lesotho is landlocked by the Republic of South Africa, RSA, on all sides. This is illustrated on the map in Figure 1 (Grauso et al., 2020). This chapter gives an overview of existing knowledge about the topics covered in the thesis, together with a description of the study area. First, the concept of water resource management is explained. An overview of Lesotho's climate and water resources is given, following a description of the focus area Hlotse river basin and Caledon river. The connection between water resource management and hydrological models is given, including the theory behind the WEAP model applied for the study. The current situation in Lesotho and possible future development within each sector of the water-energy-food nexus are described, including water supply, agriculture, and energy.

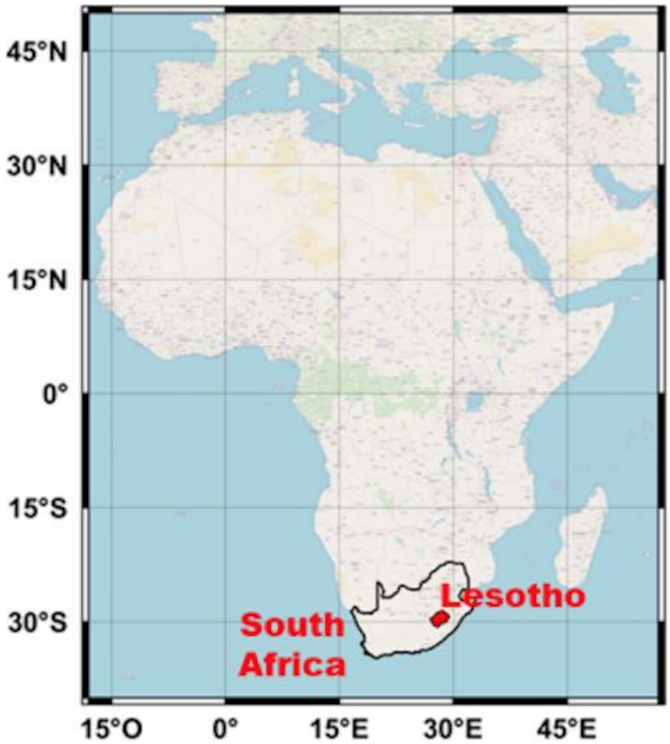


Figure 1 Location of study area (Grauso et al., 2020)

2.1 Water resource management

Water resource management (WRM) is defined by the World Bank as the process of planning, developing, and managing water resources, in terms of both water quantity and quality, across all water use (World Bank, 2017b). The fact that freshwater resources are irregularly distributed in both time and space creates a need for regulation of water resources by the construction of infrastructure to meet the demand for different purposes. There are different views from region to region regarding approaches to water resource management since each watercourse faces different challenges. However, the core of an integrated approach to water resource management is balancing the human exploitation of water resources for various purposes versus the environment and ecosystem services.

Water is one of Lesotho's most important natural resources in view of the relative abundance of water and elevation compared to the neighbouring country South Africa. A specific example of water resource management in practice is the Treaty comprising the Lesotho Highlands Water Project, LHWP, signed between the Government of Lesotho and the Republic of South Africa in 1986. The LHWP was envisioned in the 1950s in the context of the relative abundance of water in the highlands of Lesotho and water deficits combined with growing demands in South Africa (Winston, 2008). By constructing a series of dams and tunnels, the LHWP provides water transfers to South Africa and generates hydroelectric power for Lesotho. The Treaty gives provisions of rights and obligations for each of the parties, such as operation, deliveries, responsibilities, and revenues (Treaty on the LHWP, 1986). The LHWP generates revenue for Lesotho in the form of royalty payments received from South Africa for the water transfers and electricity sales from hydropower generation (Ministry of Water, 2018; WRP Ltd, 2012). The LHWP is further discussed in Section 2.4 and the following sections.

2.2 Climate and water resources of Lesotho

The water of Lesotho is drained by three major catchments, being Senqu in the eastern part of the country, Makhaleng in the middle, and Mohokare/Caledon at the western border to South Africa. This is illustrated in Figure 2, where the map is derived using the STRM digital elevation model and river network from the HydroSHEDS dataset (Lehner et al., 2008; USGS, 2000). The international name for the Mohokare river, Caledon river, is applied in this report. The four dams illustrated in Figure 2 are presented later in the report. The entire area of Lesotho is located within the Orange-Senqu River basin, an international river basin shared by the four counties Lesotho, South Africa, Namibia, and Botswana (ORASECOM, n.d.). The water draining from Lesotho flows in the south-western direction in Figure 2 into the Orange-Senqu river, where the water resources of Lesotho are valuable due to its strategic position in the basin. The area of Lesotho comprises only 3% of the total area in the Orange-Senqu River basin but provides more than half of the total flow in the river system due to its relative mean annual rainfall (Grauso et al., 2020; Lange et al., 2007).

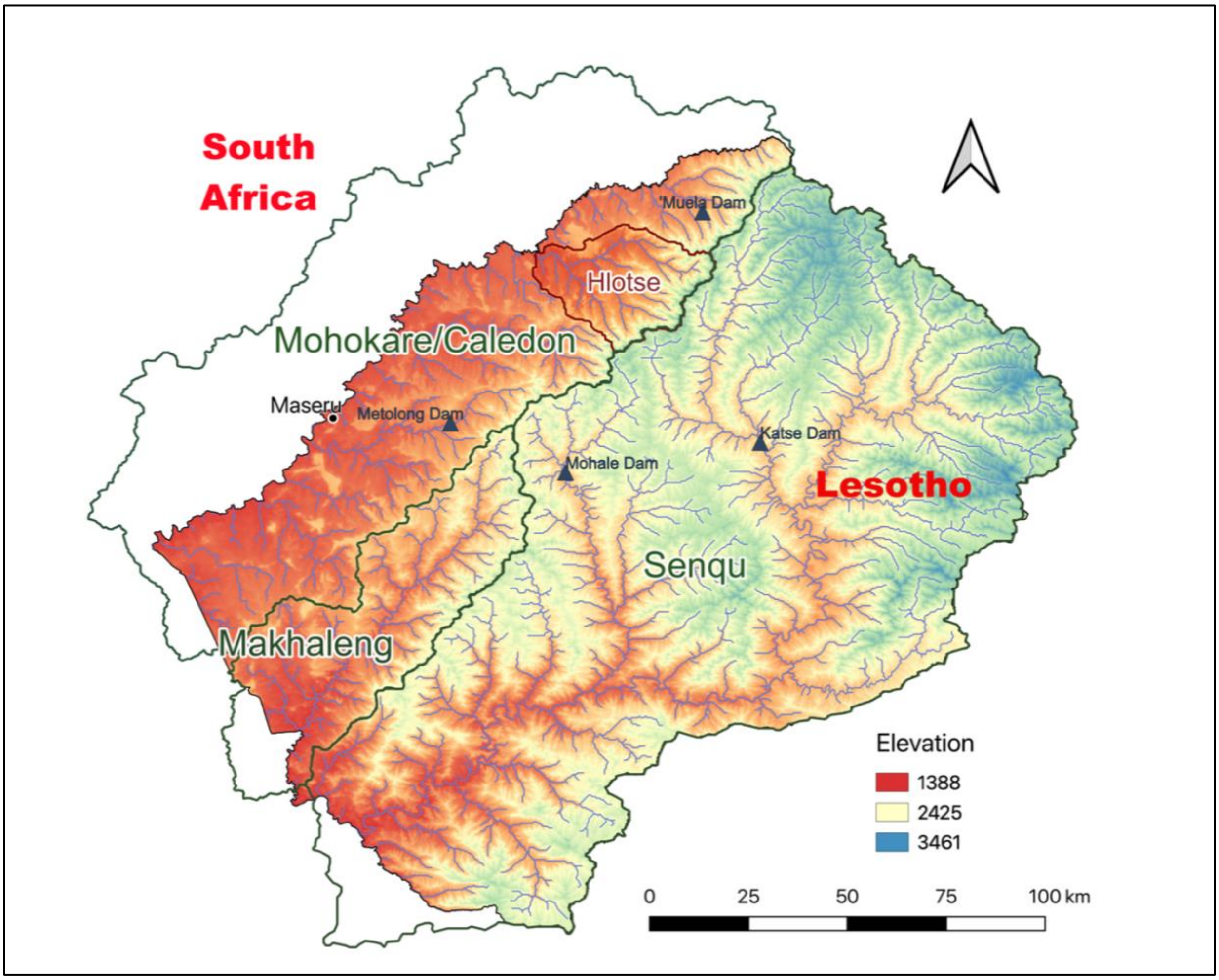


Figure 2 Digital elevation model and catchments of Lesotho. Derived using the STRM and HydroSHEDS datasets (Lehner et al., 2008; USGS, 2000).

The climate of Lesotho is largely influenced by its elevation range from about 1400 meters above sea level in the lowlands to about 3480 in the highlands (Lesotho Meteorological Services, 2021). The topography causes a precipitation regime largely dominated by seasonal rainfall. The climate of Lesotho is defined as temperate with dry winters and warm summers, code "Cwb", according to the Köppen-Geiger climate classification system (Beck et al., 2018). This system classifies climate depending on threshold values and seasonality of air temperature and precipitation. There is a large spatial rainfall variation, with the mean annual rainfall ranging from 300 mm in the lowlands to 1600 mm in the highlands. Normally, 85% of the rainfall takes place in the summer months between October to April (Ministry of Water, 2018). Snowfall is frequent for the mountainous regions in the winter months from May to September. The seasonal variations are illustrated in Figure 3, showing the average monthly temperature and precipitation of Lesotho for 1901-2016. The climate data in Figure 3 is derived from the Climate Research Unit (Mitchell et al., 2003).

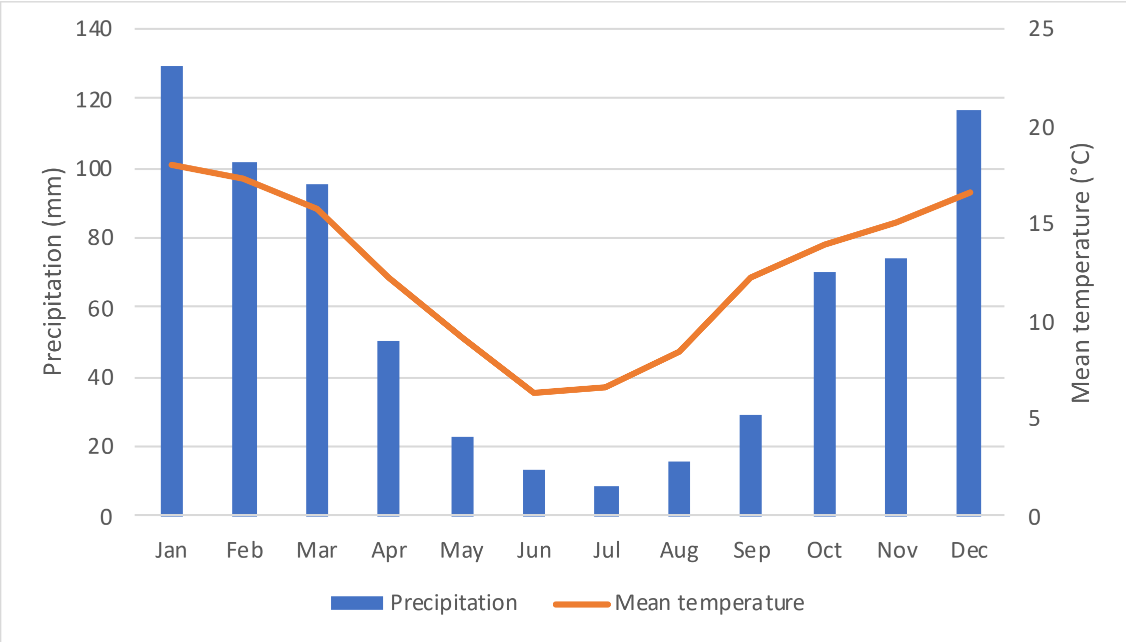


Figure 3 Average monthly temperature and precipitation. Derived from Mitchell et al. (2003)

2.2.1 Hlotse river basin

The focus area for this study, Hlotse river basin, is highlighted in Figure 2 as a part of the Mohokare/Caledon catchment. The topography of the focus area is diverse as it includes both parts of the topographical regions called the highlands, foothills, and lowlands. Hlotse river is a tributary to the Caledon River, forming the border to South Africa on the north-western side of Lesotho. To evaluate the effects of future development in Hlotse river basin in a larger context, the full modelling area for this study is including the upper part of Caledon river downstream to the capital Maseru. The water resources of the Caledon river are locally important for various water-use sectors, including domestic, industrial, and agricultural water consumption. The river flows in the Caledon catchment reflects seasonal rainfall where flow mainly occurs in the wet season. Most of the smaller streams draining to the Caledon river have ephemeral flow patterns, meaning flow only occurs in the wettest year. This gives that the Caledon river is faced with periodical water scarcities (Ministry of Water, 2019; Schäfer et al., 1991).

2.3 Hydrological models

Planning and management of water resources among stakeholders and different water uses can be assisted by the use of model simulations. Hydrological modelling can provide a better understanding of the dynamics of available water resources by a simplified presentation of a real hydrological system (Devia et al., 2015). Rainfall-runoff modelling is commonly used where parameter values for catchments characteristics are set to represent the hydrological response of the catchment to metrological inputs. Many hydrological models for different purposes have been developed over the years with varying features and characteristics.

For the purpose of water resource management and planning, so called water allocation models or water resource simulation models are widely accepted as an assisting tool. The modelling tool selected for this study, WEAP, can be categorized within these. These models are often coupled with other hydrological models to calculate the hydrological process or contain integrated hydrological calculation procedures. Search in literature gives examples of other water allocation models commonly used, such as RIBASIM (Van der Krogt, 2010), REALM (Perera et al., 2005), MIKE BASIN (DHI Water & Environment, 2003), MODSIM (Labadie et al., 2007).

2.3.1 WEAP

The Water Evaluation and Planning system (WEAP) is a water resource modelling software developed by the Stockholm Environmental Institute (SEI). The WEAP model is designed to evaluate alternative water development and management strategies for different water use sectors. The software provides an integrated approach to water resource management by linking hydrological processes and water system operations in one analytical platform (World Bank, 2017a). The model is computer-based with an intuitive and spatially oriented user interface. The user defines a model with one or more river basins and represents the water system by including associated water system elements. Various supply sources such as rivers, reservoirs, and groundwater can be linked with water demand sites. Water treatment facilities and instream flow requirements can also be set up. Priority values from 1 to 99 are assigned to each demand site or element to classify demand priorities, with 1 being the highest and 99 the lowest priority value (Sieber, 2015). Future scenarios can be set up for alternative sets of future developments to analyse possible effects.

WEAP operates using the principle of water balance by using linear programming to solve the water allocation problem at each time step, subject to given demand priorities, water supply availability and other constraints. Available water volume at the beginning of the chosen timestep is distributed to satisfy demands. In cases where available water is not enough to satisfy all demands with the same priority, the demands will have the same percentage of demand fulfilment. The program does not consider time lag in supply and return flow for demand sites by assuming flow occur instantaneously and that water is both consumed and returned at the same timestep (Bakken et al., 2016).

The catchment processes and response from meteorological input can be calculated using five different methods in the program. Among these five methods, the Soil Moisture Method is chosen for this study. This is the most complex representation of the catchment processes among the methods available by accounting for soil moisture and snow changes. The soil moisture method can be categorized as a rainfall-runoff method. The catchment runoff routine is represented by two soil layers, illustrated in Figure 4 to the left. The reservoir zones illustrated in the same figure are explained later in the following. The upper soil layer contributes to direct surface runoff, interflow, and percolation. The lower soil layer transports water to base flow which can be manually connected to groundwater recharge if included in the modelling.

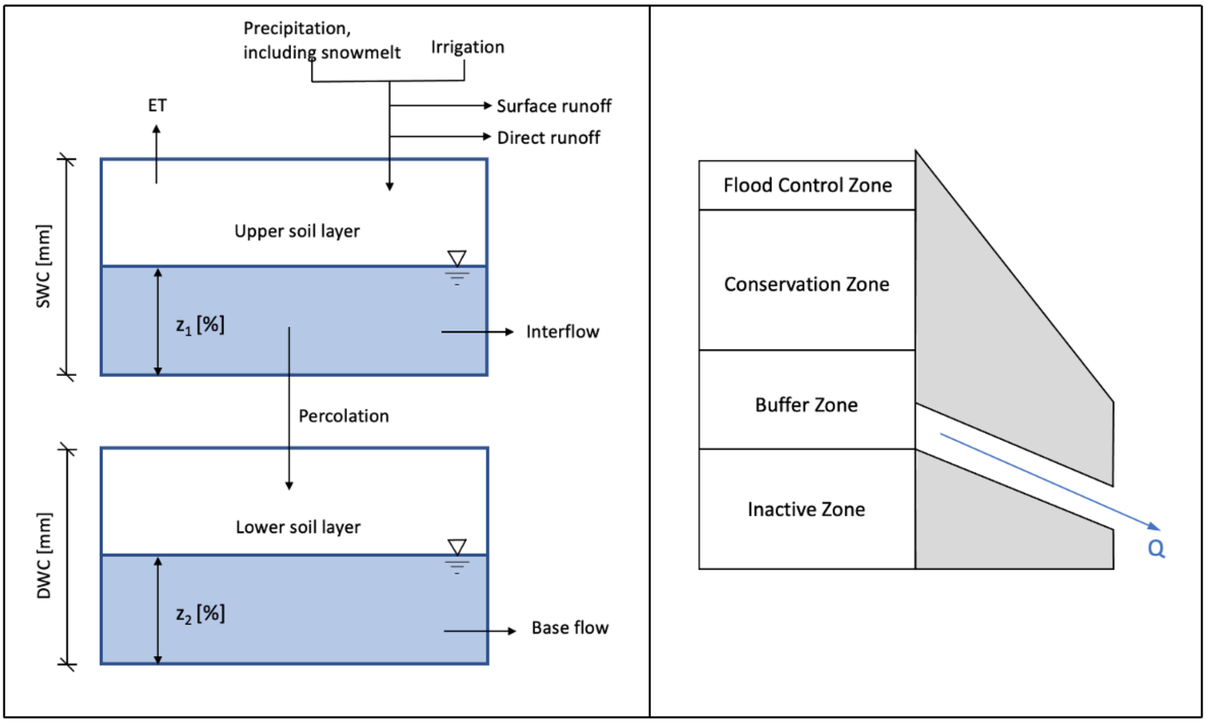


Figure 4 Conceptual runoff routine (left) and reservoir zones (right). Adopted from Sieber (2015).

The User guide for the software contains detailed information about the algorithms and physical equations used in the program. The list below provides an explanation of assumptions and calculations in the program that are of particular relevance to this task.

- The hydrological modelling component of WEAP is a semi-distributed model, meaning that input data can be distributed between different catchments but averaged/lumped within each individual catchment. WEAP does not calculate runoff distribution within a catchment. To account for runoff for different parts within a catchment, the user can insert additional runoff/infiltration links and weight the inflow to these depending on the area drained to each point.
- WEAP contains various integrated methods for calculating water volume and timing for irrigation purposes depending on climate and irrigation-related variables specified. Alternatively, irrigation demands can be added manually as withdrawal nodes from the river with fixed volumes and a given variation over the year.
- The potential evapotranspiration, PET, in WEAP is calculated using the Penman-Monteith equation in a modified version. The actual evapotranspiration, ET, is calculated by multiplying the PET with a specified crop coefficient, Kc.
- Time series of temperature and precipitation is fundamental data input required for calculation with the Soil Moisture Method. Historical climate data from the global gridded dataset Princeton is available in the WEAP model. Other global datasets integrated with the software is digital elevation data and river network from HydroSHEDS and the land cover dataset ESA-CCI-LC. These are further explained in section 3 Materials and Methods.
- Model parameters can be calibrated against observed values of streamflow, reservoir levels and snow depth. The software provides a link to a Parameter Estimation Tool (PEST) for automatic calibration.

Hydropower generation in WEAP is simulated based on available water in the reservoir or river. The energy generation is computed from the run-of-river streamflow or release from the reservoir and constrained by the maximum flow capacity set for the turbine. Optimization algorithms for hydropower production are not included in the model (Bakken et al., 2016). Depending on the demand priorities and amount of water available for hydropower generation, WEAP calculates an energy output by multiplying volume through the turbine with an HydroGenerationFactor, HGF. This factor is a function of the density of water, gravitational force, head, plant factor, and generating efficiency. For hydropower generation with reservoirs, the available head is calculated from reservoir elevation at the beginning of the timestep minus the tailwater elevation. The plant factor specifies the amount of time the power plant is running, while the generating efficiency accounts for the energy losses in the system.

Reservoirs are divided into four operational zones illustrated in Figure 4. The reservoirs active storage is the conservation zone plus the buffer zone. Reservoir releases are determined by the priorities set for demands in the system, subject to priorities set for demands downstream of the reservoir. This can be overruled by inserting specific energy targets and priorities for energy generation. Seasonal regulation of hydropower production is feasible in the model by setting target hydropower production requirements or adjusting the plant factor.

2.3.2 Previous applications

WEAP is a well-known tool for the purpose of water allocation modelling with applications worldwide for a range of research purposes. A total of 619 selected scientific publications is cited on the webpage for the software developer SEI (Stockholm Environment Institute, 2021). The program is widely used for the assessment of available water for different water users under a range of future scenarios, especially climate change assessments. However, the software is also applied for other purposes such as flood analysis, water quality modelling and modelling of ice glaciers. WEAP is also widely used at academic institutions for educational purposes and governmental use as a planning tool. The license for the software is offered free for the governmental and academic organisation in developing countries. WEAP can be integrated with another software developed by SEI, LEAP, for advanced analysis of energy planning by setting up the full energy system in addition to the water resource assessment in WEAP. This link is not considered in this study as the assessment is delimited only to include energy generation from hydropower resources.

The literature review for this study found that WEAP is applied in previous assessments of the water resources of Lesotho. Two master's theses are found where water availability for different users in Caledon river is evaluated by use of WEAP (Ayele, 2016; Mohobane, 2015). The World Bank developed a WEAP model for Lesotho as a tool in a recent terminated project assessing water security and climate change in Lesotho (World Bank, 2016). SMEC (2017) applied WEAP as a tool for the assessment of water supply for some selected regions in the lowlands of Lesotho. All these existing models are developed with a monthly timestep. The climate change assessment by the World Bank points to areas for further development. Among them, further development of the WEAP model to a daily timestep for the area is recommended to evaluate operational strategies for water allocation among competing uses. Another water allocation model, RIBASIM, is also applied in Lesotho by Deltares and introduced at the Department of Water Affairs (DWA) in Lesotho (Deltares, 2017).

2.4 Current and future water supply

The major historical water infrastructure developments in Lesotho are concentrated in the highlands in connection with the Lesotho Highlands Water Project (LHWP). With the overall aim of transferring water to South Africa and generate hydroelectric power for Lesotho, three major dams and one hydropower plant were constructed in Phase 1 of this project (LHDA, n.d.). Construction started in 1989, and the project today consists of the two major dams Katse and Mohale, a smaller dam 'Muela tailpond dam, and a hydropower plant at 'Muela hydropower station illustrated in Figure 2. A series of water transfer tunnels is constructed between the reservoirs, where the water transfer tunnel to South Africa extends north from 'Muela tailpond dam. The project provides a power generation of 72 MW for Lesotho and a transfer capacity of 28.5 m^3/s to South Africa. The first parts of the project were completed in 1998, while the complete Phase I were finished in 2002 (Winston, 2008). Further development of the LHWP is planned where Phase II is currently under construction.

The LHWP were designed to maximize water transfers to South Africa, and the current water supply to the population of Lesotho is largely disconnected from the LHWP (World Bank, 2017a). The connection between the LWHP infrastructures and the study area of Caledon river comprises environmental flow releases from the 'Muela Tailpond dam and a water transfer tunnel from Katse Dam into Hlotse river. The population of Lesotho are concentrated in the lowlands and the foothills along the Caledon and Makhaleng river, where 75 percent of the population lives in the lowlands (World Bank, 2016). The Water Sewage Company (WASCO) provides retail water to the urban areas of Lesotho. Water supply for both domestic, industrial, and agricultural use is mainly served by local supply sources of both direct river abstractions and groundwater pumping from boreholes (Ministry of Water, 2018). 66% of the population lives in rural areas where groundwater plays an important role in water supply (Bureau of Statistics, 2016; Davies, 2003). Rural water supply is the responsibility of the Department of Rural Water Supply (DRWS). 43.5% of the rural population were served by functioning water systems in 2011, while 56.5% are categorized as "un or under-served" (WRP Ltd, 2012).

Higher demands, urbanisation, and commercial activity have increased the pressure on the water resources in the lowlands (Parkman Ltd, 2004; World Bank, 2016). The Lesotho Lowlands Water Supply Scheme (LLWSS) aims to address the challenges of water security in the lowlands of Lesotho. The project was initially designed in 2008 involving construction of water infrastructure to meet domestic and industrial demands for eight different zones in the lowlands. Phase 1 of the project was completed in 2013, comprising the Metolong Dam to meet the demands of the region of the capital Maseru. In connection with the ongoing project of LLWSS for water supply to the lowlands, a water intake in Hlotse river is planned to meet future water demands for Hlotse town and Maputse town, comprising zone 2 and 3 for the LLWSS project. This construction is the so-called Lesotho Lowlands Water Development Project (LLWDP) Phase II. The planned water abstraction from the Hlotse river is greater than recorded low flows in the river. Therefore, additional water transfers from Katse dam into Hlotse river is planned for low flow events. The LHWP Treaty (Article 4) and protocols regulating water transfers from Katse dam today allow for releasing 3.75 MCM annually into Hlotse river and 1.25 MCM for environmental flows at 'Muela dam (Ministry of Water, 2019; World Bank, 2018b). Augmenting flow releases from the Katse Dam to the lowlands of Lesotho has previously taken place during drought conditions in 2015 and 2018 (Ministry of Water, 2019). However, details for the historical and current operational strategy of the water transfers to the lowlands remain unknown.

There is limited data concerning the actual water use for the South African side of the modelling area. Volumes of extracted water remain unknown despite the existence of the national register of water use for South Africa, Water Authorization and Registration Management System (WARMS). Irrigation is the most important water user in Africa, accounting for 60 percent of total water withdrawn (FAO, 2016).

2.5 Agriculture of Lesotho

Agricultural production, both livestock and crops, provide a lifeline for the rural population of Lesotho. Lesotho does not have any significant commercial agriculture and very little crop irrigation compared to other countries in the Orange-River basin. Both South Africa and Namibia have a strong commercial agricultural sector with large-scale crop irrigation (Lange et al., 2007). The agricultural production in Lesotho for the growing of crops is almost exclusively rainfed (World Bank, 2016). The principal crops reported for the study area is maize, sorghum, and wheat (Bureau of Statistics, 2019). Arable land is estimated at 429 300 ha (FAO, 2018). The agricultural sector is reported with a contribution of 5 percent to gross domestic product (Bureau of Statistics, n.d.). The existing area currently under irrigation in Lesotho is found to be approximately 1000 ha, of which 703 ha of these are confirmed located within five existing irrigation schemes (World Bank, 2016). Little data exists about current irrigation practices in Lesotho, but several irrigation practices are reported with a combination of sprinkler systems from direct surface water abstractions and groundwater pumping.

Previous studies and reports have pointed out a lack of data and statistics related to current agricultural practice in Lesotho (Ayele, 2016; World Bank, 2016). Improvement of production, analysis and accessibility of agricultural and rural statistics is identified as a key objective in the strategic plan for agriculture in Lesotho (Bureau of Statistics, n.d.). The share of arable land has been declining in recent years in combination with poor agricultural practice, mainly due to high rainfall variability (Tongwane & Moeletsi, 2015). The agricultural dependence on rainfall makes the agriculture of Lesotho vulnerable to climatic variations. Expanded irrigation is necessary to ensure agricultural productivity in the future. Irrigation development can contribute to increased food security and poverty reduction for a population largely exposed to food deficits and nutrition insecurity today (Bureau of Statistics, n.d.; World Bank, 2016). 12 500 ha is estimated by FAO as the long-term irrigation potential in Lesotho (FAO, 2005).

The crop cultivation of the focus area for this study, Hlotse, is extensive compared to the rest of the country. 256 hectares of land comprising the irrigation schemes named Ts’ehlanyane and Likutlong is reported to be under irrigation (World Bank, 2016). The literature search for this study revealed potential developments within the agricultural sector for the Hlotse river basin, where significant potential for irrigation expansion is identified in previous reports. FAO estimated the irrigation potential of 500 hectares for the Hlotse area (FAO, 2005). Assessment of irrigation development by SMEC (2017) identified 21 686 hectares as the irrigation potential for the areas surrounding Hlotse river.

2.6 Energy sector of Lesotho

The energy sector of Lesotho is characterized by reliance on biomass fuels such as wood, shrubs and dung and imports of coal, petroleum and paraffin (Department of Energy, 2017). Only 47% of the total population has access to electricity. Electricity access is 38% and 71% for rural and urban areas, respectively (World Bank, 2018a). Out of a total installed electricity capacity of 77 MW, 75.8 MW is met by hydropower and 1.2 by diesel. Main energy generation is concentrated at the 72 MW 'Muela hydropower plant, commissioned in 1999 and constructed as a part of the Lesotho Highlands Water Project (LHDA, 2021). With a peak demand of 140 MW, deficits are met by imports from South Africa and Mozambique (Liu et al., 2019). The gap between existing generation capacity and demands are illustrated in Figure 5. In addition to the Muela hydropower plant, there are five small-scale hydropower plants in Lesotho with capacity ranges from 180 kW to 2 MW. Due to technical and operational problems, only two out of these plants are currently operational (Lesotho Electricity Company, 2021).

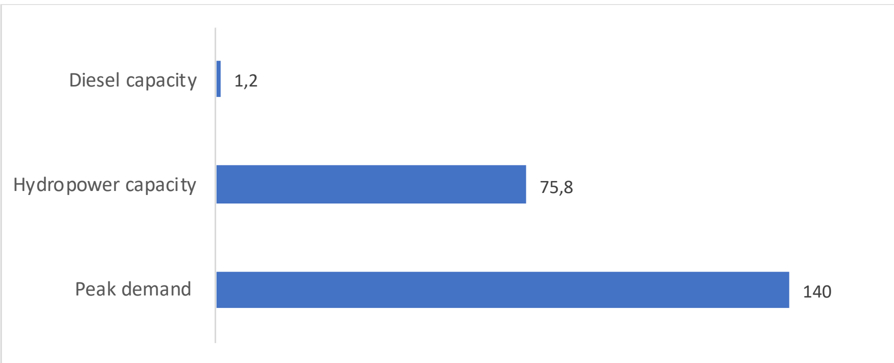


Figure 5 Electricity demand and installed capacity [MW]. Adopted from Liu et al. (2019)

Expansion of electricity access and increased share of energy from renewable sources is the overall objective of the Scaling-up Renewable Energy Programme (SREP) Investment Plan adopted by the Government of Lesotho. Lesotho possesses significant resources for renewable energy production with a technical potential of 2 312 MW generation capacity from renewables identified in the SREP Investment Plan (Department of Energy, 2017; Liu et al., 2019). Among the different renewable technologies, utility-scale solar photovoltaics, wind, and small-scale hydropower is viewed as the three most viable technologies for Lesotho. The development of hydropower is focused in this report.

SSI conducted technical assessments for the development of small hydropower (< 10 MW) as a part of the Power Generation Master Plan for Lesotho in 2009. As a results, eleven sites for small hydropower development were proposed with a total capacity of 88 MW (SSI, 2009). These plans were re-evaluated, and a total of six sites with a combined capacity of 34.8 MW is selected under the SREP Investment Plan. Hlotse hydropower plant, Hlotse HPP, is one of these selected sites and are specially considered in this study. The proposed project of Hlotse HPP is designed to exploit the energy potential in the Hlotse river and two tributaries, Morotong and Mphosong, by the construction of three rockfill dams for reservoir regulation and headrace tunnels of a total length of 23 km. The hydropower regulation will give a diversion reach of about 21 km in the main river, Hlotse. The proposed development of Hlotse river with three reservoirs is illustrated later in the report following section 3.6 Scenario definition. Some technical characteristics for the proposed project are reproduced in Table 1 from SSI (2009).

Table 1 Key characteristics for the proposed Hlotse HPP (SSI, 2009)

Parameter	Value	Unit
Installed capacity	6.50	MW
Average annual generation	39.70	GWh
Capacity factor	69.72	%
Rated discharge	6.00	m^3/s
Maximum gross head	125	m
Costing	39.00	mln. USD
Investment per kWh	0.98	USD

The environment and conditions in Lesotho are generally described as conducive for small hydropower development in light of the abundance of hydropower resources, isolated rural areas favouring decentralized systems and a legislation system allowing for independent power producers (Liu et al., 2019; Taele et al., 2012). However, technical, practical, institutional, financial, and social obstacles limit small hydropower development constraints (Liu et al., 2019). Previous development aid hydropower projects in Lesotho have proven limited success. The first two hydroelectric power plants in Lesotho were funded and implemented by Norwegian bilateral development assistance, NORAD, in 1989 (NVE, 1991). Only one of them is currently operational due to erosion problems and lack of maintenance. A subsidiary of Tarini in India has been trying for some years to commence construction works for two hydropower plants, Quinthing and Oxbow projects, proposed in the highlands. A study by Liu et al. (2019) points to key barriers for small hydropower development in Lesotho, such as difficulties for international partners to find viable business models, lack of integrated planning and institutional responsibilities not clearly defined.

3 Materials and Methods

This section describes the procedure of the WEAP model setup applied in the study. Starting with an explanation of the river basin configuration of the study area and a description of climate data applied. Following, the procedure of calibration and validation of the model is given. The data collection procedure and estimation of input data for the hydrological representation of the study is then given. The method for implementation of scenarios and development of these are given in the following section 3, while the detailed input data for each scenario is presented together with the simulation of scenarios in section 4 Results. The data applied is mainly obtained from Multiconsult and their partners in association with the EFlow assessment in Hlotse river. Additional data applied is collected from sources available online.

3.1 River basin configuration

A hydrological and water allocation model for the study area is developed by using the software WEAP Version 2019.2.1.45. The WEAP software is found suitable for this study due to its integrated approach to water resources planning by introducing scenarios for water allocation among different water users. A daily timestep is chosen for the model as this was recommended as the next step for further analysis of the water resources in the area (World Bank, 2016). The Soil Moisture Method is chosen as the method to simulate catchment processes in the model.

Initially, this study aimed to model the whole catchment of Caledon river for evaluation of water management strategies. Due to data availability, the modelling area for the study is limited to the northern part of the catchment upstream of Maseru, with a particular focus on Hlotse river basin. The catchment is divided into sub-catchments for the main tributaries using the Automatic Catchment Delineation Mode in WEAP. This function allows the user to automatically delineate catchments and rivers, using global datasets for elevation. The digital elevation data built into WEAP are downloaded from the HydroSHEDS database (Lehner et al., 2008).

The tributaries of Caledon river upstream of Maseru are in this study given names from the nationally accepted river network of quinary catchments for South Africa, Swaziland and Lesotho (Maherry et al., 2013). The modelling area is divided into seven main tributaries of about the same size in addition to two smaller rivers in the north-eastern part of the basin, Nque and Moroeroe, to facilitate placements of reservoir and water withdrawals at these locations. The area falling outside of these nine sub-catchments is assigned to the main river Caledon. A flow chart illustrating the main river and its tributaries, gauge stations, demand centres and water withdrawals are given in Appendix B. The river basin configuration in WEAP for the modelling area is presented in Figure 6. For one of the scenarios explored in this study, the river basin of Hlotse is further divided with two additional tributaries. This is explained in section 3.6.

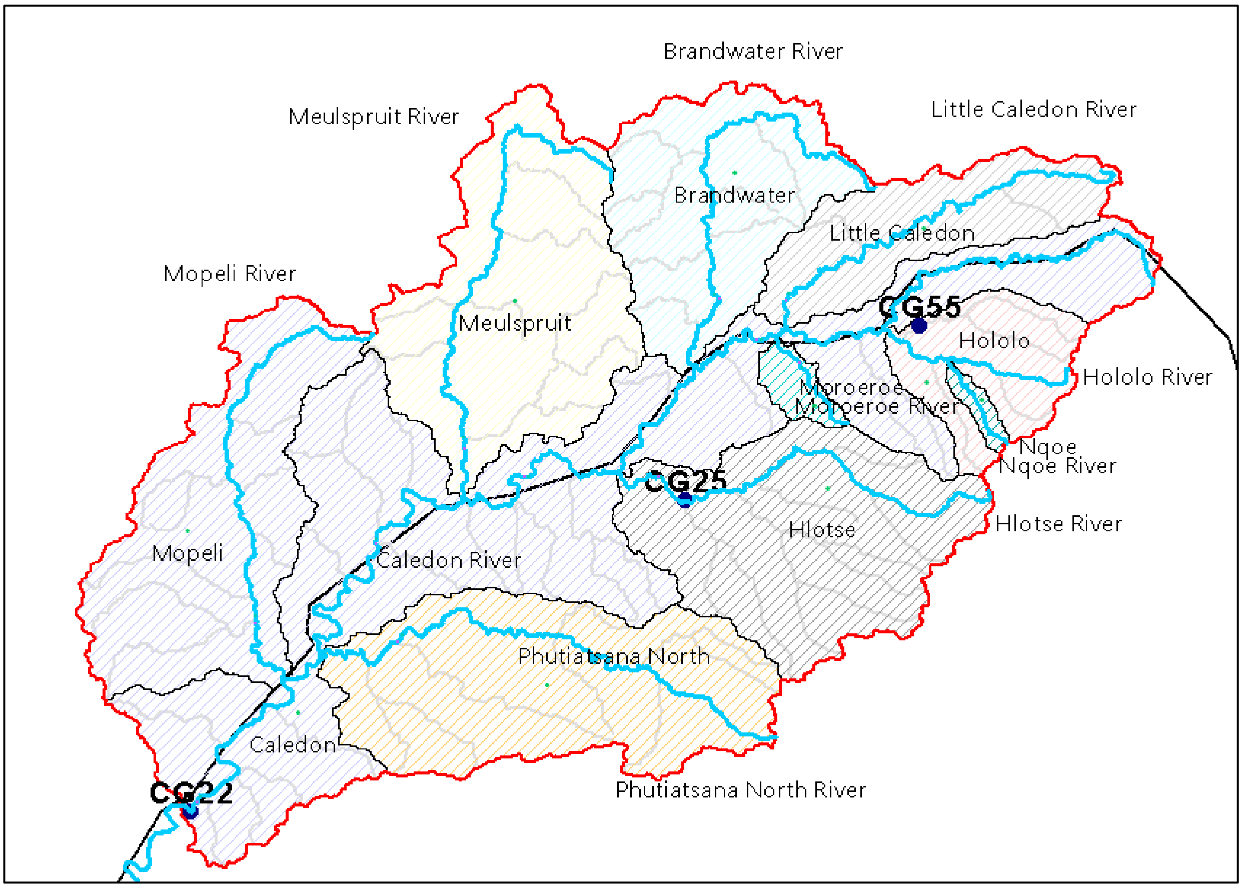


Figure 6 Catchment delineation of the modelling area. Screen dump from the WEAP model for Reference scenario.

WEAP can create elevation branches within each catchment and calculate the area within each elevation band from the digital elevation data. Branches for land cover classification can also be created by use of the integrated global landcover dataset ESA-CCI-LC (Defourny, 2019). Branches for elevation and land use is not included in this model setup due to limited hydrological data to justify a separation of parameter set for the different area types and elevation zones. A simplification is made by finding a common parameter set for the catchments. However, data for elevation and land cover of the catchments are used as a supplement for the calibration and validation process of the model in this study.

3.2 Climate data

Global gridded climate data of precipitation, temperature, and wind speed at daily timestep from the integrated Princeton dataset available in WEAP is applied for this study. The Princeton climate dataset is created by merging reanalysis data with observations to form a global gridded dataset of temperature, precipitation, and wind speed (Sheffield et al., 2006). Climate data is available at daily and monthly time resolution for the historical period 1948-2010 at a spatial resolution of 0.25 degrees, which is approximately 28 km. Alternatively, the user can upload specified climate data.

Monthly rainfall data measured at eight meteorological stations in the area have been available for this work. The location of observation points for both rainfall and discharge data applied in this study is illustrated in Figure 7. The data period available for each station is given in the figure. However, there are significant discrepancies in the continuity of data for some of the stations. The measured rainfall data of monthly resolution are used to assess the quality of the gridded precipitation in the Princeton dataset. Monthly precipitation values from the Princeton dataset are extracted from the WEAP model and compared with observed values. The gridded climate data for this assessment is extracted from the nearest elevation band in WEAP corresponding to the elevation for each station. Ideally, observed values for both precipitation and temperature of daily time resolution should have been used to properly assess the quality of the input data.

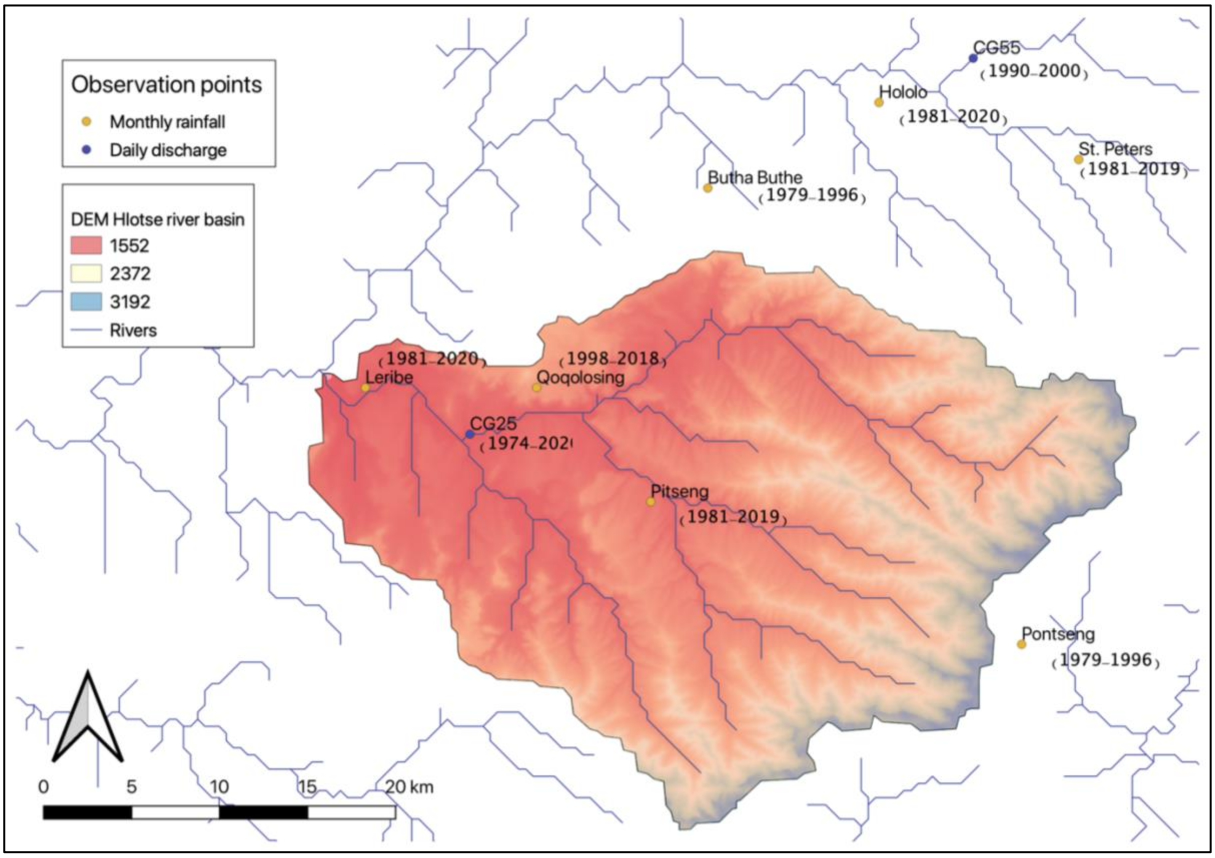


Figure 7 Observation points with available data period indicated in parentheses for each station. Derived using the STRM and HydroSHEDS datasets (Lehner et al., 2008; USGS, 2000)

The average annual rainfall for each station is calculated by the sum of all precipitation values divided by the number of years included. The Leribe station is chosen for comparison of monthly precipitation data due to the length of continuously observed data and its location close to the discharge station in Hlotse. The months where observed data is missing are not considered in the comparisons. The average precipitation for each month for Leribe station is calculated for the global gridded data and observed values to evaluate the seasonal distribution of the year. It is noted that observed rainfall data was not available for the time of the calibration process in this study. The model is calibrated based on the assumption of the gridded climate data to be representative.

3.3 Calibration

The catchment of Hlotse river is used to calibrate the model parameters in the Soil Moisture Method due to observed discharge data for only this gauge station, CG25, were available at the time for the calibration process. The catchment area upstream of station CG25 is 726 km^2, representing 8.6% of the whole modelling area of 8434 km^2. Figure 8 illustrates the land cover distribution and elevation range for the catchment of Hlotse compared to the whole river basin of Caledon down to Maseru. The mean elevation of Hlotse is 1988 m.a.s.l. compared to 1783 m.a.s.l. for the rest of the modelling area. The whole modelling area has a larger share of agricultural land compared to the calibration catchment. The catchment for calibration is considered an unregulated catchment for the calibration period as the historical water withdrawals from the river are unknown. Historical water withdrawals are generally considered to be small for the area but may prove important in the dry season. The main water supply for Hlotse town is today abstracted downstream of the gauge station CG25. Table 2 gives an overview of the catchments used for calibration and validation of the model. The process of parameter transfer and model validation is explained in section 3.4. The location of the gauge stations for discharge measurements are illustrated in previous figures, Figure 6 and Figure 7.

Table 2 Catchments used for calibration and validation

Catchment	Gauge station	Drainage area [ha]	Model use	Water withdrawals
Hlotse	CG25	72 635	Calibrated for 1988-2000	Assumed unregulated
Ngoajane	CG55	14 569	Validated for 1988-2000	Unregulated
Upper Caledon	CG22	843 974	Parameters transferred	Demands representative for reference scenario 1990-2010

Daily discharge data for 46 years has been available for station CG25 from October 1974 to December 2020. As the climate data integrated with WEAP extends until 2010, this gives 36 years available for comparison of simulated and observed discharge. Lack of observed discharge data is found for the years 1984/1985 and 2000-2003. Irregularities for some days in 1987 is suspected to be the result of measurement errors. The exact time for constructing the water transfer tunnel into Hlotse river is unknown but assumed to be in 2002 when Phase I of the LHWP was finished (Winston, 2008). The years after 2002 are omitted from the calibration period to avoid uncertainties introduced by regulation strategies. Thus, the period from 1st of October 1988 to 30th of September 2000 is chosen for calibration. Daily discharge data is compared to simulated values to minimize the difference between them.

A sensitivity analysis of the parameters to be calibrated is performed in advance of the calibration process. The objective of the sensitivity analysis is to determine which parameters affect the model the most and locate the uncertainty of the model output (Saltelli, 2002). The parameters initially chosen for calibration are:

- Crop coefficient (Kc)
- Soil Water Capacity (SWC)
- Deep Water Capacity (DWC)
- Runoff Resistance Factor (RRF)
- Root Zone Conductivity (RZC)
- Deep Conductivity (DC)
- Preferred Flow Direction (PFD)

Each of the chosen parameters is changed from the default value and varied with +/-50% to evaluate the effect of water volume compared to the initial volume. The sensitivity is calculated as a relative change in water volume divided by the relative change of the parameter tested. The complete results from the sensitivity analysis are given in section 4.2. The sensitivity analysis indicates that the model is most sensitive to changes in the Crop Coefficient, Kc. This coefficient affects the evapotranspiration in the model directly and will typically vary over the year depending on land use and crop types for the area. Due to the significant effect the adjustment in Kc gives on the corresponding water volume, it is considered appropriate to find a representative value for this parameter independent from the calibration process.

An estimation of Kc for the catchment is found by analysing the land cover and crops grown in the area. For the agricultural crops, maize, sorghum, wheat, peas, and beans are considered representative crops for the study area. Monthly values for Kc representative for these crops are adapted from published work by the World Bank from the study area, originally from the FAO Irrigation and Drainage Paper 56 (World Bank, 2017a). A representative Kc-factor is found by weighting this Kc-factor for the agricultural land with a Kc-factor of 0.95 which is assumed to represent forest and grassland. The weighting is found by analysis of land cover in the area, presented in Figure 8. The monthly values found for Kc are implemented into the daily model by interpolation between the different months. The combined factor found for Kc is given in Results section 4.2.

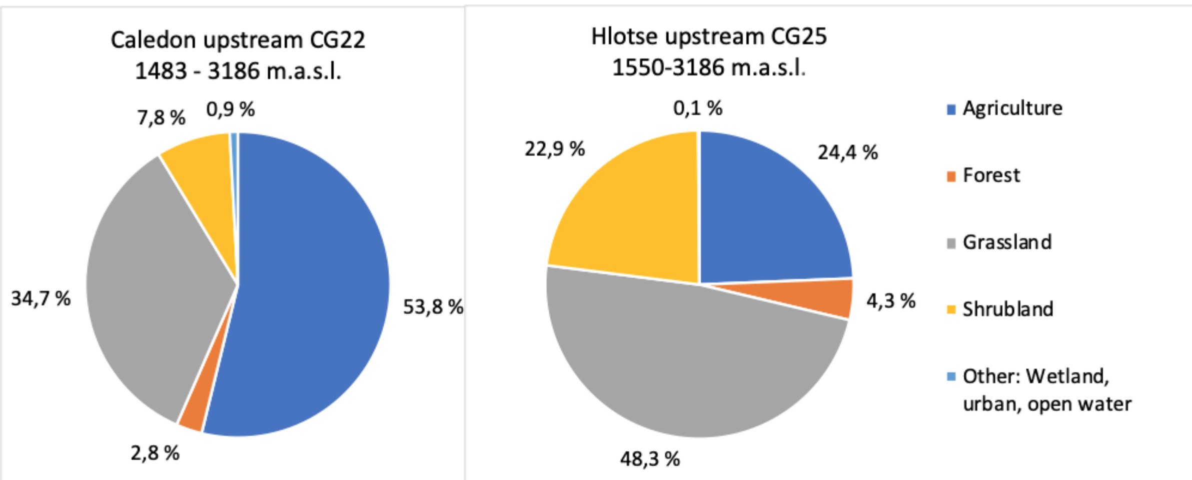


Figure 8 Land cover distribution derived from the ESA-CCI-LC landcover dataset available in WEAP

The parameter estimation tool (PEST) in WEAP is used as an initial start for the calibration by automatic modification of model parameters to match the simulated values and historical observations. However, the parameter set found by PEST, in this case, tends to underestimate high flows and overestimate low flows. Thus, parameter modifications are done manually, and results are exported to Excel. Mathematical comparisons of simulated and observed discharge from the different parameter sets in Excel is used to evaluate the model performance. After work by Moriasi et al. (2007), two quantitative statistics and their recommended performance ratings are chosen for this evaluation. The percent bias, PBIAS, is chosen to evaluate the model performance for calibration of water balance. The PBIAS is calculated with equation (1),

$$PBIAS = \frac{\sum_{i=1}^{n}\left(Q_i^{obs} - Q_i^{sim}\right) * 100}{\sum_{i=1}^{n}(Q_i^{obs})} \tag{1}$$

Where Q_i^{obs} is the observed discharge, Q_i^{sim} being the simulated discharge at timestep *i*. Positive values indicated model underestimation while negative values indicate model overestimation. The optimal value of PBIAS is 0.0%. Performance ratings by Moriasi et al. (2007) reported very good model performace for PBIAS < 10% and unsatisfactory performance for PBIAS > 25% for models with monthly timestep. The Nash-Sutcliffe efficiency, NSE, NSE is calculated with equation (2),

$$NSE = 1 - \frac{\sum_{i=1}^{n}\left(Q_i^{obs} - Q_i^{sim}\right)^2}{\sum_{i=1}^{n}(Q_i^{obs} - Q^{mean})^2} \tag{2}$$

Where Q^{mean} is the mean of the observed discharge over the evaluation period. NSE ranges between $-\infty$ and 1, where 1.0 is considered the optimal value and negative values gives that the mean is a better predictor than the model. Very good performance is reported for NSE between 0.75 and 1, while unsatisfactory performance is reported for NSE < 0.50 for monthly timestep. Daily discharge values from the simulations in WEAP are coupled to monthly values for the comparison of NSE. However, it did not prove easy to obtain a good performance of the model simulations in this study using the traditional statistical methods PBIAS and NSE. Thus, the ability of the model simulations to reproduce the measured flow duration curves and daily average over the year is emphasized for the final choice of parameter set for the model. The importance of graphical methods is also emphasized by Moriasi et al. (2007) for watershed simulations. The final choice of parameters and calibration results are given in section 4 Results.

3.4 Validation

The parameter set calibrated for the Hlotse river basin is transferred to the other catchments in the model. Model validation is made possible in this study by extracting a limited selection of discharge data from previous work in the study area (Ayele, 2016). Daily discharge data for gauge station CG55 in Ngoajane catchment is applied for model validation. The location of gauge station CG55 is illustrated in Figure 7. The catchment area of Ngoajane upstream of CG55 is 146 km^2, and thus smaller than the catchment of Hlotse applied for calibration. However, the elevation properties are very similar as they both are located in the foothills of Lesotho. The Ngoajane catchment is less cultivated compared to Hlotse and correspondingly more grassland and shrubland in percentage of the total area. The Ngoajane catchment is considered to have little water-intensive development (Parkman Ltd, 2004). Based on this, the catchment upstream CG55 is considered an unregulated basin for the validation period 1988-2000. The results from the model validation are given in section 4 Results. Due to the data situation, the validation of the model is performed at the end of the study period. No adjustments of model parameters or modifications of input climate data are made with respect to these validation results.

3.5 Current water withdrawals for Reference scenario

Information regarding existing and historical water withdrawals within the catchment area has been limited for this work. It has not succeeded in obtaining a complete overview of current withdrawals for the area. To replicate the current state of the catchment, historical and existing water withdrawals are found from previously published studies and reports. The different sources of information are not consistent with the amount of water extracted for the different demand centres and the amount of these abstracted directly from the rivers. Thus, estimates of water withdrawals for each demand centres in the modelling area are based on population statistics and estimates for annual water use. These estimates for water withdrawals are found representative for a reference scenario for 1990-2010.

The total population growth in South Africa is found to be 39.1% for the reference period 1990-2010 (World Bank, 2019). For the municipalities in the study area located in the Free State of South Africa, the population growth from 2001-2011 is found to be declining with a percentage of 0.05%, 0.90%, and 0.81% for Dihlabeng, Setsoto and Mantsopa, respectively (Statistics South Africa, n.d.). Based on this, the census 2001 population statistics are considered a representative estimate for the whole reference period. Water withdrawals per inhabitant in 2013 are found to be 294 m^3/year, including water for irrigation, livestock, municipalities and industry (FAO, 2016). With the given amount of 78.2% of this volume abstracted from surface water, the annual water withdrawal volume per inhabitant is found to be 230 m^3/year.

The annual water use in Lesotho is reported in 2001 to be 24 m^3 per inhabitant, including water for irrigation, livestock, municipalities and industry (FAO, 2005). Population estimates for the different districts are obtained from census 2006 and assumed to represent the reference period 1990-2010 (Bureau of Statistics, 2013). For the district of Leribe, more detailed data were available for current water withdrawals. The total water estimate for Leribe is divided into three withdrawals concerning a percentage of reported water consumption by WASCO of 34%, 62%, and 5% for the demand centres of Hlotse, Maputsoe, and Peka, respectively. The populations for each district include both urban and rural inhabitants.

The estimates for current water withdrawals for the Reference scenario are given in section 4 Results, specifically in Table 8 for South Africa and Table 9 for Lesotho. The location of the different demand centres is schematised in Appendix B. Each of the withdrawals is added as nodes for "Demand Sites" connected with a "Transmission Link" and "Return Flow" to specify the location of the intakes and returns for unconsumed withdrawals. The consumption rate of the withdrawals is assumed to be 75%.

It is known that there exist several local reservoirs on the South African side of the catchment for both agricultural, municipal, and industrial purposes. A total of 38 smaller dams within the modelling area upstream of Maseru is found registered in the List of Registered dams of South Africa. By investigating satellite images, three of these reservoirs are found to be of considerable size and located directly on the tributaries included in the model setup. Thus, these three reservoirs are considered to directly impact the simulated runoff from the catchment and included in the model with storage capacities given in Table 3. For the Lesotho side of the catchment, only 'Muela Tailpond Dam is included in the model setup. The only local reservoir in addition to 'Muela found on the Lesotho side of the catchment is the Maqalika reservoir located in Maseru. Maqalika reservoir has served as the main source of water supply to Maseru since 1983 by pumping surface water from Caledon river (Letsie & Allopi, 2008). Today, the main water supply to Maseru is served by the Metolong dam located outside of the modelling area. Thus, the local reservoir Maqalika is not included in the model setup and the water supply to Maseru is represented with as a "Demand Site" node. Operational strategies for the reservoirs included in the model setup is unknown except for 'Muela Tailpond Dam where flow releases are set to mimic the mean annual runoff. No specific data for the operational strategy of the reservoirs are included in the model setup. The location of these reservoirs is schematised in Appendix B.

Table 3 Reservoirs included in model setup

Name	**Tributary river**	**Capacity [mill m^3]**	**Purpose**
'Muela Tailpond Dam	Nque	6	Provides head for water transfers to RSA
Verdun Dam	Little Caledon	0.45	Irrigation
Meulspruit Dam	Meulspruit	2.6	Municipal and industrial use
Moperi Dam	Mopeli	1.18	Municipal and industrial use

3.6 Scenario definition

A set of scenarios for water management strategies is set up to assess the effects on the water availability for the different water uses along Hlotse river. The development of scenarios to be assessed in this study is based on findings in previously published reports from the study area in combination with independent assumptions and estimates for some of them. The different scenarios considered in the study are visualized in Figure 9 and labelled with the letters A to D. Water supply for domestic and industrial purposes is termed WS, while water supply for irrigation is termed IRR. Operational strategies for each scenario are defined and given in Table 4. Detailed information on the implementation of each scenario is provided in the following sections.

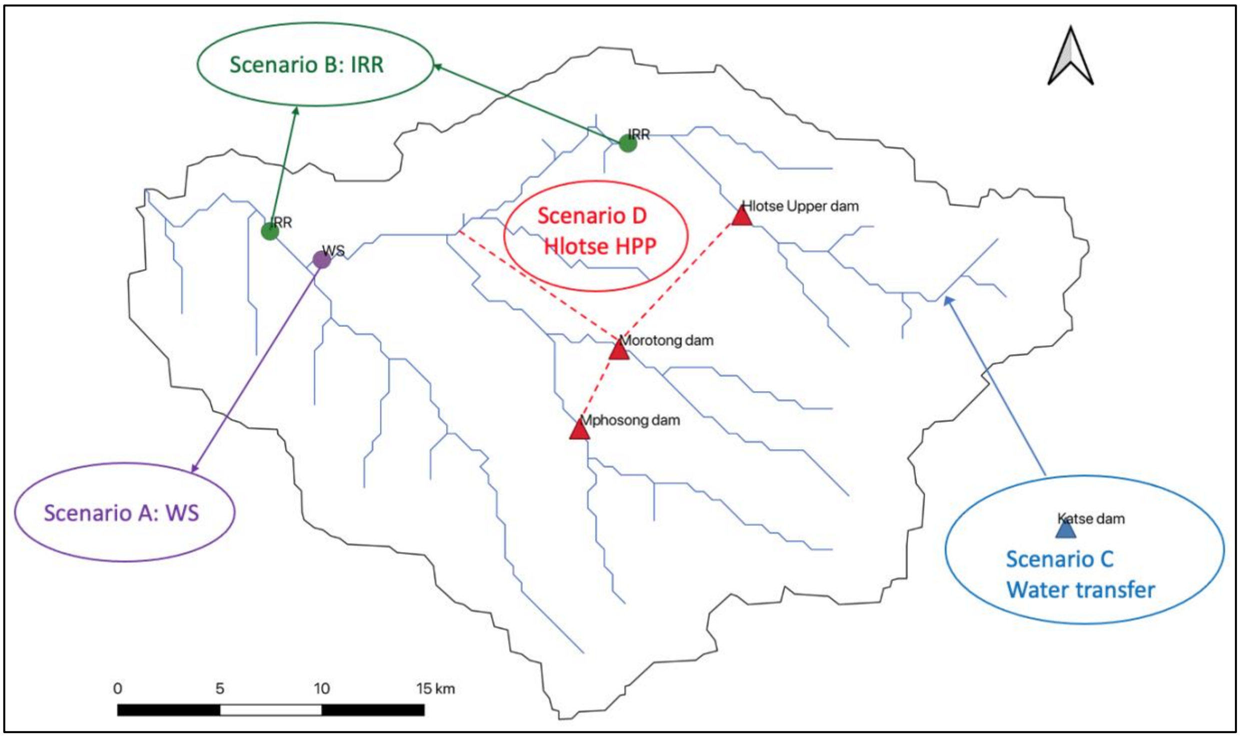


Figure 9 Visualization of scenarios considered for Hlotse river basin. Map derived using the HydroSHEDS dataset (Lehner et al., 2008).

Table 4 Scenarios for different operational strategies in Hlotse river

Scenario		**Operational strategy**	
A & B		Direct river abstractions	
C	C1	Water transfers from Katse dam in the LHWP	Constant release of 0.12 m^3/s
	C2		Seasonal release 0.2 m^3/s Apr-Oct
D	D1	Reservoir regulation	Reservoir releases set to maximize hydropower production
	D2		Reservoir releases set to fulfil demands downstream

Scenario A explores the impacts of the planned water abstractions in Hlotse river to meet domestic and industrial demands for Zone 2 & 3 in the LLWSS project for Phase 1 in 2030 and Phase 2 in 2045 (Ministry of Water, 2019). Water demands for this purpose are assumed constant over the year. A simplification is made by assuming the existing water supply to Hlotse town in the Reference scenario to be located at the same place as the future water supply defined in scenario A.

Scenario B explores the development of irrigation systems along Hlotse river in addition to the planned water abstractions for domestic and industrial supply explored in Scenario A. Three demand levels of irrigation development within the Hlotse river basin are considered in this study. A maximum irrigation development to 21 686 hectares proposed by SMEC (2017) is considered as the full irrigation potential for the study area. In addition, two additional demand levels for irrigation in 2030 and 2045 are defined in this study, considering an irrigation expansion of approximately 100 hectares per year from the current 2021. An annual water requirement for irrigation of 2130 m^3/ha is applied, adopted from the irrigation report by SMEC (2017). The spatial distribution of irrigation development within Hlotse river basin is highly simplified by manually adding two withdrawal points along the river. Runoff distribution within the catchment is accounted for by inserting additional runoff/infiltration links to Hlotse river upstream of these withdrawal points weighted with the percentage share of the area draining to these. To account for seasonal variation of irrigation demands it is assumed that demands for irrigation will follow the same pattern as the seasonal variation of the Kc-factor.

Scenario C explores the effects of water transfers from the Katse dam into Hlotse river. It is expected that operational rules for these water transfers will be refined, including possible expansion to accommodate future developments in Hlotse river, but details remain unknown at the time for this study. Thus, two different operational strategies are formulated within the existing regulatory framework allowing for an annual transfer of 3.75 MCM from the Katse dam, given in Table 4. This scenario is implemented in the WEAP model by adding a transmission link from a node for "Other Supply" located outside of the catchment.

Scenario D explores the effects of hydropower regulation in the basin. The three reservoirs and associated infrastructure for the proposed Hlotse hydropower plant, Hlotse HPP, are included in the model as good as possible within the structure in WEAP. The physical characteristics of the hydropower plant and reservoirs are extracted from the project report by SSI (2009). Several assumptions are introduced to provide input to the model at a more detailed level than the information provided in the report for the project. The method for introducing these assumptions is given in the following, while the detailed input data and characteristics for each reservoir is given in Appendix D. The storage capacity and inactive zone for each of the three proposed reservoirs are found by assigning the given total volume in relation to the proposed heights of the dams. The initial storage of reservoirs is set to active level. Buffer zone and flood control zones are not specified in the model representation. The volume-elevation curve for each reservoir is estimated by following a similar relationship between volume and height for another proposed dam in Hlotse river by SMEC (2017). The net evaporation from the three reservoirs is estimated by subtracting monthly open water evaporation for a dam proposed in the study area by SMEC (2017) with the average rainfall for each month in the Princeton climate dataset. The monthly values are divided into daily values by assuming an equal distribution to each day within a month. Inflow to each reservoir is accounted for by weighing the percentage of the area draining to the reservoirs by inserting additional runoff/infiltration links. Environmental flow releases from the reservoirs are not considered for this study. The system of headrace tunnels for the proposed power plant is slightly simplified by concentrating power production to one reservoir, Morotong, with a rated discharge of 6 m^3/s for one turbine instead of two turbines of 3 m^3/s as proposed in the project report. The tunnel system for the hydropower scenario is sketched in Figure 9, where water is transferred from Hlotse Upper and Mphosong dam to Morotong dam by inserting transmission links in the WEAP model. Priorities for the two operational strategies considering reservoir releases are given in Table 4. For Scenario D1 with maximum hydropower production as first priority, the projected monthly production for the proposed power plant is adopted from the report by SSI and set as energy demand for each day in the WEAP model by assuming an equal distribution to each day within a month.

The specific input data for each scenario are given in section 4 Results. Demand nodes for water supply and irrigation are added as demand sites with transmission links and return nodes with a consumption rate of 75%. The WEAP model is initially set up with a Reference scenario with estimated demands for the historical period 1990-2010 given in Table 8 and Table 9 in section 4 Results. All scenarios considered in this study are simulated for this historical period of climate input. The scenarios are implemented in the model despite the lack of satisfactory validation of the model and no correction of climate data input. Appendix C provides an overview of the different model setups applied for this study in addition to screen dumps of the setups for exploring each scenario.

3.6.1 Performance measures

WEAP allows the user to display numerous results and variables for all scenarios, rivers, catchments, and demand sites. To be able to quantify the relative change and performance for the different scenarios and effects of regulation measures, the following control parameters are applied for this study:

- Reliability [%]
- Unmet demand [m^3/s]
- Mean annual runoff [m^3/s]
- Hydropower generation [GWh]

The reliability replicates the percent of timesteps in which demand is not fully satisfied. Unmet demand is chosen to illustrate the magnitude and timing of the shortages. The mean annual runoff is used to assess the impacts of the developments introduced both locally and further downstream. Hydropower generation is applied as measure for scenario D in addition to the other performance measures.

4 Results

This section represents all the results from the analyses performed in the study. Analysis of the climate data input is first given, followed by the results from the calibration and validation of the model. Input data and results from each of the simulated scenarios are then presented together.

4.1 Input data validation

Table 5 gives the average annual rainfall for each of the climate stations where data for 1981-2010 were available. The deviation between average annual rainfall for observed and gridded climate data ranges from -43 to +128 mm.

Table 5 Average annual rainfall 1981-2010

Station name	**Altitude [m.a.s.l.]**	**Average annual rainfall [mm]**		
		Observed	Princeton dataset	Deviation
Leribe	1740	742	773	+32
Pitseng	1780	633	653	+20
Hololo	1640	640	768	+128
St.Peters	1860	721	678	-43

Figure 10 gives a scatter plot of observed and gridded monthly rainfall data for Leribe station. The red line is drawn to indicate a perfect fit of 1:1. The R^2 for the observed and gridded data is 0.62 where the trend line in blue is located below the 1:1 line, oriented towards the x-axis for gridded rainfall data.

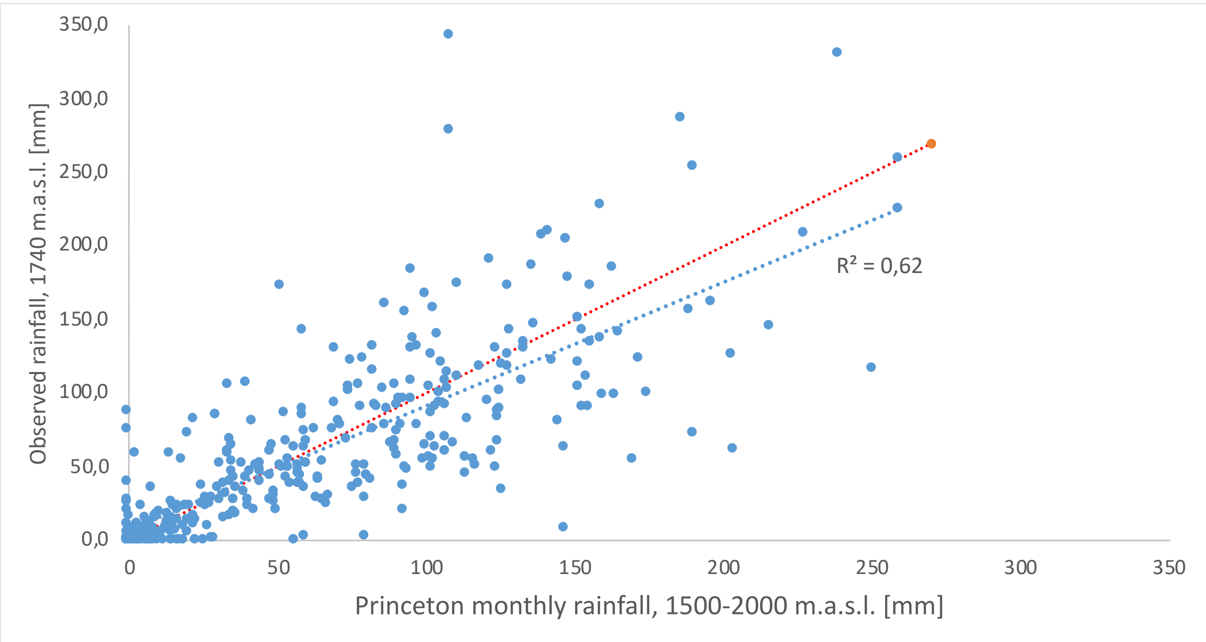


Figure 10 Correlation of monthly precipitation, Leribe station (1981-2010)

To evaluate the ability of the gridded dataset to replicate seasonal variations, the average rainfall for each month for Leribe station is given in Figure 11. The deviation between observed and gridded rainfall ranges from -27 to +11 mm.

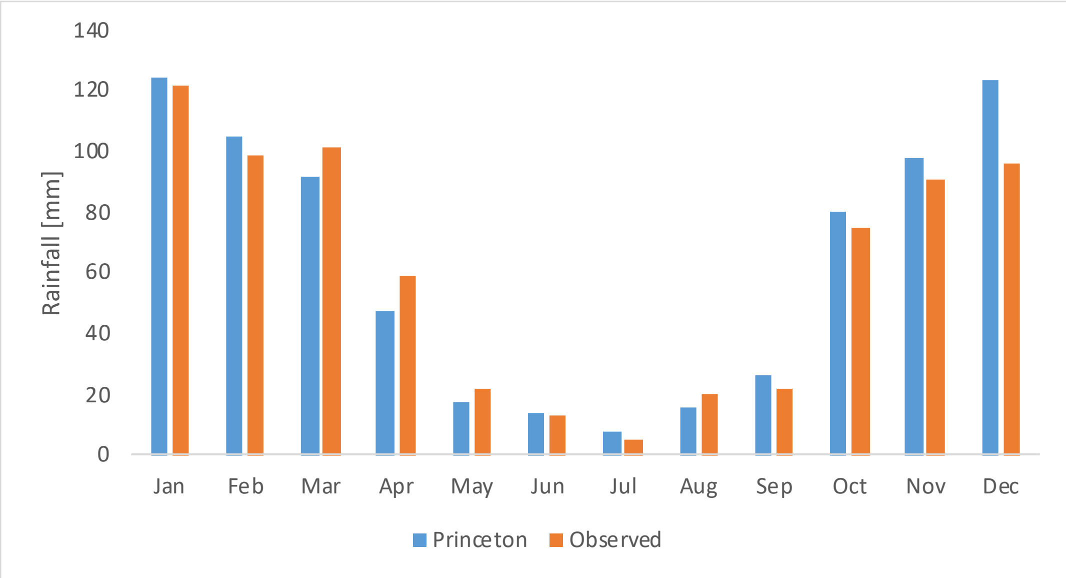


Figure 11 Seasonal rainfall distribution, Leribe station (1981-2010)

4.2 Model calibration and validation

The results from the sensitivity analysis for the chosen model parameters are given in Table 6. The sensitivity analysis indicates that the model is most sensitive to changes in Kc, Crop Coefficient, and least sensitive to changes in PFD, Preferred Flow Direction. The seasonal variation found for the Kc factor is given in Figure 12.

Table 6 Sensitivity analysis of model parameters

Parameter	Default value	Test value		Sensitivity	
		-50%	+50%	-50%	+50%
Kc	1	0.5	1.5	145%	-74%
SWC	1000 mm	500	1500	7%	-2%
DWC	1000 mm	500	1500	-2%	2%
PFD	0.15	0.075	0.225	0%	0%
RRF	2	1	3	44%	-9%
DC	20 mm/day	10	20	1%	1%
RZC	20 mm/day	10	20	-54%	37%

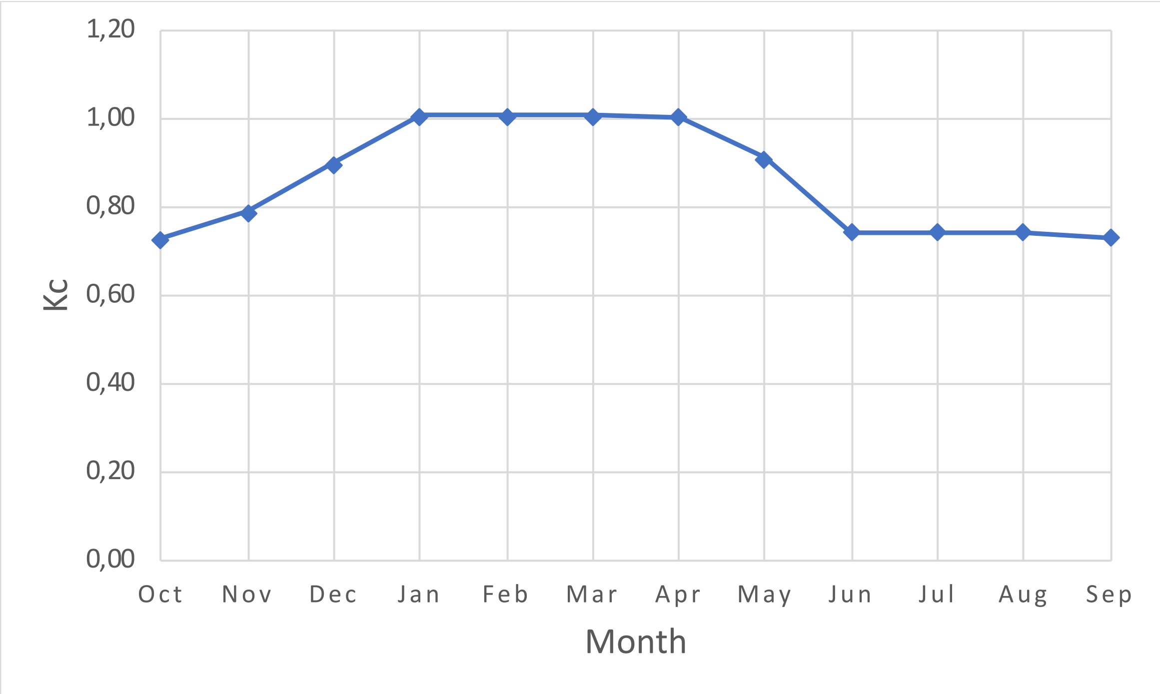


Figure 12 Seasonal variation of the Crop Coefficient, Kc

The calibrated values and chosen parameter set for the Hlotse catchment is given in Table 7. The initial soil moisture, Z1 and Z2 is kept at default at 30%.

Table 7 Chosen parameter set for the model

Parameter	**Kc**	**SWC**	**DWC**	**PRF**	**RRF**	**DC**	**RZC**
Unit	-	[mm]	[mm]	[-]	[-]	[mm/day]	[mm/day]
Value	0.95	150	35	0.99	26	1	12

The final calibration of the Hlotse catchment upstream of gauge station CG25 results in an overall PBIAS of -1.7% for the period from 1st of October 1988 to 30th of September 2000. The NSE for monthly values is found to be 0.30 for the calibration period. Figure 13 gives the simulation results for the calibration with daily discharge on the left vertical axis and annual average discharge on the right vertical axis. The annual average for a hydrological year from 1st of October to 30th of September is displayed on the 1st of April for the corresponding year. A complete list of PBIAS for each year is provided in Appendix E. The largest underestimation is found for year 1988/1989 with a PBIAS of 53%. The largest overestimation is found for year 1991/1992 with a PBIAS of -103%.

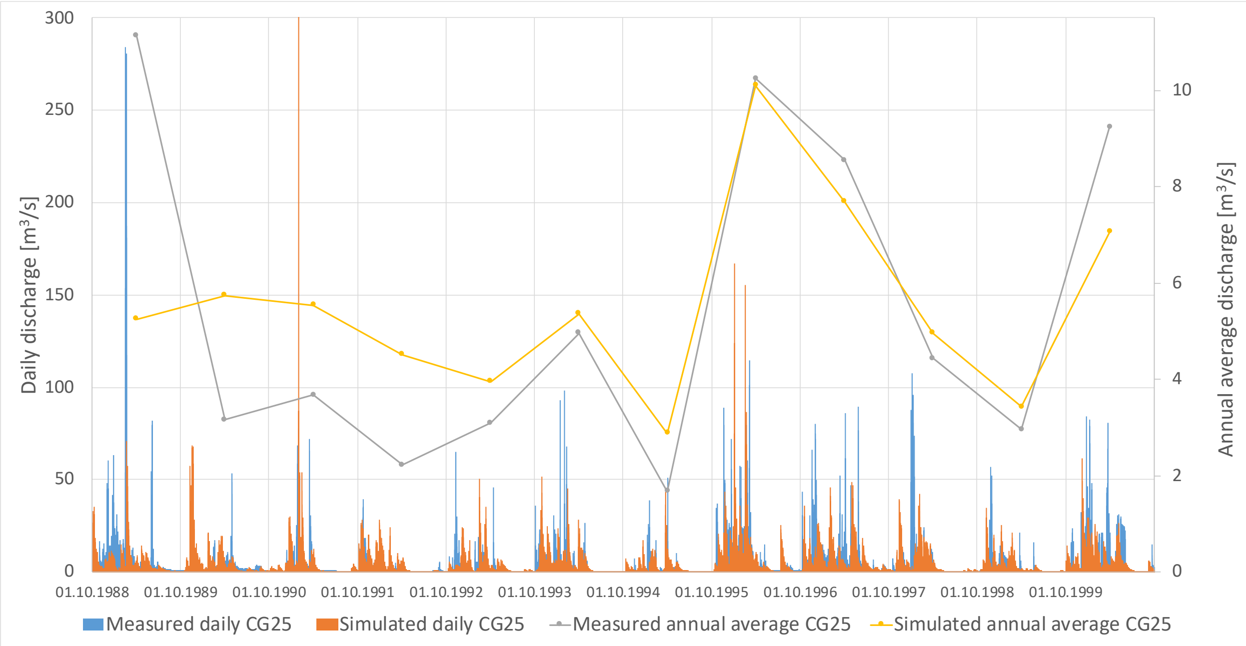


Figure 13 Daily discharge and annual average discharge for gauge station CG25

From Figure 14 one can observe the daily average of the simulated and measured discharges, where the seasonal variations and magnitude of the high and low flows is replicated in the model simulations. The peak of measured discharge is 30 m^3/s the middle of February and peak of simulated discharge of 35 m^3/s at the end of January. The flow duration curve for measured and simulated discharge at station CG25 is given in Appendix E.

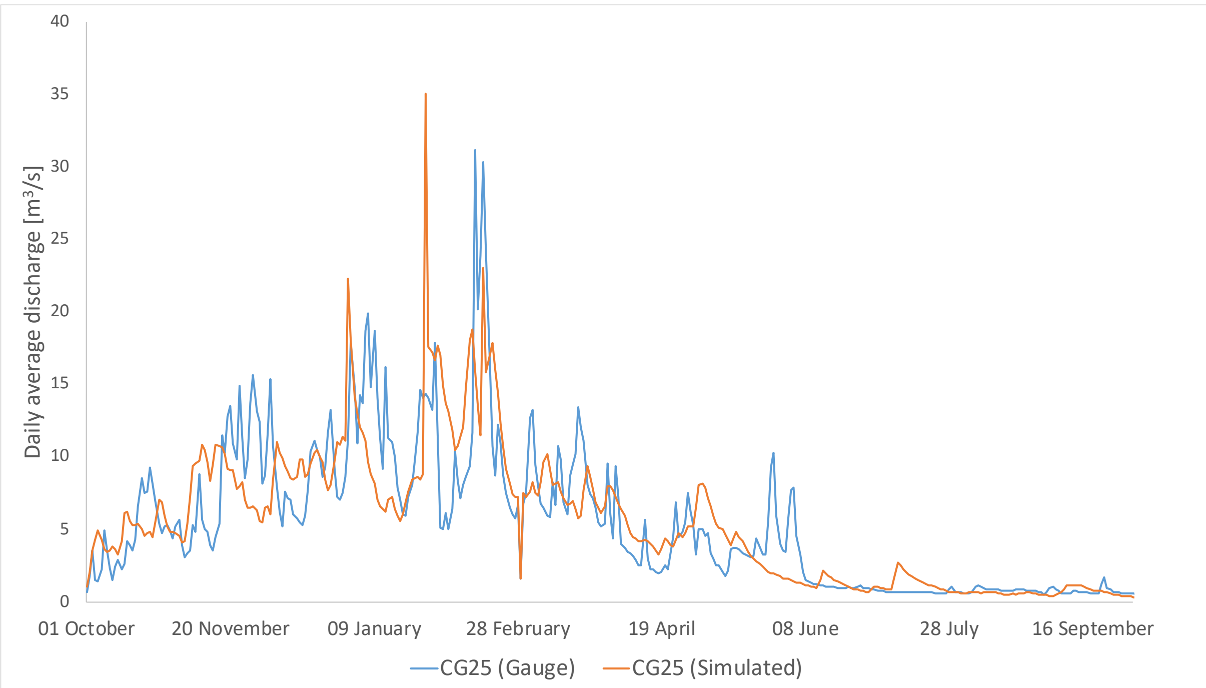


Figure 14 Measured and simulated daily average discharge, CG25

Observed and simulated discharge for gauge station CG55 in the Ngoajane catchment are compared for validation of the model when calibrated parameter set are transferred. The result from this comparison is given in Figure 15. The validation in Figure 15 is displayed with same setup as calibration results in Figure 13 with daily discharge on the left vertical axis and annual average discharge on the right vertical axis. For station CG55, an overall PBIAS is found to be -41%. The NSE for monthly discharge values is found to be 0.31. The largest overestimation is found for year 1994/1995 with PBIAS -732%, and largest underestimation is found for year 1988/1989 with PBIAS 65%. Figure 16 gives the daily average discharge for the validation at station CG55 in Ngoajane. The peak of measured discharge is 6 m^3/s at the end of November, while the peak of simulated discharge is 15 m^3/s at the end of January.

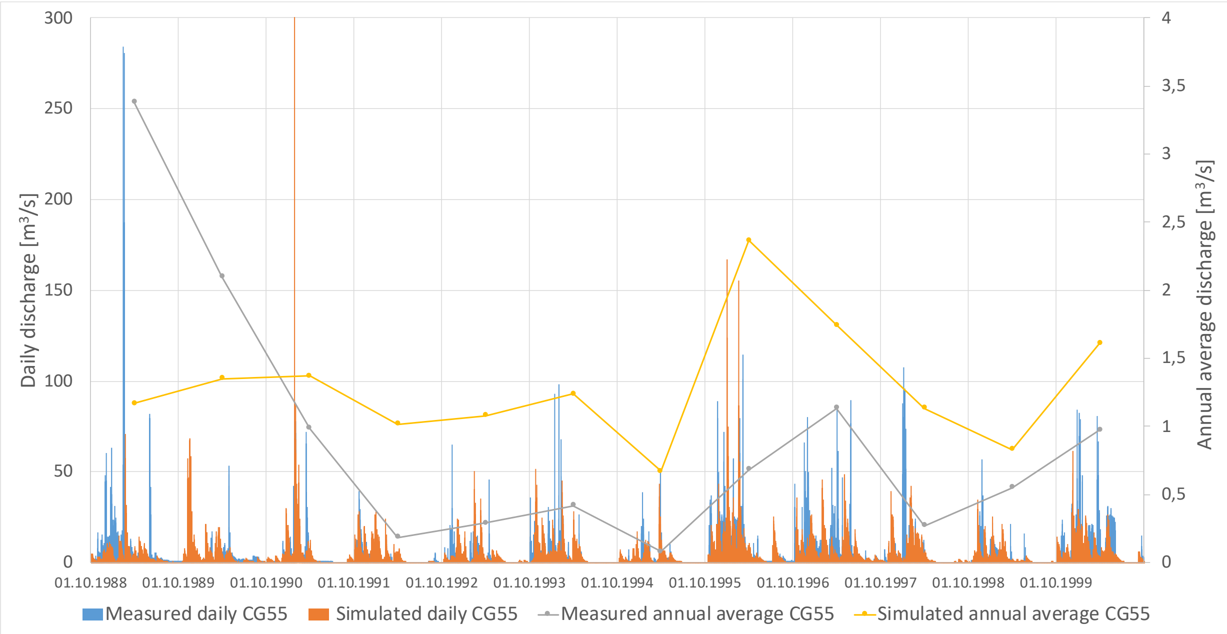


Figure 15 Daily discharge and annual average discharge for gauge station CG55

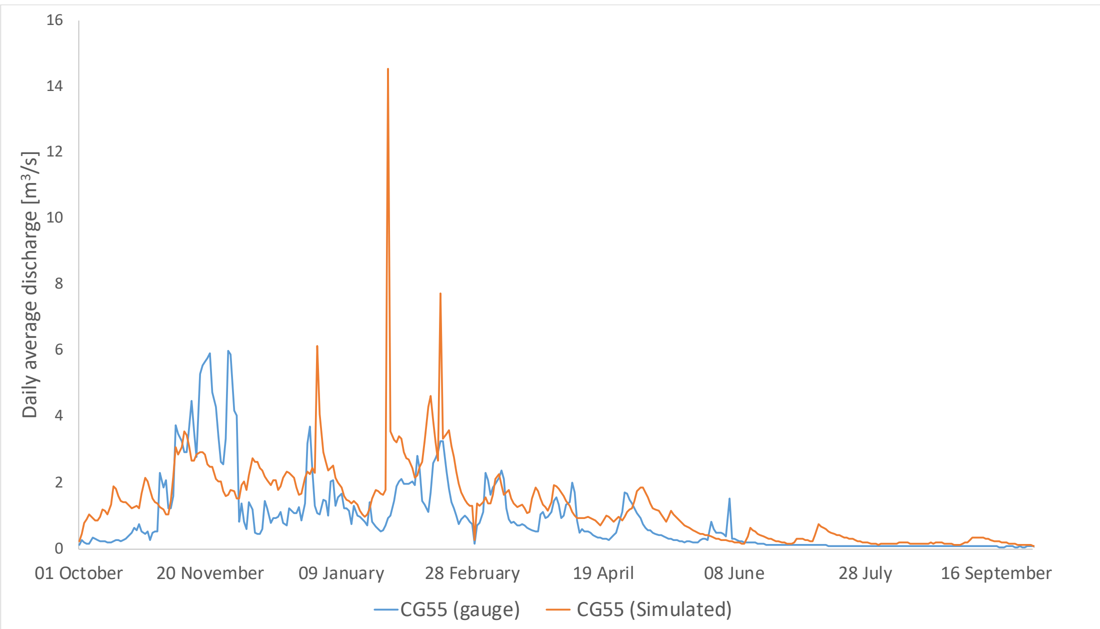


Figure 16 Measured and simulated daily average discharge, CG55

4.3 Results from scenario simulations

This section provides the data input together with the simulation results for each scenario. The reference scenario is given for the complete model area down to Maseru, while the following scenarios are focused to the Hlotse river basin. All future scenarios are simulated with climate data for the reference period 1990-2010.

4.3.1 Reference scenario (1990-2010)

The estimates of current water withdrawals for the Reference scenario are given in Table 8 and Table 9. The annual water withdrawals per inhabitant are assumed to be 230 m^3 for South Africa and 24 m^3 for Lesotho (FAO, 2005, 2016). This includes water for both irrigation, livestock, municipalities, and industry.

Table 8 Estimates of water withdrawals in South Africa

Municipality	**Population (2001)**	**Estimated annual water use [m^3] (1990-2010)**
Dihlabeng	129 338	29 735 841
Setsoto	123 194	28 323 286
Mantopa	55 342	12 723 569
Total South Africa		70 782 696

Table 9 Estimates of water withdrawals in Lesotho

District	**Demand center**	**Population (2006)**	**Estimated annual water use [m^3] (1990-2010)**
Butha-Buthe	Butha-Buthe	110 320	2 647 680
Leribe	Hlotse	293 369	2 360 363
	Maputsoe		4 345 214
	Peka		335 279
Berea	Teyateyaneng	250 006	6 000 144
Maseru	Maseru	431 998	10 367 952
Total Lesotho			26 056 632

The reliability in percent simulated for each demand site for the Reference scenario is given in Figure 17. The lowest reliability is found for demand site Dihlabeng to be 61.7% while highest reliability is 100% for both Maseru and Peka.

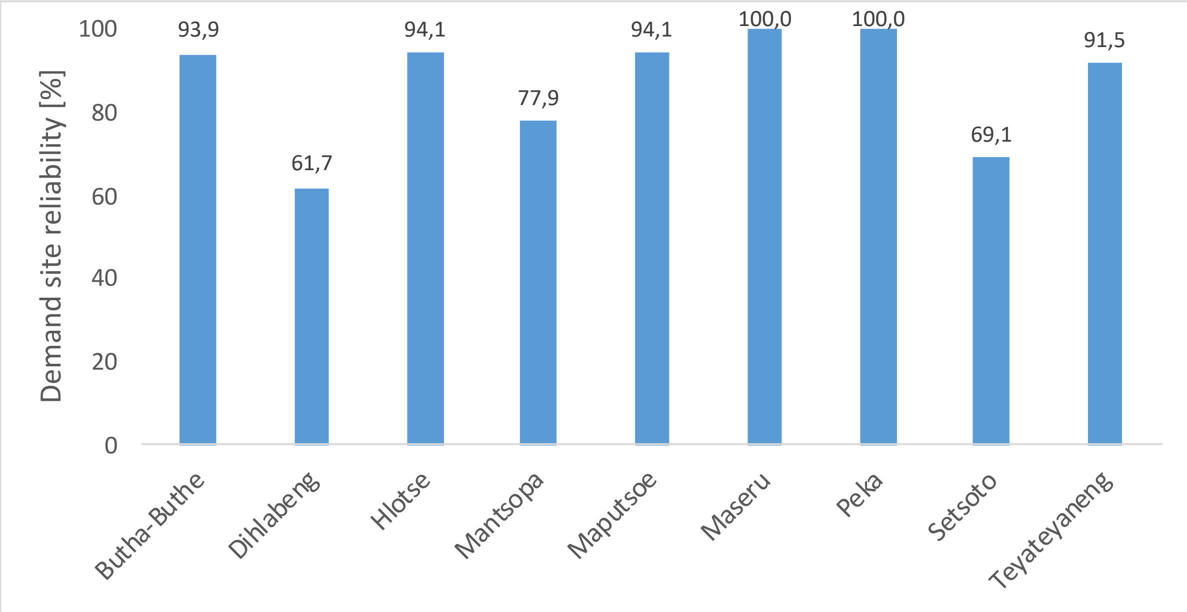


Figure 17 Demand site reliabilities for Reference scenario

Gauge station CG22 represents the total outflow from the model of the study area upstream of Maseru. Annual average discharge out of the model compared with gauge measurements is given in Figure 18. It is observed that the simulated water volume out of the model is twice as much as measured for the period 1991-2010.

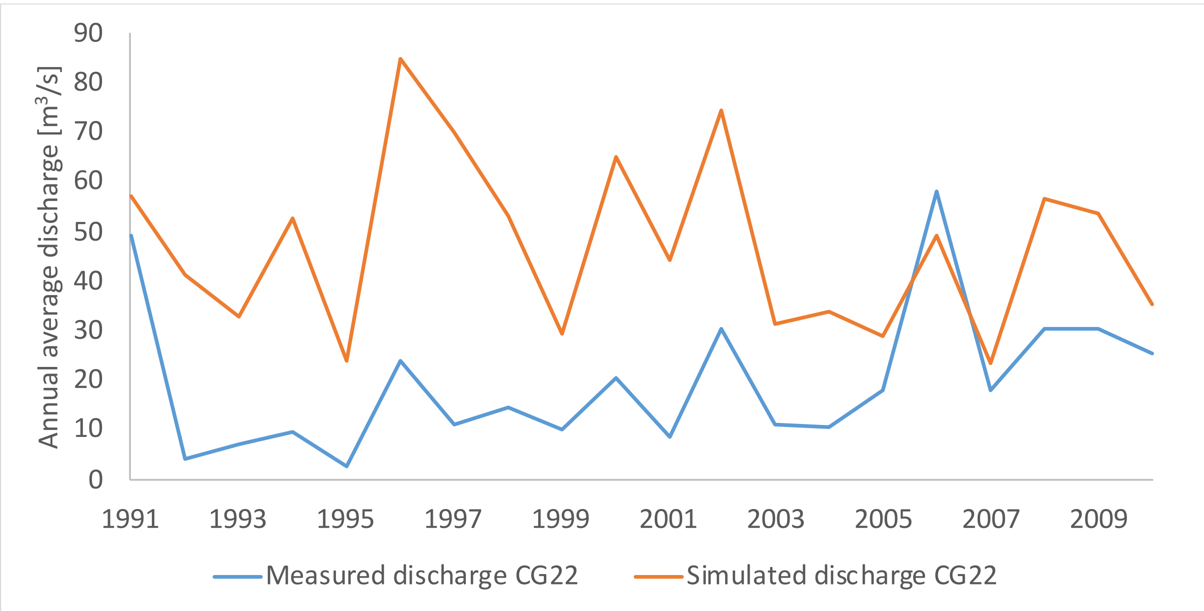


Figure 18 Measured and simulated annual average discharge CG22

4.3.2 Scenario A: Domestic and industrial water supply

Two demand levels for scenario A in addition to the reference are given in Table 10 to evaluate effects of the planned domestic and industrial water supply directly from the Hlotse river. For scenario A, only this purpose is evaluated and given first priority for the model simulations.

Table 10 Water demands for Scenario A

Demand level	Demand [m^3/day]	Demand [m^3/year]
WS Reference	6 467	2 360 363
WS 2030	52 308	19 092 420
WS 2045	66 279	24 191 835

The simulation results for different demand level reliabilities in scenario A are given in Table 11. The reliability indicates the percentage of time demand is fulfilled, where a variation from 94.1 to 75.6 percent is found for the different demand levels. The reliability for demand at Maseru in the most downstream part of the study area remains at 100% for all demand levels in scenario A. The mean annual runoff, MAR, for the simulation period 1990-2010 is given for both Hlotse river and Caledon river right upstream of Maseru. The percentage change is given in relation to the reference scenario. The highest percentage decrease in mean annual runoff is found in Hlotse river of 6%, the corresponding decrease in Caledon river is -0.9%.

Table 11 Demand site reliabilities and mean annual runoff for scenario A

Demand level	Demand site reliability (%)	MAR Hlotse river		MAR Caledon river	
		[m^3/s]	% Change	[m^3/s]	% Change
WS Reference	94.1%	6.81		47.68	
WS 2030	78.3%	6.49	-4.7	47.36	-0.7
WS 2045	75.6%	6.40	-6.0	47.27	-0.9

Figure 19 gives the daily average of unmet demands for water supply for the given demand levels in scenario A. The graph indicates a significant supply shortage in the dry season from the middle of April to October for the demand levels 2030 and 2045. More minor cases of unmet demands are the found in the period between this.

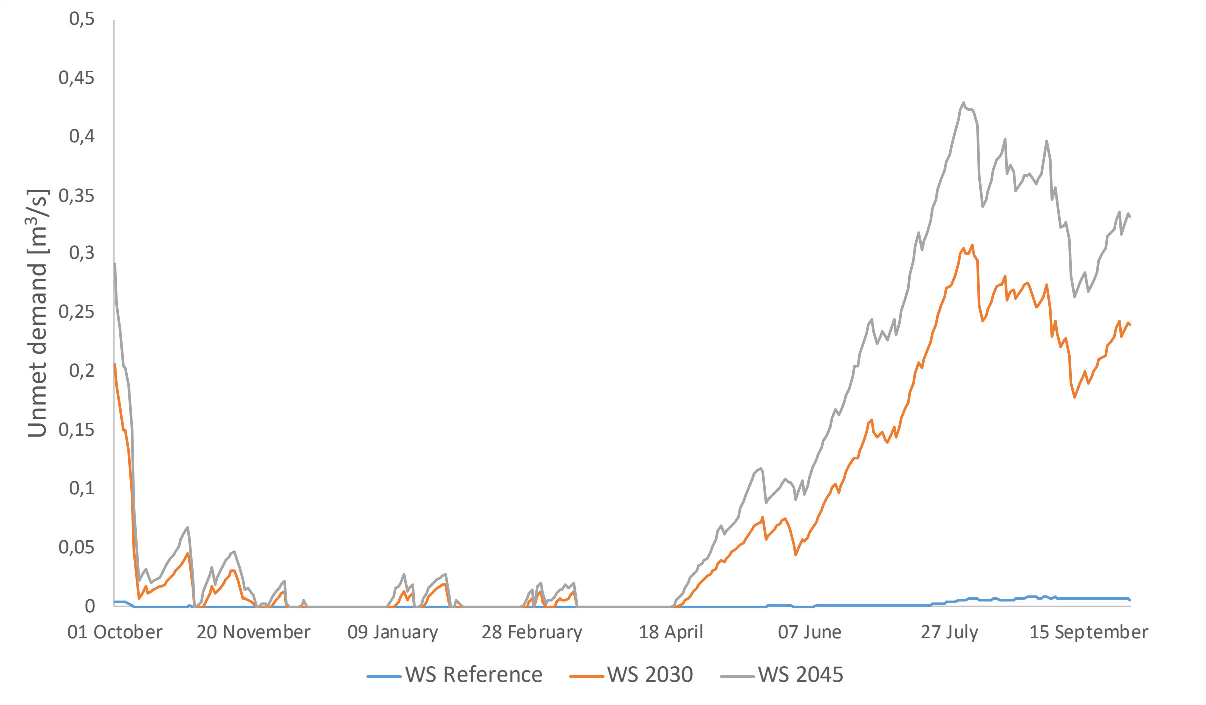


Figure 19 Daily average of unmet demands for water supply scenario A

4.3.3 Scenario B: Irrigation development

Three demand levels for irrigation development within the Hlotse river basin are defined in addition to the reference and provided in Table 12. Demand levels for 2030 and 2045 are based on 100 ha increased irrigation area per year in addition to existing irrigation areas. The demand level termed "IRR Max" reflects the irrigation expansion to all areas suitable for irrigation purposes in the study area proposed by SMEC (2017). For scenario B, water supply for irrigation is set as priority 2 in the model and is added on top of the demands defined in scenario A.

Table 12 Water demands scenario B

Demand level	Area irrigated [ha]	Water demand [m^3/year]
WS + IRR Reference	256	545 280
WS + IRR 2030	1150	2 449 500
WS + IRR 2045	2650	5 644 500
WS 2045 + IRR Max	21 686	46 191 181

The reliability simulated for each demand site in scenario B is given in Table 13. The highest reliability is found for reference scenario of 94.2%. The lowest reliability for scenario B is 63.7% found for demand level considering full irrigation development, "IRR Max". Reliability of 63.7% corresponds to 133 days over the year where demand is not fulfilled. Reliability for demand centre Maseru further downstream is found to be 100% for all demand levels in scenario B.

Table 13 Demand site reliabilities for scenario B

Demand level	Reliability WS [%]	Reliability IRR [%]
WS + IRR Reference	94.1	93.8
WS + IRR 2030	78.4	89.7
WS + IRR 2045	75.8	83.7
WS 2045 + IRR Max	75.6	63.7

Table 14 gives the mean annual runoff, MAR, simulated in Hlotse river and Caledon river for Scenario B. The MAR is displayed for both 1990-2010 and for 2006/2007 which is considered a dry year. For the period 1990-2010, the demand level comprising full irrigation expansion gives a decrease of 18% in mean annual runoff in Hlotse river and a decrease of 2.6% further downstream in Caledon river. The decrease in mean annual runoff is even more pronounced in a dry year with 33.6% and 5.1% for the two rivers.

Table 14 Mean annual runoff for scenario B

Demand level	MAR Hlotse river			
	1990-2010		Dry year 2006/2007	
	[m^3/s]	% Change	[m^3/s]	% Change
WS + IRR Reference	6.80		3.63	
WS + IRR 2030	6.44	-5.3	3.23	-11.0
WS + IRR 2045	6.28	-7.6	3.06	-15.7
WS 2045 + IRR Max	5.55	-18.4	2.41	-33.6
	MAR Caledon river			
	1990-2010		Dry year 2006/2007	
	[m^3/s]	% Change	[m^3/s]	% Change
WS + IRR Reference	47.66		23.90	
WS + IRR 2030	47.30	-0.8	23.50	-1.7
WS + IRR 2045	47.15	-1.1	23.33	-2.4
WS 2045 + IRR Max	46.42	-2.6	22.68	-5.1

Figure 20 shows the daily average of unmet irrigation demands for Scenario B, given the simulated historical period 1990-2010. For demand levels of 100 ha increase to 2030 and 2045, the unmet demands are prominent for the approximately same period as unmet demands for water supply in scenario A from the middle of April to October. Unmet demands for full irrigation development, "IRR Max" are prominent for almost the entire period, with peak in the beginning of August.

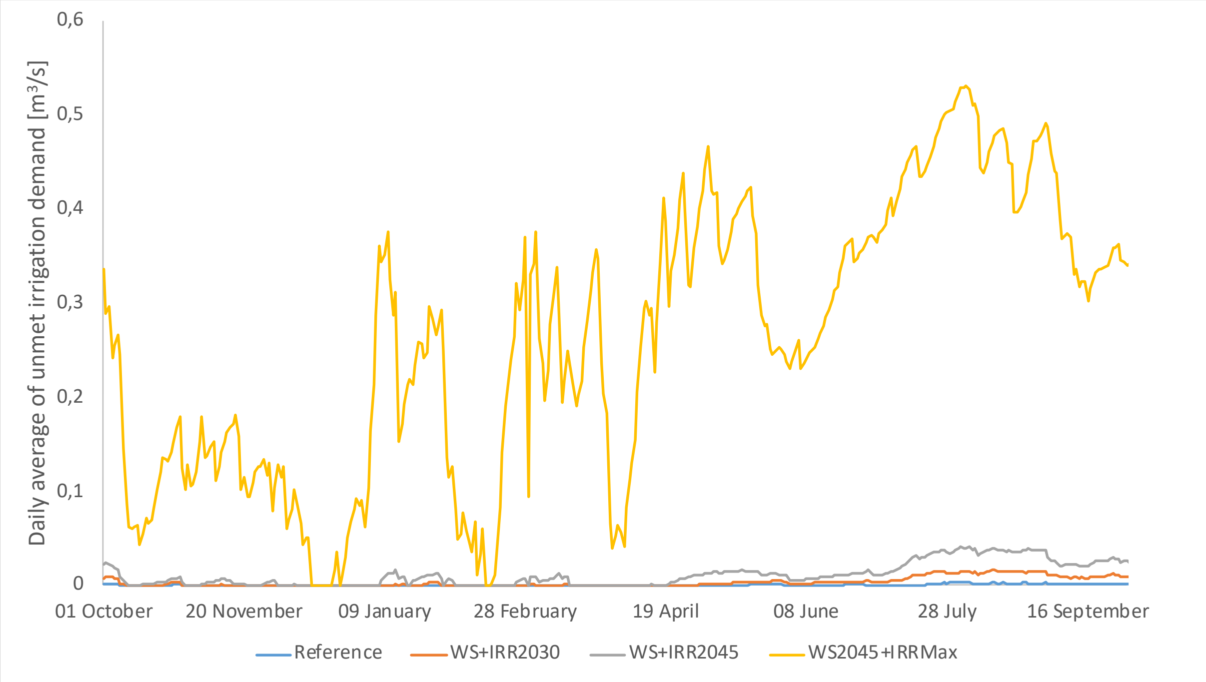


Figure 20 Daily average of unmet irrigation demands, scenario B

Figure 21 shows the unmet demands for a dry year for water supply and irrigation 2030 and 2045. The magnitude of unmet demands for level "IRR Max" is found to be of significantly larger magnitude than the other demand levels and is chosen to be excluded from Figure 21 to highlight the unmet demands for the levels of a smaller magnitude. This figure shows that all demand levels, including the reference, has the bulk of unmet demands in the period from July to September.

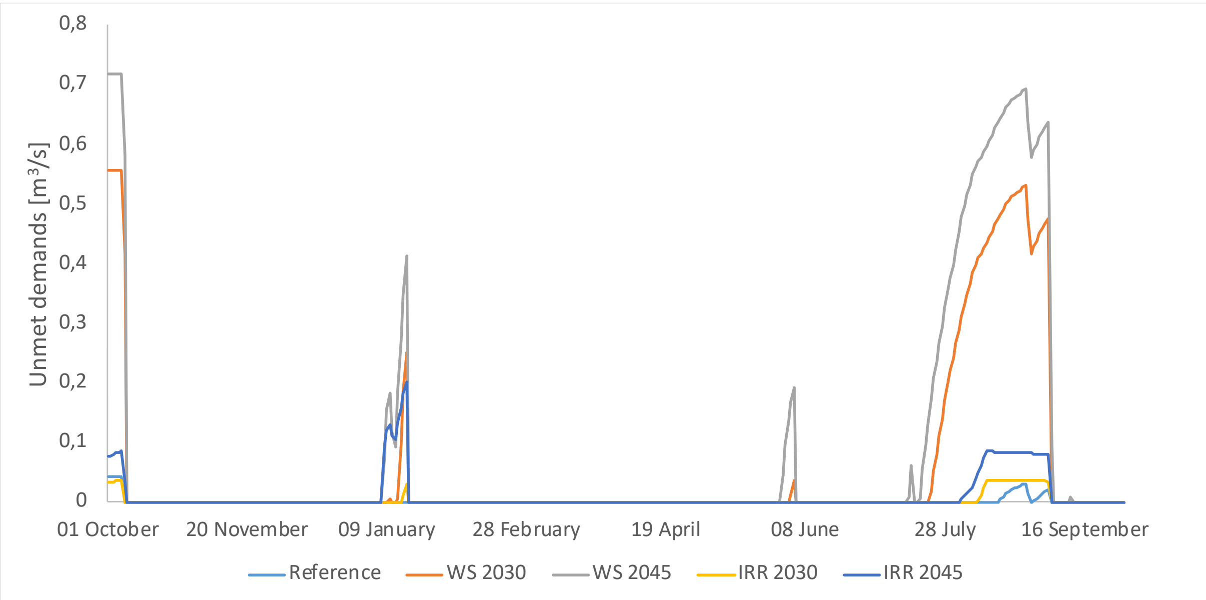


Figure 21 Unmet demands for a dry year 2006/2007, scenario B

4.3.4 Scenario C: Water transfers from the LHWP

Scenario C explores two different operational strategies of water transfers from Katse dam in the LHWP into Hlotse river. Scenario C1 is defined as a constant supply of 0.119 m^3/s over the year which totals an annual volume of 3.75 MCM. Scenario C2 is defined as seasonal supply with 0.2 m^3/s from April to October with a total annual volume of 3.68 MCM. The simulated reliabilities for each demand site and level for scenario C are given in Table 15. The reliabilities range from 65.5% as lowest to the highest of 100%.

Table 15 Reliabilities for demand sites in scenario C

Demand levels	**Reliability WS [%]**		**Reliability IRR [%]**	
	C1: Constant	C2: Seasonal	C1: Constant	C2: Seasonal
Reference	98.4	100	98.1	100
WS + IRR 2030	80.7	82.2	91.5	92.5
WS + IRR 2045	77.5	78.5	87.8	89.1
WS 2045 + IRR Max	77.5	78.5	65.3	65.7

The unmet demands for Scenario C1 with a constant transfer are given in Appendix E as these curves are identical to Figure 19 for scenario A and Figure 20 for scenario B, B but shifted down with a decrease of 0.1 m^3/s in magnitude due to the constant transfer from Katse dam. The daily average of unmet demands for potable water supply in Scenario C2 with the seasonal transfer of 0.2 m^3/s from April to October are given in Figure 22. A similar seasonal variation of unmet demands as given in Figure 19 can be observed but with a reduction of the peak in the dry season.

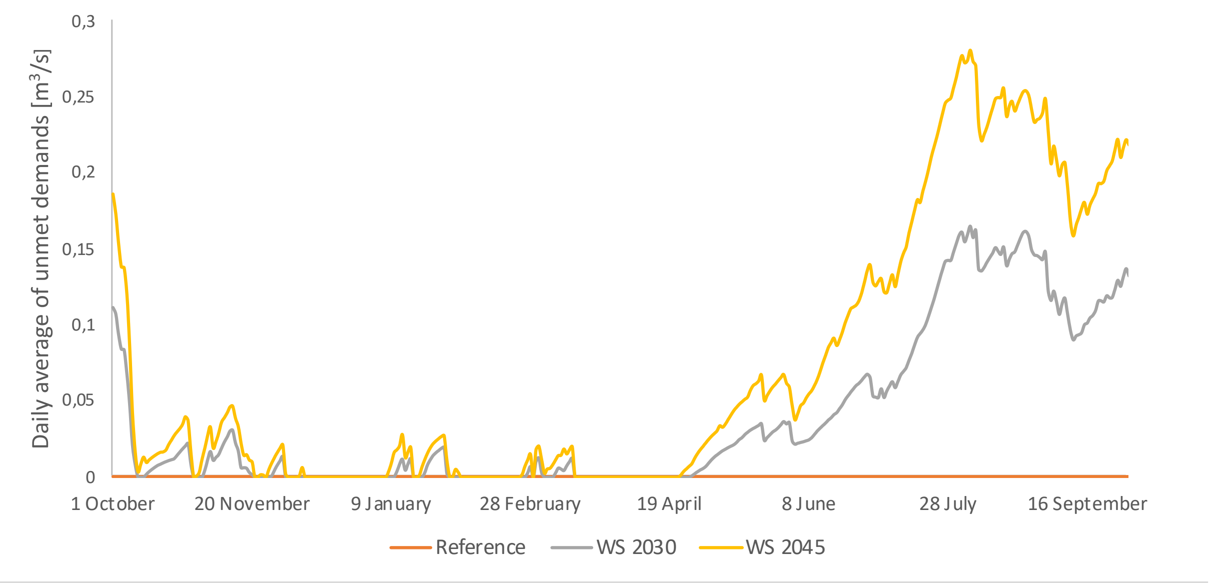


Figure 22 Daily average of unmet demands for water supply, scenario C2

Figure 23 gives unmet demands for a dry year 2006/2007 for scenario C2. This figure shows that all demand levels, except for "IRR Max", has the bulk of unmet demands in August. The unmet demands for maximum irrigation level are more evenly distributed over the year with peak of unmet demands in January.

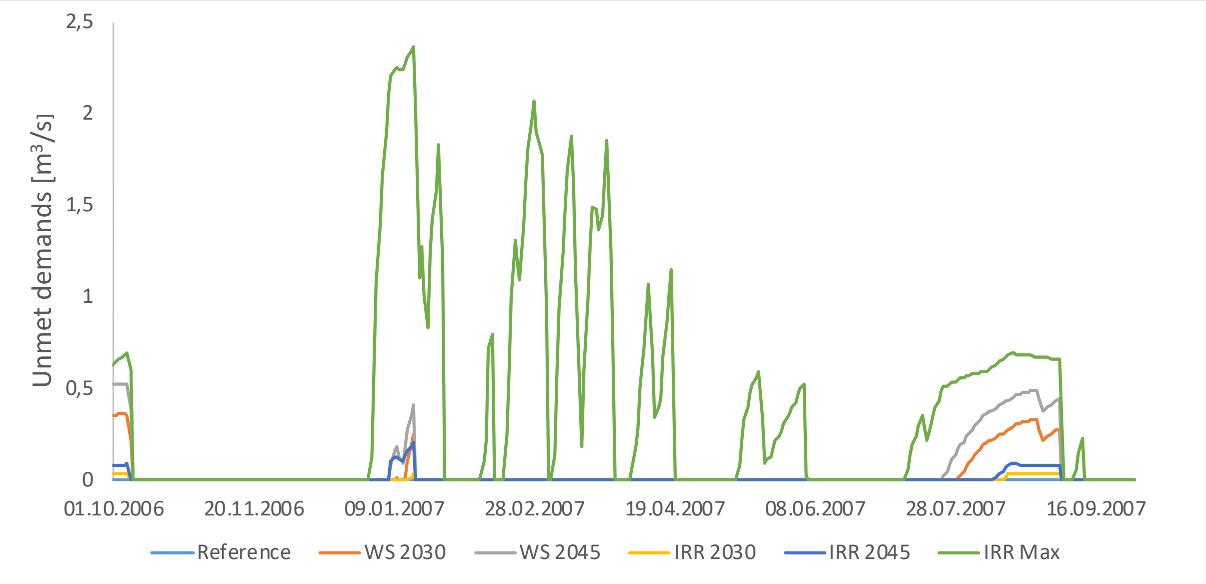


Figure 23 Unmet demands for a dry year 2006/2007, scenario C2

4.3.5 Scenario D: Hydropower development

The three reservoirs for the proposed Hlotse HPP are introduced in the model for scenario D. The following two setups are simulated for scenario D:

- **Scenario D1:** Hydropower demand is set to priority 1, and reservoir releases are set to maximize hydropower production independent of demands downstream. Demands for domestic and industrial purposes are set priority 2, and water demands for irrigation set to priority 3.
- **Scenario D2:** Reservoir releases are set to fulfil demands downstream. Demands for domestic and industrial water supply are set to priority 1, and irrigation as priority 2.

The simulated reliabilities for the demand sites for the two operational strategies are given in Table 16, with reliabilities ranging from 68.2 to 100%. For Scenario D1 the reliabilities for ranges from the lowest percentage of 68.2 to highest of 96.4 percent. For Scenario D2 it is observed that three of the four demand levels are 100 percent satisfied.

Table 16 Reliabilities for demand sites in Scenario D

Demand levels	**Reliability WS [%]**		**Reliability IRR [%]**	
	D1	**D2**	**D1**	**D2**
Reference	96.4	100	96.1	100
WS + IRR 2030	83.4	100	89.7	100
WS + IRR 2045	81.1	100	82.9	100
WS 2045 + IRR Max	80.7	91.1	68.2	89.6

The average annual hydropower generation simulated in the model for scenario D1 is found to be 16.3 GWh. The variation over the period is shown in Figure 24, together with the projected generation for the proposed hydropower plant of 39.7 GWh. The production ranges from the lowest of 9.2 GWh to highest of 24.9 GWh. Thus, the simulated generation in the model constitutes 41% of the projected generation for the proposed project.

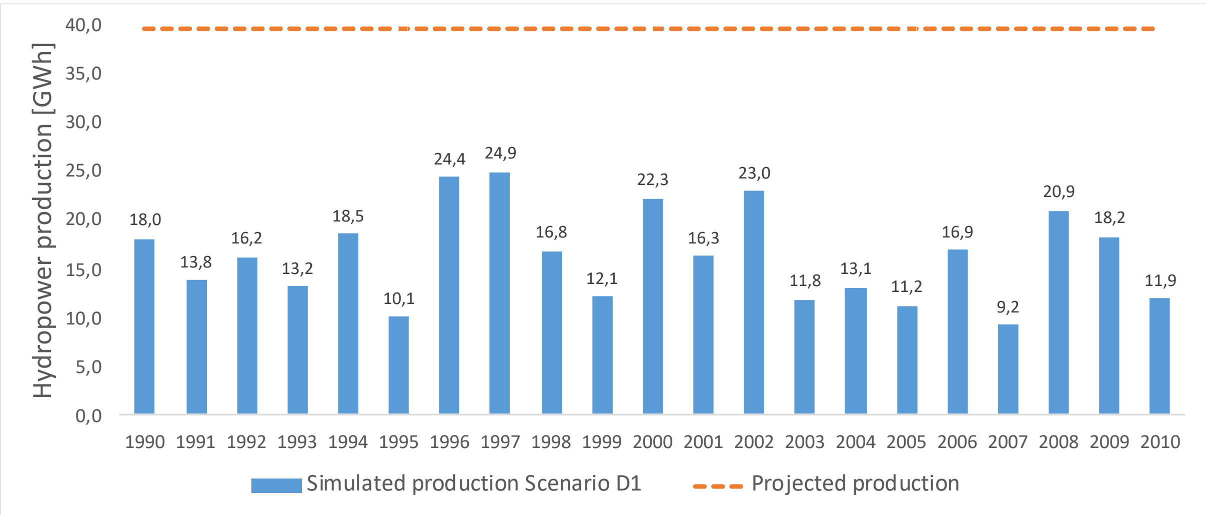


Figure 24 Hydropower production for scenario D1 with hydropower priority

The annual hydropower production for each year in scenario D2 when reservoir releases set to meet demands downstream are shown in Figure 25. The production ranges from the lowest of 5.8 GWh in 1995 to highest of 18.3 GWh in 2000. The average annual production is found to be 10.6 GWh for all demand levels combined. Thus, the simulated production for scenario D2 constitutes 26.7% of the projected production.

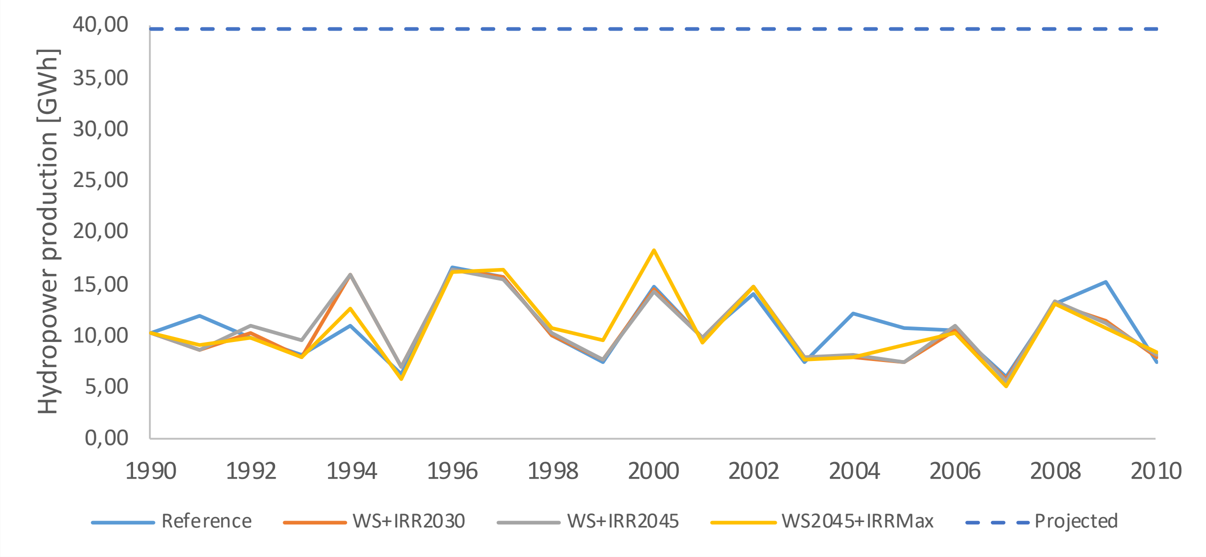


Figure 25 Hydropower production for Scenario D2 with downstream priority

Additional simulation results showing daily average of unmet demands for potable water supply and irrigation in scenario D1 and D2 are displayed in Appendix E.

The results for each scenario are chosen to be displayed one at a time to avoid confusion due to several demand levels in the previous sections. To compare the regulation effect of the different scenarios C and D for downstream water users, the demand level 2045 is selected to demonstrate the effect. Figure 26 shows that scenarios C1, C2 and D1 follows the same seasonal trend as scenario A but reduces the magnitude of unmet demands for water supply in 2045. In contrast, no unmet demand is found for water supply in 2045 for Scenario D2, which is zero for the entire year.

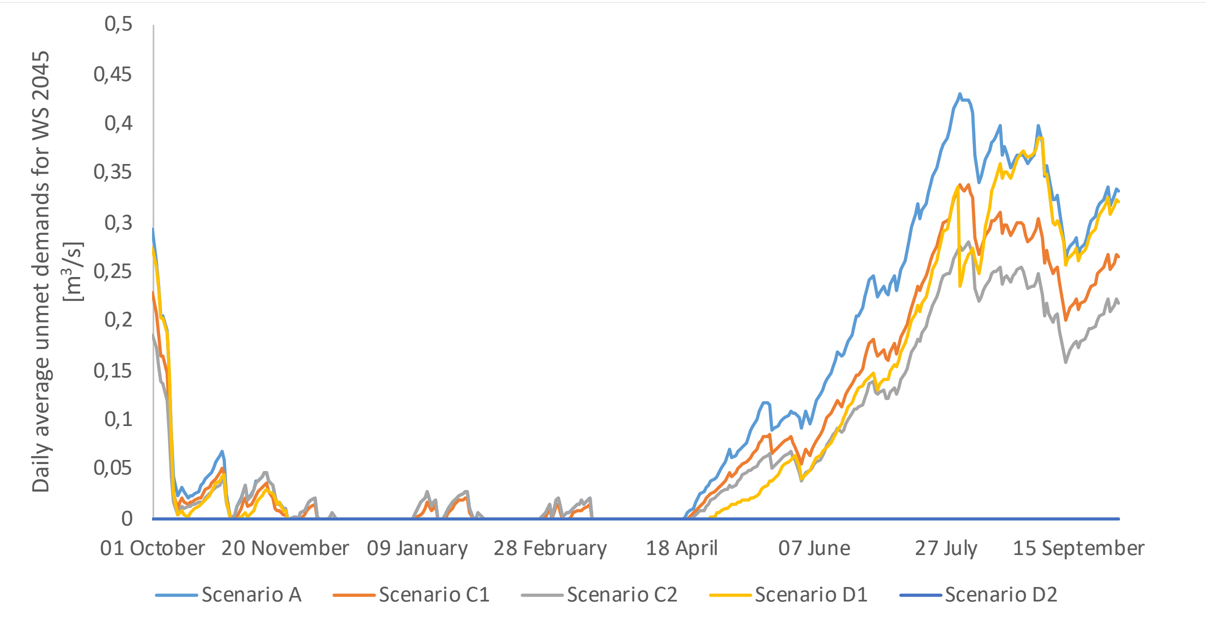


Figure 26 Regulation effect on unmet demands for WS 2045

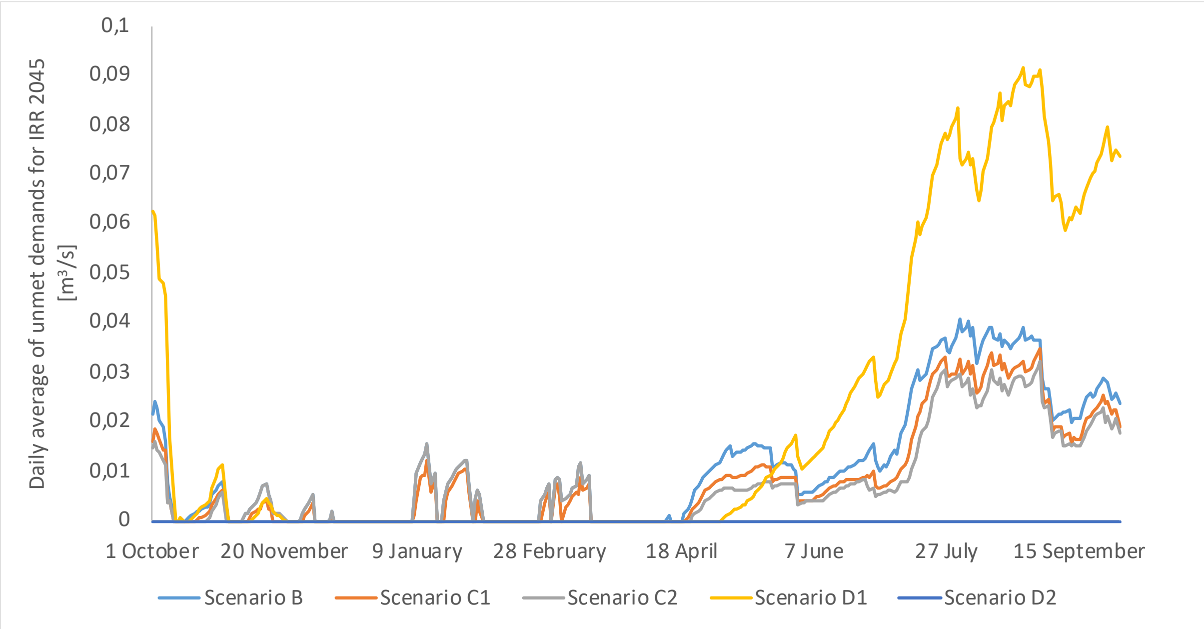


Figure 27 Regulation effect on unmet demands for IRR 2045

Figure 27 gives, in the same way as Figure 26 for water supply, the regulation effect on unmet demands for irrigation level 2045. The figure demonstrates that scenario D1 significantly increases unmet demands in the dry season for irrigation purposes. No unmet demand is found for irrigation in 2045 for scenario D2. Scenario C1 and C2 follow the same seasonal trend as direct river abstractions in scenario B.

5 Discussion

This section serves to discuss the findings of this study and what implications they may have. The findings are considered in relation of limitations and uncertainties, chosen method, existing knowledge, and previous analysis performed.

5.1 Input data and model performance

A hydrological model is a simplified representation of a real system. Observations of hydrological variables at the basin level is fundamental for understanding the dynamics water resources available. The quality of the model simulations for a rainfall-runoff model will largely depend on quality of input data, and the accuracy of a model will never be better than the accuracy of the input data to the model.

5.1.1 Climate data

Observed values for climate data with daily time resolution has not been available for this study to assess the quality of the daily gridded data applied. Global gridded climate datasets of this origin, multi-satellite products, have previously been found to overestimate low values and underestimate high precipitation values (Yeggina et al., 2020). An important aspect when comparing model-based gridded data and traditional gauge data is the uncertainties and possible errors associated with the measured gauge data. Comparisons of monthly rainfall values for one selected rainfall station, Leribe, are given in Figure 10 and Figure 11. The scatter plot for Leribe station gives that the gridded rainfall values from the Princeton dataset are generally higher than observed values, where the trend line in blue is located below the 1:1 line, oriented towards the horizontal axis for gridded rainfall data. An R^2 of 0.62 indicates a moderate fit between observed and gridded values, but a general spread in the values is observed. Figure 11 shows the average rainfall values for each month for both observed and gridded rainfall, where the discrepancies vary for the different months. However, the figure shows that the gridded dataset applied for this study can reproduce the seasonal variation of rainfall for the study area. This property is considered important for this study area, where seasonal variations largely influence the hydrological regime.

The climate dataset applied for this study is recommended best use for broad-scale problems and long-term research rather than applications for specific dates and locations (Sheffield et al., 2006). To evaluate the goodness of the daily gridded data to capture the local climatic variations, daily resolution of observed climate variables is necessary. Based on the monthly rainfall values available, the average annual rainfall for four of the climate stations is given in Table 5. For three stations, the deviation is moderate, while one station, Hololo, stands out particularly with a significant deviation. As mentioned earlier, there is no guarantee of measured gauge data being entirely correct. An overall consideration of Figure 10 and Table 5 indicates that the global gridded data tend to overestimate the precipitation values compared to observed values. This overestimation is further confirmed in Figure 15 for the model validation when calibrated values for Hlotse catchment are transferred to Ngoajane catchment for validation. Here, the model is found to overestimate the streamflow. This is further discussed in the following section.

Observed data of temperature for the study area has not been available for this study. Temperature is a crucial parameter for calculating parts of the hydrological process, such as evapotranspiration and modelling of the snow process. Errors in modelling the snow process such as volume and timing of snow accumulation and snow melt will largely influence the runoff from the model. This gives that error in temperature data may affect the model's ability to reproduce the seasonal variations of the hydrological response in the catchment. However, the uncertainties considering the snow process are not considered significant for modelling the lowlands of Lesotho. If the model is to be developed to include the highlands of Lesotho, the temperature would be a key parameter to consider as the snow process would be a major driver for the hydrological response.

5.1.2 Calibration

Calibration of the WEAP model developed for this study is limited by access to observed discharge for one gauge station in Hlotse river. This has further limited the focus area for this study to apply for Hlotse river basin. The chosen parameter set provided very good performance for water volume when considering the entire calibration period as a whole, with the overall PBIAS of -1.7% for 1988-2000. However, there are larger deviations between simulated and observed water volumes for some years where model performance is considered unsatisfactory with significantly high absolute values for PBIAS. Figure 13 gives that the daily discharge simulated fails to reproduce the timing of some extreme values and underestimates high flows. However, Figure 14 shows that the model reproduces the seasonal variation of the runoff response for Hlotse catchment in a satisfactory way. Unsatisfactory model performance is found for an NSE of 0.30 for monthly discharge values. However, a better fit for the flow duration curve and daily average were emphasized in the final choice of parameter set for the model. This negatively affected the model performance for the traditional statistical values, such as NSE, which is sensitive to errors in the timing of extremes. Simulations using the model parameter set found by the automatic PEST tool provided better statistical performance for NSE than the manual calibration but were found to underestimate high flows and overestimate low flows. Manual adjustment of parameters and visual inspection of hydrographs were necessary to reproduce the low flows in the river. Automatic calibration may be less time consuming, but this finding highlights the benefits of a manual calibration process by trial and error by providing better control of the catchment response.

Significant uncertainties are introduced by the assumption of considering the calibration catchment as an unregulated catchment by ignoring historical water abstractions for the calibration period. Generally, the water use upstream of gauge station CG25 are considered to be small but may prove to be important in the low flow season. Ignoring historical water abstractions may not be this prominent for Hlotse river basin as the volume of water abstracted is limited for this restricted area. However, when scaling this assumption to the larger catchment of Upper Caledon river, the effects can prove significant with larger quantities of additional simulated water volumes. This is further discussed in section 5.1.3. Figure 16 shows the discharge comparisons for Ngoajane catchment, an unregulated catchment, used to validate model performance after transferring the calibrated parameters. Here, the model generally overestimates streamflow but reproduces the variations between the different years after 1991. The simulated average annual discharge is generally higher than observed for most years, where significant negative values for PBIAS are found.

When transferring calibrated model values from one catchment to another, the catchment characteristics should be compared to evaluate the representativeness of the calibration. Significant differences in catchment area size, topography and land use may defend adjustment of some model parameters to account for these factors influencing the runoff regime. In this case, the larger catchment of Caledon river upstream of Maseru has a larger share of cultivated land compared to the calibration catchment. This could justify a change of the Crop factor, Kc, for the larger catchment, as this factor is found in this study by weighting for percentage area of agricultural land. In addition, the Kc-factor is found to be a key parameter from the sensitivity analysis. Adjustment of model parameters for different sub-catchment characteristics is not applied for this study because missing data for other elements, such as lack of data for existing and historical water use, is considered constituting a greater uncertainty for the analysis. Data for model validation were made available at the end of this study, giving no time to adjust parameter values or climate data input.

5.1.3 Current water use data for the modelling area

Climate data, discussed in the previous sections, is a fundamental input for water resources modelling. Lack of site-specific climate data can be compensated by using global climate datasets derived from sophisticated satellite technologies. However, information about historical and existing water use is essential for the water balance of a catchment and such information is not readily available from global datasets. Such data is site-specific for the modelling area, where careful inspection and site visits are often necessary to obtain a complete picture of the situation. This is a desktop study performed purely through research without physical investigations of the study area. Current and historical water use for the model area is highly uncertain for this study. Due to a lack of consistent information, a rough simplification is made in this study to quantify water withdrawals for the reference scenario. Estimates for historical water withdrawals for reference scenario are highly simplified for this study by combining population statistics and water use consumption reported by FAO. This method of quantifying historical water use based on consumption and population statistics is also applied for previous studies of Caledon river (Ayele, 2016; Mohobane, 2015). Table 8 and Table 9 provides the reference data for water use applied for this study. The annual water withdrawals per inhabitant are about 10 times higher for South Africa than Lesotho when using numbers reported by FAO. The significantly higher water use in South Africa can be explained by the extensive developed agricultural sector that accounts for 60% water use. 38 smaller reservoirs are found for the South African side of the catchments, indicating a more extensive water use development than the Lesotho side. However, it is an open question whether the reported water use for South Africa is representative of the region studied. The demand site reliabilities for the reference scenario in Figure 17 shows significantly lower reliability for the demand sites Dihlabeng, Mantsopa and Setsoto on the South African side of the catchment. Relative high demand site reliability for the demand centres in Lesotho for Reference scenario compared to the demand sites in South Africa. The significant difference in consumption assumed for the two countries can explain the deviations in reliability.

Figure 18 shows the total discharge from the model area where a general overestimation of water flows of the Caledon river is found. The simulated water volume out of the model at gauge station CG22 is twice as much as measured for the reference period. However, the general pattern of observed flow variations between different years is replicated in the model simulations but of a larger magnitude. This can be explained by the considerable uncertainty of human water use in the area and ignorance of infrastructures such as the smaller farm dams on the South African side of the catchment. These elements are missing from the model representation and are likely to affect the direct runoff from the river. The limitation of detailed climate input and limited observed data of discharge for calibration of the catchment influences the model performance. However, the lack of detailed insight into historical and current water uses are considered to be the most influential for the uncertainties in this study.

5.2 Effects of future development

This part of the discussion evaluates the effects of both planned and desired future developments in the Hlotse river basin based on results from the simulation of scenarios. The scenarios are implemented in the model despite the lack of satisfactory validation of the model and no correction of climate data input. This gives that the results cannot be used directly but may give indications of possible conflicts and bottlenecks for the future.

5.2.1 Water shortages for direct river abstractions

Scenario A and B defined in this study explore the effects of direct water abstractions for future sector developments in Hlotse river. The simulations confirm that seasonal rainfall largely influences the river discharge. If future water users depend on supply from direct river abstractions, the simulations show that available water flow is not sufficient throughout the year to satisfy all demands. Section 2.4 in this report describes the water-related challenges in the lowlands of Lesotho, where a lack of access to well-function water systems for the population is prominent. Therefore, the planned development of water supply systems in Hlotse river is an essential step to address these challenges. The simulations of the planned water supply for domestic and industrial users defined in Scenario A results in reliabilities of 94.1% for the reference scenario and 75.6% for the demand level of 2045. Reliability of 75% corresponds to approximately 90 days over the year where demand is not fulfilled. This finding is also confirmed in Figure 19, showing the daily average of unmet demands, illustrating significant supply shortages in the dry season from April to October for both demand levels 2030 and 2045 for direct river abstractions in Hlotse river. The peak of unmet demands can be observed at the beginning of August. Uncertainties are associated with the simplification made for this study by ignoring seasonal variations of demand for domestic and industrial water supply. Regardless, the results from scenario A demonstrate a need for water transfers from Katse dam into Hlotse river in the low flow season.

The literature search for this study found that expansion of irrigation areas will play an important role for Lesotho in the future to reduce vulnerability for climatic conditions and ensure agricultural productivity. Scenario B explores effects of three demand levels for irrigation development in Hlotse river basin. Considerations regarding limitations and assumptions regarding water estimations for irrigation purposes and amount of irrigation expansion are discussed in the next sub-section. Considering the irrigation demand levels with expansion of 100 ha per year, reliabilities of 89.7% for 2030 and 83.7% for 2045 are found. The daily average of unmet demands for these irrigation demand levels occurs for the same period as unmet demands for scenario A. The scenario "IRR Max" considering an irrigation expansion to its full potential for the area to 21 686 hectares stands out with a lower reliability of 63.7% and daily average of unmet demands distributed throughout the year, even for the high flow season. 63.7% reliability corresponds to approximately 130 days over the year where demand is not fulfilled. The findings for Scenario A and B demonstrate that the amount of available water in Hlotse river is not sufficient to supply various demands throughout the year. Thus, augmenting flows from Katse dam are necessary for secure supply for the planned abstractions. The need for regulation of Hlotse river for both timing and volume of water flows will have potential impacts for other interests in the river not considered in this thesis, such as environmental qualities, social aspects, and health of the ecosystem. These challenges are to be addressed in the ongoing project by Multiconsult and their partners in the EFlow assessment in Hlotse river.

Figure 21 shows the unmet demands for scenario A and B for a dry year. All scenarios, including the refernce scenario, have the bulk of unmet demands from July to September. Compared to the daily average of unmet demands over the whole simulation period, unmet demands for a dry year occurs for a shorter period but with double magnitude. This indicates that the needed water transfers from the Katse dam to meet demands in Hlotse river may vary from year to year, both in volume and time. Variations between years and seasonal variations within a year must be taken into account in planning and managing the augmenting flows to ensure a stable supply.

5.2.2 Water transfers from the LHWP

The scenarios for simulation of water transfers from Katse dam, located in the highlands, are in this study defined within the existing framework and Treaty for the LHWP, which allows an annual transfer of 3.75 MCM into Hlotse river. The simulation results illustrate that a constant transfer of 0.1 m^3/s gives a marginal effect on the security of supply. For this scenario, reliabilities increase with an average of 2.5% for potable water supply and 2.9% for irrigation. For the seasonal transfer in scenario C2, reliability of 100% is obtained for the reference scenario. For demand levels of 2030 and 2045, reliabilities increase with an average of 3.8% for potable water supply and 4.1% for scenario with seasonal transfer. This illustrates that the seasonal transfer of 0.2 m^3/s provides better reliability than the constant transfer of 0.1 m^3/s. However, water demands are not met for demand levels 2030 and 2045. Figure 23 display unmet demands for a dry year for scenario C2 with the seasonal transfer. The figure illustrates that unmet demands for a dry year still occurs for a shorter period but with double magnitude despite the seasonal transfer. In addition, unmet demands also occur in the high flow season of January for a dry year. This demonstrates the need for planning and refining the operational rules of water transfers from the LHWP, facilitating flexible water transfers for various climatic conditions to meet the demands for water supply in the lowlands. The other possibility for river regulation with reservoirs for hydropower production in Hlotse river is further discussed in 5.2.4.

When completing the report for this study, information regarding planned operation rules for flow releases from Katse dam into Hlotse river was made available. The planned water transfers from Katse dam are higher than assumed for the simulations in this study. In addition, the water withdrawals for domestic and industrial use defined in Scenario A are slightly higher than the detailed plans. This implies that the water deficiencies found in this study may not be as prominent for what is now planned. Transfers are scheduled for four months, from June to September. The results of this study illustrate potential challenges for water supply beyond these months. This finding emphasizes an essential aspect of water resource management. As soon data are made available and new project plans emerges, this must be integrated into tools for water management. Models for water resource management must be continuously developed, and simulations run again with updated data.

5.2.3 Irrigation development

Due to limited information about existing irrigation practice and plans for irrigation expansion, uncertainties are associated with the assumptions and simplifications in this study for irrigation scenarios. Instead of using integrated methods for irrigation requirements available in WEAP, water withdrawals with fixed demands are manually implemented in this study where seasonal variations follow the Kc-factor. The spatial distribution of irrigation development within Hlotse river basin is highly simplified by manually adding two withdrawal points along the river.

In the process of developing irrigation scenarios for this study, significant differences were found for previous estimates provided by different sources. FAO reported in 2005 a potential irrigation area of total 12 500 hectares for Lesotho, where 500 hectares of these located within the Hlotse river basin. A water resource assessment by SMEC (2017) justified an irrigation potential for 21 686 hectares for Hlotse river basin alone. The share of an area considered suitable for irrigation results from a set of prerequisites that must be present. These are mainly physical factors such as soil characteristics, slope criteria, site access, and distance to the supply source. Volume and timing of water for irrigation depend on both climatic conditions, selected crops, and crop calendar. The irrigation assessment by SMEC initially proposed an area of 5 486 hectares as irrigable land in Hlotse river basin. This was increased to 21 686 hectares after assuming a larger buffer distance from the riverbanks. This illustrates how the criteria selected for the assessment impacts the results. This is one of the advantages of an integrated model approach where the models can be actively used to check effects for different assumptions.

Considering that the irrigation potential by SMEC of 21 686 hectares involves an increase of irrigation areas of 8359 percent compared to the current situation of 256 hectares, an additional scenario set for irrigation development is formulated in this study. An irrigation expansion of 100 ha per year is assumed a realistic estimate for this study. This resulted in a water requirement for irrigation in 2045 of 5.6 MCM in relation to the estimate of 21 686 ha requiring 46 MCM annually. This explains the large differences in reliability and unmet demands for the different levels defined in scenario B. In practice, other factors such as economic, institutional, and social factors play a vital role in the development within an area that is not always considered from an engineering point of view. This combination emphasizes the complexity of water resource management, where an interdisciplinary and holistic approach required for efficient use of available water resources.

5.2.4 Hydropower development

Section 2 of this report describes the current energy situation in Lesotho. In addition to wind and solar photovoltaics, the development of small-scale hydropower is selected as renewable technologies in the SREP Investment Plan for Lesotho with the overall aim of electricity access expansion and increased share of renewable energy sources. Scenario D defined in this study explores the effects of the proposed Hlotse HPP by implementing these project plans in the WEAP model. However, information about the planned power plant are limited to the information presented in the report for the project by SSI (2009). Thus, uncertainties are introduced by the assumptions due to a lack of information and simplifications due to limitations of the model.

The hydropower component of WEAP applied for this study is highly dependent on reservoir releases and available water volume in the reservoirs. Reservoir characteristics for the proposed project are in the project report only given as a total of the three proposed reservoirs. Reservoir volume and inactive zone for each of the reservoirs are in this study assigned based on the given dam heights. The volume-elevation curves are simplified without considering the different topography of the three dam sites. These simplifications and assumptions introduce uncertainties to the hydropower calculations in this study due to the central role of reservoirs in the hydropower component of WEAP, where the reservoir releases are highly influential.

An additional generation capacity of 6.5 MW for Lesotho is planned by the construction of the proposed Hlotse hydropower plant. This is a considerable contribution to the current generation capacity of 77 MW in Lesotho by an 8.4 percentage increase. Scenario D1 defined in this study explores the effects of hydropower production when reservoir releases are prioritized to meet the target production for the power plant. The simulations for Scenario D1 with hydropower as the first priority in the model are given in Figure 24, resulting in a significantly lower annual power production of 16.3 GWh compared to the projected production of 39.7 GWh. Large variations are simulated for the different years, with the lowest annual production being 9.2 GWh in a dry year and the highest of 24.9 GWh in a wet year. In addition to the uncertainties associated with reservoir characteristics described earlier, the underestimation of energy production can possibly be described by the calibrated model that does not reproduce all the high-water flows observed. Despite these uncertainties, the model reproduces the water balance over the whole calibration period while the discrepancy between the projected and simulated energy production is significant. Even in a wet year, the most optimistic year for hydropower production, the results significantly differ between simulated and projected power production. This indicates that the planned power plant will have problems achieving the projected potential if the project is executed. This study is limited to evaluate the water allocation between sectors and does not consider the economic aspects in detail for the different scenarios. Nevertheless, a rough assessment of the key parameters for the proposed hydropower project reproduced in Table 1 is feasible for this study. The investment cost for the proposed project is 0.98 USD/kWh for the target production of 39.70 GWh. The simulations in this study provide an annual production of 16.3 GWh and thus, an investment cost of 2.40 USD/kWh. This corresponds to a percentage increase of 145 percent for the investment costs. Higher investment costs and lower production than planned will result in significantly reduced revenues for the proposed project. A new assessment is therefore recommended to address the profitability of the project.

Compared to scenario A and B for direct river abstractions, the reliability for potable water supply increased with an average of 4.5% and 1.8% for irrigation for scenario D1 with hydropower production as first priority. The reason why reliability increases more for potable water supply than for irrigation is due to one of the withdrawal points for irrigation is located at the diversion reach for the proposed power plant.

Figure 27 shows that the hydropower regulation with reservoirs in scenario D1 significantly increases the magnitude of unmet demands in the dry season for irrigation purposes compared to scenario B without the regulation. This is explained by the fact that one of the withdrawal points for irrigation is located in the diversion reach for the downstream part of the Hlotse Upper dam. Scenario D2 explores the effects of hydropower production when reservoir releases are set to fulfil demands downstream. The results from Figure 25 gives an annual power production of 10.6 GWh for this scenario. This corresponds to a further decrease in energy production of 35 percent from scenario D1 where energy production is set as priority in the system. Despite the low energy production simulated for scenario D2, the reliabilities given in Table 16 demonstrates the positive regulation effect of the proposed reservoirs for downstream users. 100 percent reliability is achieved for all demand levels for both potable water supply and irrigation, except for the demand level comprising the maximum irrigation expansion to 21 686 hectares. The level of maximum irrigation expansion achieves significantly better reliability from 68.2 for scenario D1 to 89.6 for scenario D2.

This study does not consider environmental flow releases from the dams, nor the possible effects of water transfers from the Katse dam for energy production. Additional water transfers into the Hlotse river gives opportunities for increased energy production that is not accounted for in the design phase of the proposed hydropower plant. A central element of water resource management is not only managing, but also developing the resources across all water uses. The model simulations from this study illustrate the hydropower plant's potential to generate positive benefits for downstream users as a non-consumptive water user. If the proposed hydropower plant is to be realized, it must be designed to serve demands for potable water supply downstream. From a management perspective for water allocation, it will be difficult to justify a high priority for hydropower when large deficits are prominent for more basic human needs than electricity for the population. However, the value of the regulation effect of the reservoirs may justify investments for hydropower development.

A study by Liu et al. (2019) clearly points to key barriers for small hydropower development in Lesotho. Of particular interest for this study is the barriers of institutional responsibilities being not clearly defined and the lack of integrated planning. Several previous studies have assessed the challenge of water resources in the lowlands of Lesotho, with the focus on climate change, water supply and irrigation purposes. None of these studies addresses the potential for increased hydropower production proposed in the SREP Investment plan for the area in combination with other water-related challenges. This study demonstrates the need for a nexus approach to evaluate the linkages between development plans for different sectors to support a transition to sustainability, electricity expansion and economic development for the area.

5.3 Downstream effects

As mentioned earlier, this study initially aimed to model the entire catchment of the Caledon river, but data availability has limited the modelling area to the Upper Caledon upstream of Maseru, with particular focus in Hlotse river. Figure 18 illustrates the overestimation of discharge in Caledon river in the model simulations. Relative change in discharge is therefore focused as a measure to evaluate impacts further downstream of Hlotse river.

Table 14 gives the mean annual runoff for scenario B, considering both potable water supply and irrigation. The demand level for 2030 gives a relative decrease of 5.3 percent in mean annual runoff in Hlotse river, where a decrease of only 0.8 percent is found for the corresponding level in Caledon river upstream of Maseru. A larger relative decrease for mean annual runoff is observed for demand level 2045 with maximum irrigation development. For this demand level, the relative decrease is 18.4 percent for Hlotse river and 2.7 percent for Caledon river. The reliability of water supply for demand centre Maseru remains at 100 percent for all scenarios. This indicates that a significant change in runoff for the Hlotse river will give marginal effects downstream to Maseru. However, the relative change runoff in Hlotse and Caledon river is more evident for a dry year. The mean annual runoff for a dry year is half the magnitude of MAR for the whole simulation period. This confirms that the Caledon river is vulnerable to seasonal variations both within and between different years.

Separate assessments regarding the possible effects of climate change for the future is not performed in this study. The scenarios for possible future developments are simulated based on historical climate data. A climate change assessment by the World Bank (2016) projected higher air temperatures for the study area from the period 2030 to 2050. No strong consensus was found for future precipitation projections as some models indicated both wetter and drier conditions for the same period. The same conclusions were drawn by Mohobane (2015) where the climate change models predicted increased temperature while significant disagreement was found for precipitation projections. Increased temperature, and hence, evapotranspiration will affect the hydrological balance of the watershed. However, the disagreements found for future precipitation gives uncertainties for future predictions of the available water resources in the Caledon river.

The downstream impacts in Caledon river of changes introduced in Hlotse river are demonstrated in this study to be marginal. Nevertheless, the impacts for Caledon river will be more prominent if the changes in Hlotse with increased water withdrawals also apply for the other tributaries. The Hlotse river basin is in a unique position compared to the other tributaries for Caledon river on the Lesotho side of the catchment due to the proposed hydropower plant and the transfer tunnel from the highlands. The planned water abstractions in Hlotse river will supply a larger area, including demand centres located outside of the Hlotse river basin. The possibility of water transfers from the highlands to meet demands for the population in the lowlands also applies to the Hololo catchment located further upstream of Hlotse where water can be released from 'Muela dam, given current existing infrastructure. Regarding hydropower development and the potential sites selected under the SREP Investment Plan for Lesotho, only one site in addition to Hlotse HPP is located within the Caledon river basin. This applies to the proposed Phuthiatsana HPP with an installed capacity of 5.4 MW and annual generation of 18.9 GWh (SSI, 2009). The planned reservoir for this project is located at the same site as Metolong Dam, constructed in 2013-2016, which now provides water supply for the region of Maseru. This means that the basis for this projected power plant is different. Additional feasibility studies must be conducted to evaluate if available water volumes in the reservoir are sufficient for a retrofitting of this dam to include both hydropower production and water supply for other purposes. With all this considered, there is no definitive answer if the implications for future scenarios in Hlotse river can be transferred to general for the other tributaries. However, the possibilities for development of the agricultural sector and irrigation expansion in Hlotse also applies to the other tributaries on the Lesotho side of the catchment. Thus, an expansion of large-scale irrigation for the tributaries will affect the runoff to Caledon river.

5.4 Water resource management in Lesotho

Valuation of water is central to integrated water resource management. This study does not consider the economic aspect of future developments within the water-energy-food nexus for the study area. As traditional economic counting often forms the basis for political decisions, the complex and unclear relationship between the price and value of water complicates the challenges of water resource management. There are different views and perspectives of the value of water among and within various groups and stakeholders. It is difficult, and often futile, to quantify the value of water for different water users, such as domestic use, the human right to water, food security, or environmental flow for maintaining biodiversity, to mention a few. Previous studies for the area have found the task of economic valuation of water resources challenging due to limited baseline historical data (United Nations, 2021; World Bank, 2016).

The strategic position of the water resources in Lesotho is central to the country's management of these resources. The planning, development, and management of water resources in Lesotho has until recent years been centred on development of the LHWP. The government of Lesotho manages the LHWP through the Lesotho Highlands Development Authorithy, LHDA. This project generates mutual benefits for Lesotho and South Africa, where revenues for Lesotho is achieved in the form of both electricity and royalty payments from exports of water. At the same time, the literature search for this study highlights specific challenges in Lesotho in supplying the population with basic human needs such as access to water, food, and energy. A key challenge for the government is balancing the development of water resources for export versus the development of water services and access for the population of Lesotho (World Bank, 2016).

This study considers the scenarios for water transfers from Katse dam within the current framework of the Treaty between Lesotho and South Africa based on information available for the general public. The result from this study demonstrates a need for a water volume transferred from the highlands to the Hlotse river exceeding the current quota of 3.75 MCM stipulated in the Treaty today. This demonstrates the need for planning and refining the operational rules from the LHWP, facilitating flexible water transfers for various climatic conditions to meet the demands for water supply in the lowlands. The current Treaty allows Lesotho to undertake ancillary developments to provide water for irrigation, potable water supply, and other uses, as long as the specified quantities for water provision to South Africa are maintained (Treaty on the LHWP, 1986). As previously mentioned, information regarding planned operation rules for flow releases from Katse dam in the LHWP into Hlotse river was made available when completing the report for this study. The volumes required for water transfers into Hlotse river during four months in the low season are expected to be available at the dam. A study by the World Bank (2016) found that additional volumes of water transfers to meet demands for potable water supply in the lowlands would not affect the reliability of water supply and exports to South Africa. However, this study points to a need for flexible operational rules for the water transfer for different climatic conditions. In addition, even larger water volumes beyond what is currently planned for four months in the low flow period are required to meet demands in Hlotse river for extensive irrigation development. This demonstrates a possible challenge, and it should be investigated whether the required volumes of augmenting flows from Katse Dam to meet future demands in the lowlands of Lesotho will affect the reliability of water supply to South Africa concerning the associated Treaty for the LHWP.

Careful water resource management requires reliable, detailed, and well-organized information on the state of the hydrology and its influencing factors in the surrounding environment (Jarar Oulidi, 2019). There are significant differences between and within countries and regions regarding efforts put into hydrological monitoring. This also seems to apply for Lesotho, where great efforts are put into hydrological monitoring of the highlands and correspondingly less efforts in the lowlands (R. Passchier, personal communication, May 10, 2021). Mulligan (2013) indicated that regions rich in water resources related problems tend to lack hydrological monitoring and modelling capacity. This study has identified water-related challenges in the lowlands of Lesotho, but the analyses are associated with major uncertainties discussed in the previous sections. This demonstrates a need to collect more site-specific data to capture the dynamics of the water resources for the area, such as climate data, discharge data, and not least data for historical and current water use for the area. Insight to additional local information of this origin could reduce the uncertainties in the analysis, emphasising the lack of detailed insight into historical and current water use for the study area. This may be information that is already readily available for the government and local stakeholders locally in Lesotho but challenging to obtain for an external researcher as in this desktop study performed purely through research without physical investigation. Investments in hydrological monitoring could provide fundamental insight into the dynamics of water resources available for a specific site and, thus, a better basis for planning. In addition to efforts in hydrological monitoring, maintenance and updating of rating curves for discharge stations are essential to ensure the quality of the data.

5.5 Suitability of the WEAP model

Based on findings from this study, this section discusses the suitability of the model for the problem investigation. This study cannot be considered a complete evaluation of all future developments within the water-energy-food nexus for the basin. Some selected parts are selected to evaluate the interactions, such as only hydropower is considered the energy source. A systematic review of methods applied for evaluating the WEF-nexus found a limited amount of explicit and reproducible methods (Albrecht et al., 2017). To evaluate the interlinkages within a system, there will always be a need for a selection of focus areas to arrive at something. To discuss the suitability of the model, some input has been obtained from Saloranta et al. (2003), where benchmark criteria are developed to assist the choice of models for application in water management issues. The benchmark criteria are in the form of questions through which each model can be evaluated.

5.5.1 Time resolution

The literature search for this study found several cases where a monthly WEAP model is developed to assess water-related investigations in the study area. The work by the World Bank recommended further development of the WEAP model to a daily timestep to evaluate the timing of flows and operational strategies for water allocation among competing uses. Therefore, it was decided early in the process for a daily model to be set up. However, the data situation proved to be more difficult than expected, and input data were not readily available due to the postponed start of the project to which this study is connected. The amount of input data reproduced in reports for previous studies is limited, while a limited amount of available raw data for the analysis has led to simplifications. Much of the input data for the model is generated based on monthly or annual input data, further distributed equally within the days. One of the benchmark criteria by Saloranta et al. (2003) addresses the balance between the model's input data requirements and data availability, which is inadequate in this case for a daily timestep as the majority of the required input data are not available. The choice of timestep for modelling purposes should be carefully considered in relation to the purpose of the modelling and input data available. The resolution of the input data both in time and space for model applications should reflect the resolution of the model application. In addition, the time consumption and efforts put into the modelling should carefully be considered to the objective of the modelling task.

The use of monthly timestep supports a wide range of hydrological applications such as long-range streamflow forecasting and climate change impact assessment (Xu & Singh, 1998). Thus, a monthly timestep of water balance models will be adequate for strategical planning in water resource management. However, daily simulations may be necessary to capture the dynamic aspects of the hydrological process (Wang et al., 2011). Despite the uncertainties in the analyses performed in this study, the results demonstrate significant water shortages for some periods over the year for a river largely exposed to variations in discharge between and within seasons. The results from the model calibration in this study failed to reproduce the exact timing and magnitude of high flows in the river. This can be explained by the water balance function in WEAP not accounting for channel routing. For example, return flow into a river at the top of the catchment will be available immediately for downstream users within the same timestep. Therefore, the chosen timestep for the WEAP model should be carefully considered in relation to the size of the study area. Despite these uncertainties, the simulations of water flow in the river are largely variated between the days throughout the year. These hydrological variations will not be as prominent for a monthly model where extreme values are smoothed. Thus, a daily model would be suitable for an area of such climatic conditions for the timing of flows within competing water users. This requires input data of high quality to reproduce the hydrological dynamics of the basin.

5.5.2 The integrated approach

Scenario analysis is a central element of the WEAP software to evaluate the effects of different development strategies. Like several other water allocation models, the user can easily set up scenarios to investigate the possible effects of future developments based on a reference scenario. However, WEAP is a simulation tool rather than an optimisation tool. This gives that analysis is limited to explicitly exploring user-defined scenarios where results are subordinate to defined assumptions and priorities. This highlights the need for local knowledge, site inspections, and stakeholder communication for the model area to ensure realistic assumptions. The scenarios defined in this study is developed based on both planned developments and proposals for developments identified in previous studies.

The WEAP model allocates water for each timestep based on the defined priorities for the different water users. In this study, the highest priority is set for domestic and industrial water supply for the scenarios with direct river abstractions, and runoff distribution within the catchment is only accounted for in scenario C and D with additional runoff nodes along the river. In practice, it is often the location of the water withdrawals along the river which determines the water allocation priorities if no clear framework for water abstractions is set. The upstream users utilise the available water and release what is left for downstream users. This can be a possible challenge for the domestic and industrial water supply reliability from Hlotse river if water is withdrawn for irrigation purposes upstream in the dry season. This issue is not considered in the defined scenarios for this study but can be further explored by setting priorities based on location along the river.

No separate considerations have been made to analyse potential hydropower production in the basin for this study. The analysis is limited to considering possible future hydropower developments identified in previous studies. Another model should be applied if the overall objective was to optimise the basin's potential for hydropower production. However, this study demonstrates that the model is suitable for analysing how the design and operation of reservoirs will affect the water availability for various purposes. The WEAP model could be further coupled with the software LEAP for a more throughout assessment of the energy system for the area.

The WEAP model is widely applied for water management purposes worldwide and is therefore well documented both in the scientific community, with an extensive user manual, technical documentation, and tutorials. These are important model characteristics emphasised by Saloranta et al. (2003). The main strength of the WEAP model seen in the context of this study is the integrated approach by coupling the water allocation among different water users with a hydrological model. The WEAP software offers several integrated methods for assessing various aspects in water resource modelling, which is not applied for this study, both due to lack of information and limited experience with the software at the beginning of the process. The software has proven to be user-friendly either way, allowing for an intuitive model setup for problem investigation. Another strength of the model seen in the context of this study is the possibility of directly integrating global gridded data for digital elevation model, land use and historical climate. This possibility enables model setups for any area as a starting point for the modelling and can be further developed with site-specific data if this is available. The model is flexible in how the complexity of the modelling can be adapted to the information at hand for each individual case and the modeller's skills. This gives that the program can be useful for both skilled researchers and non-specialist users, such as local stakeholders and authorities. The model simulations for this study demonstrate the suitability of the model to identify trade-offs between different water users and the effects of measures for water management. This gives that the model is well functioning for its purpose as an assisting tool for water resource management but does not provide finite answers and cannot replace a skilled planner.

6 Conclusions

Significant water shortages are found for water allocation for planned and desired future potable water supply and irrigation expansion relying on direct river abstractions in the Hlotse river. The daily average of unmet demands is mainly evident from April to October for both potable water supply and irrigation expansion for 2030 and 2045. The daily average of unmet demands for the full potential irrigation expansion in the river basin is evident throughout the year. Unmet demands for a dry year occur for a shorter period but double magnitude compared to the daily average. The lowest reliability for potable water supply is 75.6 percent for demand level 2045. The lowest reliability for irrigation is found to be 63.7 percent for the full potential irrigation expansion level. The findings confirm that the Hlotse river and Caledon river runoff is largely exposed to seasonal variations both within and between years, and demonstrates a need for regulation measures to ensure a stable water supply for future sector developments in the river basin. The highest relative decrease of mean annual runoff due to direct abstractions in Hlotse river is 18.4 percent for the highest demand level in scenario B. The corresponding relative decrease in mean annual runoff in Caledon river upstream of Maseru is 2.7 percent. This demonstrates that significant changes in the Hlotse river runoff will give marginal effects further downstream.

Regulation measures considered within the current quota of annual 3.75 MCM transfer volume from the LHWP into Hlotse river are insufficient to meet future demands in the Hlotse river basin. The seasonal transfer in scenario C2 with 0.2 m^3/s from April to October provides better reliability for future water users than the constant annual transfer of 0.1 m^3/s. The seasonal transfer halves the magnitude of unmet demands for both potable water supply and irrigation in the low flow season, but unmet demands are still present for this scenario. Significant differences in timing and magnitude for unmet demands are found for daily average compared to a dry year. This demonstrates a need for planning and refining the operational rules from the LHWP, facilitating flexible water transfers for various climatic conditions to meet the demands for water supply in the lowlands. This will require further assessments of the possible effect on the security of water supply to South Africa and the associated Treaty.

Model simulations with reservoir regulation in scenario D1 for the proposed hydropower plant in Hlotse river, Hlotse HPP, gives an annual power production of 16.3 GWh, constituting only 41% of the projected 39.7 GWh for the proposed project. Annual average production of 10.6 GWh is simulated for scenario D2 when reservoir releases are set to fulfil demands downstream. The result for scenario D2 gives a significant improvement in reliability for downstream users with 100 percent reliability for three out of four demand levels. This demonstrates the potential of the hydropower plant to generate positive benefits for downstream users as a non-consumptive water user. Further assessment is recommended to address the project’s profitability given the significant discrepancies in simulated compared to projected production. However, the value of the regulation effect of the reservoirs may justify investments for hydropower development.

The suitability of the model to identify trade-offs between different water uses and effects of measures for water management by evaluating water balance dynamics is demonstrated by the results from this study. The limited amount of site-specific data applied for climate and discharge for model calibration limits the model performance. The lack of detailed insight into historical and current water uses is considered the most influential for the uncertainties in this study. The simulation results cannot be used directly but may give indications of possible bottlenecks for the future. Collection and processing of data, both in quantity and quality, and implementing these into existing tools and plans are necessary for such models to function as an effective tool. The WEAP model is considered well suitable for evaluating the water-energy-food nexus by capturing the interlinkages between different water uses with the integrated approach of combining a hydrological model with water allocation. This gives that the model is well functioning for its purpose as an assisting tool and supplement for decision-making in water resource management. However, modelling is just one out of several tools in the process of planning, developing, and managing water resources across all water uses.

References

Albrecht, T. R., Crootof, A., & Scott, C. A. (2017). The Water-Energy-Food Nexus: A systematic review of methods for nexus assessment. *Environ. Res. Lett*, *13*(4), 43002. https://doi.org/10.1088/1748-9326/aaa9c6

Ayele, A. S. (2016). *Application of water evaluation and allocation planning (WEAP) model to assess future water demands and water balance of the Caledon River Basin* Central University of Technology, Free State, South Africa.

Bakken, T., Almestad, C., Melhuus Rugelbak, J., Escobar, M., Micko, S., & Alfredsen, K. (2016). Climate Change and Increased Irrigation Demands: What Is Left for Hydropower Generation? Results from Two Semi-Arid Basins. *Energies*, *9*(3), 191. https://doi.org/10.3390/en9030191

Beck, H., Zimmermann, N., McVicar, T., Vergopolan, N., Berg, A., & Wood, E. (2018). Present and future Köppen-Geiger climate classification maps at 1-km resolution. *Scientific Data*, *5*, 180214. https://doi.org/10.1038/sdata.2018.214

Bureau of Statistics. (2013). *2011 Lesotho Demographic Survey, Analytical Report*. Government of Lesotho. http://www.bos.gov.ls/new%20folder/Copy%20of%20Demography/2011_Lesotho_Demographic_Survey_Report.pdf

Bureau of Statistics. (2016). *Lesotho - Cencus 2016* BOS. http://www.bos.gov.ls/2016%20Summary%20Key%20Findings.pdf

Bureau of Statistics. (2019). *Selected Indicators*. Ministry of Development Planning Retrieved May 7 from http://www.bos.gov.ls/

Bureau of Statistics. (n.d.). *Strategic Plan for Agriculture & Rural Statistics for Lesotho 2019/20-2023/24*. Bureau of Statistics.

Davies, J. (2003). *Lesotho Lowlands Water Supply Feasibility Study - Hydrogeology*.

Defourny, P. (2019). *ESA Land Cover Climate Change Initiative (Land_Cover_CCI): Global Land Cover Maps, Version 2.0.7*. Centre for Environmental Data Analysis. https://catalogue.ceda.ac.uk/uuid/b382ebe6679d44b8b0e68ea4ef4b701c

Deltares. (2017). *Upgrading the RIBASIM softwate and its institutionalising at the Ministry of Water, Lesotho*

Department of Energy. (2017). *SREP Investment Plan for Lesotho*. https://www.climateinvestmentfunds.org/sites/cif_enc/files/meeting-documents/srep_18_4_investment_plan_lesotho_final.pdf

Devia, G. K., Ganasri, B. P., & Dwarakish, G. S. (2015). A Review on Hydrological Models. *Aquatic procedia*, *4*, 1001-1007. https://doi.org/10.1016/j.aqpro.2015.02.126

DHI Water & Environment. (2003). *MIKE BASIN 2003 - A Versatile Decision Support Tool For Integrated Water Resources Management Planning* DHI.

FAO. (2005). *AQUASTAT Country Profile - Lesotho*. Food and Agrigulture Organization of the United Nations. http://www.fao.org/3/i9750en/I9750EN.pdf

FAO. (2014). *The Water-Energy-Food Nexus - A new approach in support of food security and sustainable agriculture*. Food and Agrigulture Organization of the United Nations. http://www.fao.org/3/bl496e/bl496e.pdf

FAO. (2016). *AQUASTAT Country profile - South Africa*. Food and Agrigulture Organization of the United Nations. http://www.fao.org/3/i9821en/I9821EN.pdf

FAO. (2018). *FAOSTAT Statistical database - Lesotho*. Food and Agriculture Organization of the United Nations. Retrieved May 29 from http://www.fao.org/faostat/en/#country/122

GoL. (2018). *National Strategic Development Plan of Lesotho 2018/19-2022/23*. Government of Lesotho.

Grauso, S., Pasanisi, F., & Tebano, C. (2020). Modeling the suspended sediment yield in Lesotho rivers. *Modeling Earth Systems and Environment*, *6*(2), 759-768. https://doi.org/10.1007/s40808-020-00738-5

Grill, G., Lehner, B., Thieme, M., Geenen, B., Tickner, D., Antonelli, F., Babu, S., Borrelli, P., Cheng, L., Crochetiere, H., Ehalt Macedo, H., Filgueiras, R., Goichot, M., Higgins, J., Hogan, Z., Lip, B., McClain, M. E., Meng, J., Mulligan, M., Nilsson, C., Olden, J. D., Opperman, J. J., Petry, P., Reidy Liermann, C., Sáenz, L., Salinas-Rodríguez, S., Schelle, P., Schmitt, R. J. P., Snider, J., Tan, F., Tockner, K., Valdujo, P. H., Van Soesbergen, A., & Zarfl, C. (2019). Mapping the world's free-flowing rivers. *Nature*, *569*(7755), 215-221. https://doi.org/10.1038/s41586-019-1111-9

Haddeland, I., Heinke, J., Biemans, H., Eisner, S., Flörke, M., Hanasaki, N., Konzmann, M., Ludwig, F., Masaki, Y., Schewe, J., Stacke, T., Tessler, Z. D., Wada, Y., & Wisser, D. (2014). Global water resources affected by human interventions and climate change. *Proceedings of the National Academy of Sciences*, *111*(9), 3251-3256. https://doi.org/10.1073/pnas.1222475110

Hoff, H. (2011). *Understanding the Nexus. Background paper for the Bonn2011 Conference: The Water, Energy, and Food Security Nexus.* Stockholm Environment Institute. https://mediamanager.sei.org/documents/Publications/SEI-Paper-Hoff-UnderstandingTheNexus-2011.pdf

Jarar Oulidi, H. (2019). 3 - Case Studies. In H. Jarar Oulidi (Ed.), *Spatial Data on Water* (pp. 93-136). Elsevier. https://doi.org/https://doi.org/10.1016/B978-1-78548-312-7.50003-X

Labadie, J. W., Fontane, D. G., Lee, J.-H., & Ko, I. H. (2007). Decision Support System for Adaptive River Basin Management: Application to the Geum River Basin, Korea. *Water International*, *32*(3), 397-415. https://doi.org/10.1080/02508060708692220

Lange, G.-M., Mungatana, E., & Hassan, R. (2007). Water accounting for the Orange River Basin: An economic perspective on managing a transboundary resource. *Ecological Economics*, *61*(4), 660-670. https://doi.org/10.1016/j.ecolecon.2006.07.032

Lehner, B., Verdin, K., & Jarvis, A. (2008). New Global Hydrography Derived From Spaceborne Elevation Data. *Eos, Transactions American Geophysical Union*, *89*(10), 93. https://doi.org/10.1029/2008eo100001

Lesotho Electricity Company. (2021). *Customer Services: Generation*. Retrieved April 29, 2021 from https://www.lec.co.ls/generation/

Lesotho Meteorological Services. (2021). *Climate of Lesotho*. https://www.lesmet.org.ls/home/open/Climate-of-Lesotho

Letsie, M., & Allopi, D. (2008). *Maqalika Reservoir: utilisation and sustainability of Maqalika Reservoir as a source of potable water supply for Maseru in Lesotho*.

LHDA. (2021). *Muela Hydropower, Lesotho Highlands Water Development Project Phase I*. Lesotho Highlands Development Authority. Retrieved May 9 from http://www.lhda.org.ls/lhdaweb/projectphases/phasei

LHDA. (n.d.). *The Treaty* Lesotho Highlands Development Authority. http://www.lhda.org.ls/lhdaweb/about/ourStory

Liu, D., Liu, H., Wang, X., & Kremere, E. (2019). *World Small Hydropower Development Report 2019*. I. C. o. S. H. P. United Nations Industrial Development Organization. www.smallhydroworld.org

Maherry, A., Horan, M., Smith-Adao, L., van Deventer, H., Nel, J., Schulze, R., & Kunz, R. (2013). *Delineating River Network Quinary Catchments for South Africa and Allocating Associated Daily Hydrological Information*. Water Research Commision.

Ministry of Water. (2018). *State of water resources report*. Commission of Water.

Ministry of Water. (2019). *Addendum to Environmental and Social Impact Assessment (ESIA) for Zones*

2 and 3 of the Lowlands Water Development Project Phase II.

Mitchell, T. D., Carter, T. R., Jones, P. D., Hulme, M., & New, M. (2003). *Climate Change Knowledge Portal - Derived from the Climate Research Unit*.
Mohobane, T. (2015). *Water Resources Availability in the Caledon River Basin - Past, Present and Future* Rhodes University, Grahamstown, South Africa.
Moriasi, D., Arnold, J., Van Liew, M., Bingner, R., Harmel, R. D., & Veith, T. (2007). Model Evaluation Guidelines for Systematic Quantification of Accuracy in Watershed Simulations. *Transactions of the ASABE*, *50*. https://doi.org/10.13031/2013.23153
Mulligan, M. (2013). WaterWorld: a self-parameterising, physically based model for application in data-poor but problem-rich environments globally. *Hydrology Research*, *44*(5), 748-769. https://doi.org/10.2166/nh.2012.217
NVE. (1991). *Experiences and Final Report from the Implementation of Mantsoyane and Semonkong Small Hydro Electric Schemes in Lesotho*. https://publikasjoner.nve.no/report/1991/report1991_06.pdf
Olsson, G. (2015). *Water and energy : threats and opportunities* (2nd. ed. ed.). IWA Publishing.
ORASECOM. (n.d.). *Overview of the Orange-Senqu River Basin*. The Orange-Senqu River Commission. Retrieved May 24 from http://orasecom.org/
Parkman Ltd. (2004). *Lesotho Lowlands Water Supply Scheme Feasibility Study. Water resources assessment of final development options*. WRP Consulting Engineers.
Perera, B. J. C., James, B., & Kularathna, M. D. U. (2005). Computer software tool REALM for sustainable water allocation and management. *J Environ Manage*, *77*(4), 291-300. https://doi.org/10.1016/j.jenvman.2005.06.014
Saloranta, T. M., Malve, O., Kamari, J., & Rekolainen, S. (2003). Benchmark Criteria: A Tool for Selecting Appropriate Models in the Field of Water Management. *Environmental Management*, *32*(3), 322-333. https://doi.org/10.1007/s00267-003-0069-3
Saltelli, A. (2002). Sensitivity Analysis for Importance Assessment. *Risk Analysis*, *22*(3), 579-590. https://doi.org/10.1111/0272-4332.00040
Schäfer, N. W., McKenzie, R. S., & van Rooyen, P. G. (1991). *Caledon River upstream of Welbedacht Dam: Hydrology* Department of Water Affairs (South Africa).
Sheffield, J., Goteti, G., & Wood, E. F. (2006). Development of a 50-Year High-Resolution Global Dataset of Meteorological Forcings for Land Surface Modeling. *Journal of Climate*, *19*(13), 3088-3111. https://doi.org/10.1175/jcli3790.1
Sieber, J. (2015). *User Guide for WEAP 2015*. U. S. C. Stockholm Environment Institute. http://www.weap21.org
Šiklomanov, I. A., & Rodda, J. C. (2003). *World water resources at the beginning of the twenty first century*. Cambridge University Press.
SMEC. (2017). *Final Water Resources Assessment Report: Consultancy Services for the Update of the Lowlands Water Supply Study, Detail Designs, and Construction Supervision*. The SMEC Group.
SSI. (2009). *Lesotho Power Generation Master Plan - Hydro Power Generation Option*. SSI - A DHV company.
Statistics South Africa. (n.d.). *Statistics by Place*. Stats SA. Retrieved May 4 from http://www.statssa.gov.za/?page_id=964
Stockholm Environment Institute. (2021). *Selected Publications*. Stockholm Environment Institute. Retrieved 04/02 from https://www.weap21.org/index.asp?action=216
Taele, B. M., Mokhutšoane, L., & Hapazari, I. (2012). An overview of small hydropower development in Lesotho: Challenges and prospects. *Renewable Energy*, *44*, 448-452. https://doi.org/10.1016/j.renene.2012.01.086
Tongwane, M. I., & Moeletsi, M. E. (2015). Intra-seasonal rainfall variability during the maize growing season in the northern lowlands of Lesotho. *Theoretical and Applied Climatology*, *120*(3-4), 575-585. https://doi.org/10.1007/s00704-014-1183-2
Treaty on the LHWP. (1986). *Treaty on the Lesotho Highlands Water Project*. http://www.lhda.org.ls/lhdaweb/uploads/documents/governance/lhwp_treaty.pdf

UN-Water. (2008). *Status Report on IWRM and Water Efficiency Plans for CSD16*. United Nations.
United Nations. (2015). *Transforming our world: the 2030 Agenda for Sustainable Development*. https://sdgs.un.org/2030agenda
United Nations. (2021). *The United Nations World Water Development Report 2021: Valuing water* UNESCO.
USGS. (2000). *Digital Elevation - Shuffle Radar Topography Mission (STRM) 1 Arc-Second Global*. https://earthexplorer.usgs.gov/
Van der Krogt, W. (2010). *Technical Report: RIBASIM Version 7.01 User Manual Addendum*. Deltares Institute.
Wang, Q. J., Pagano, T. C., Zhou, S. L., Hapuarachchi, H. A. P., Zhang, L., & Robertson, D. E. (2011). Monthly versus daily water balance models in simulating monthly runoff. *Journal of hydrology (Amsterdam)*, *404*(3), 166-175. https://doi.org/10.1016/j.jhydrol.2011.04.027
Winston, H. Y. (2008). *Africa Region Water Resources Unit Working Paper 1: Benefit Sharing in International Rivers*. A. R. The World Bank. https://documents1.worldbank.org/curated/en/159191468193140438/pdf/464560NWP0P1121g0AFTWR0YU301PUBLIC1.pdf
World Bank. (2016). *Lesotho Water Security and Climate Change Assessment*. http://documents1.worldbank.org/curated/en/446521472206603986/pdf/108018-PUB-Box396303B-PUBLIC-PUBDATE-7-6-16.pdf
World Bank. (2017a). *Lesotho WEAP Manual*. W. World Bank, DC. .
World Bank. (2017b). *Water Resources Management*. World Bank. Retrieved May 25 from https://www.worldbank.org/en/topic/waterresourcesmanagement#2
World Bank. (2018a). *Lesotho. Access to electricity (% of population)*. World Bank. Retrieved April 29, 2021 from https://data.worldbank.org/indicator/EG.ELC.ACCS.ZS?locations=LS
World Bank. (2018b). *Lowlands Water Development Project II - Combined Project Information Documents/Integrated Safeguards Datasheet (PID/ISDS)*. World Bank. https://documents1.worldbank.org/curated/en/630521553785008517/pdf/Project-Information-Document-Integrated-Safeguards-Data-Sheet-Lowlands-Water-Development-Project-II-P160672.pdf
World Bank. (2019). *Population, total - South Africa*. Retrieved May 11 from https://data.worldbank.org/indicator/SP.POP.TOTL?locations=ZA
WRP Ltd. (2012). *1st Annual State of Water Resources Report 2010-2011*. The Government of the Kingdom of Lesotho.
Xu, C. Y., & Singh, V. P. (1998). *Water Resources Management*, *12*(1), 20-50. https://doi.org/10.1023/a:1007916816469
Yeggina, S., Teegavarapu, R. S. V., & Muddu, S. (2020). Evaluation and bias corrections of gridded precipitation data for hydrologic modelling support in Kabini River basin, India. *Theoretical and Applied Climatology*, *140*(3-4), 1495-1513. https://doi.org/10.1007/s00704-020-03175-7

Supplementary material

Appendix A: Description of the master’s thesis

Appendix B: Flow chart for river basin configuration, demand centres and reservoirs

Appendix C: WEAP model setups for different scenarios

Appendix D: Detailed hydropower and reservoir input data, scenario D

Appendix E: Additional simulation results

NTNU
Norwegian University of Science and Technology

Faculty of Engineering

Department of Civil and Environmental Engineering

M.Sc. Thesis in Water Resources Modelling and Engineering

Candidate: Helga Løset Skodjereite

Title: Evaluating water allocation within the water-energy-food nexus in the lowlands of Lesotho

- A case study of Hlotse river basin

55 BACKGROUND

Water resources are under severe stress due to a variety of human interventions such as water abstraction, hydropower development and pollution in many river basins across the world. Climate change, population growth, land use changes and other human exploitation will give additional pressure on these precious resources. Water, energy and food securities are inherent interconnected and at the heart of human wellbeing and sustainable development. They critically depend on climate and environmental protection. Further development of renewable energy resources, as a response to climate change, will affect the availability of water resources as well as the health of ecosystems, and calls for a holistic analytical and management approach.

Water is one of the most important natural resources of Lesotho and encompass almost all aspects of life, the economy and the natural environment, and water has a unique position and the potential to contribute positively to achieving the objectives of future development goals. Lesotho falls within the Orange-Senqu River basin with the major sub-catchments being: the Senqu in the eastern part of Lesotho (24 500 km^2), the Makhaleng in the centre of the country (3 000 km^2) and the Mohokare (Caledon river) being the western border to the RSA (6 850 km^2). In order to secure the supply of drinking water, water abstraction is planned in Hlotse river, one of the tributaries in the upper parts of Mohokare (Caledon river), with potential effects on the ecosystem and other human water use. In order to compensate this, water will be transferred into Hlotse river from Katse dam in the Senqu basin in the Lesotho Highlands.

This thesis will reveal different management options in order to secure the availability of water for human consumption and agricultural production, sustain important environmental qualities, while at the same time seeking for opportunities in increasing the renewable energy production in the study area (water-energy nexus).

2 MAIN QUESTIONS FOR THE THESIS

Key question to be addressed in the thesis are;

- The trade-offs of different management strategies in Hlotse River on the water-energy-food nexus within Hlotse river basin and downstream in Caledon river

<u>These questions can be addressed by carrying out the following steps:</u>

1. Compile data on climate, hydrology, water-related infrastructure and water use in Hlotse river basin (focus area) and in Mohokare river basin (Caledon river) as the full modelling area (the areas upstream of Maseru) and evaluate the quality of the available information, which may include
    a. Climatic input data
    b. Hydrological observations
    c. Data on water use/transfer of water
2. Configure/calibrate a hydrological and water allocation model (WEAP) for Mohokare/Caledon river, with particular focus/detail on the Hlotse river basin, based on historical data. Assess the performance of the calibration and factors affecting the performance.
3. Define a set of different scenarios for water management strategies and assess the effects on the water availability/resources and various water users/interests along Hlotse River and Caledon river, which may include:
    a. Changes in water withdrawal for irrigation
    b. Reservoirs/hydropower production in the basin
    c. Changes in transfer of water
4. Based on the findings in the steps 1-3 discuss the synergies and trade-offs between different water use/management options during different climatic situations, such as dry and wet years, and the effects on the water availability along Hlotse River and Caledon river.

3 SUPERVISION, DATA AND INFORMATION INPUT

Professor Tor Haakon Bakken will be the main supervisor of the thesis work. The thesis will be carried out in close cooperation with Multiconsult, with Leif Lillehammer as the co-supervisor and principal contact, and their contracted partners. Discussion with and input from colleagues and other research or engineering staff at NTNU, power companies or consultants are recommended, if considered relevant. Significant inputs from others shall, however, be referenced in a convenient manner.

The research and engineering work carried out by the candidate in connection with this thesis shall remain within an educational context. The candidate and the supervisors are therefore free to introduce assumptions and limitations, which may be considered unrealistic or inappropriate in a contract research or a professional engineering context.

4 REPORT FORMAT AND REFERENCE STATEMENT

The report shall be typed by a standard word processor and figures, tables, photos etc. shall be of good report quality, following the NTNU style. The report shall include a summary, a table of content, lists of figures and tables, a list of literature and other relevant references. All figures, maps and other included graphical elements shall have a legend, have axis clearly labelled and generally be of good quality.

The report shall have a professional structure and aimed at professional senior engineers and decision makers as the main target group, alternatively written as a scientific article. The decision regarding report or scientific article shall be agreed upon with the supervisor.

The thesis shall include a signed statement where the candidate states that the presented work is his/her own and that significant outside input is identified.

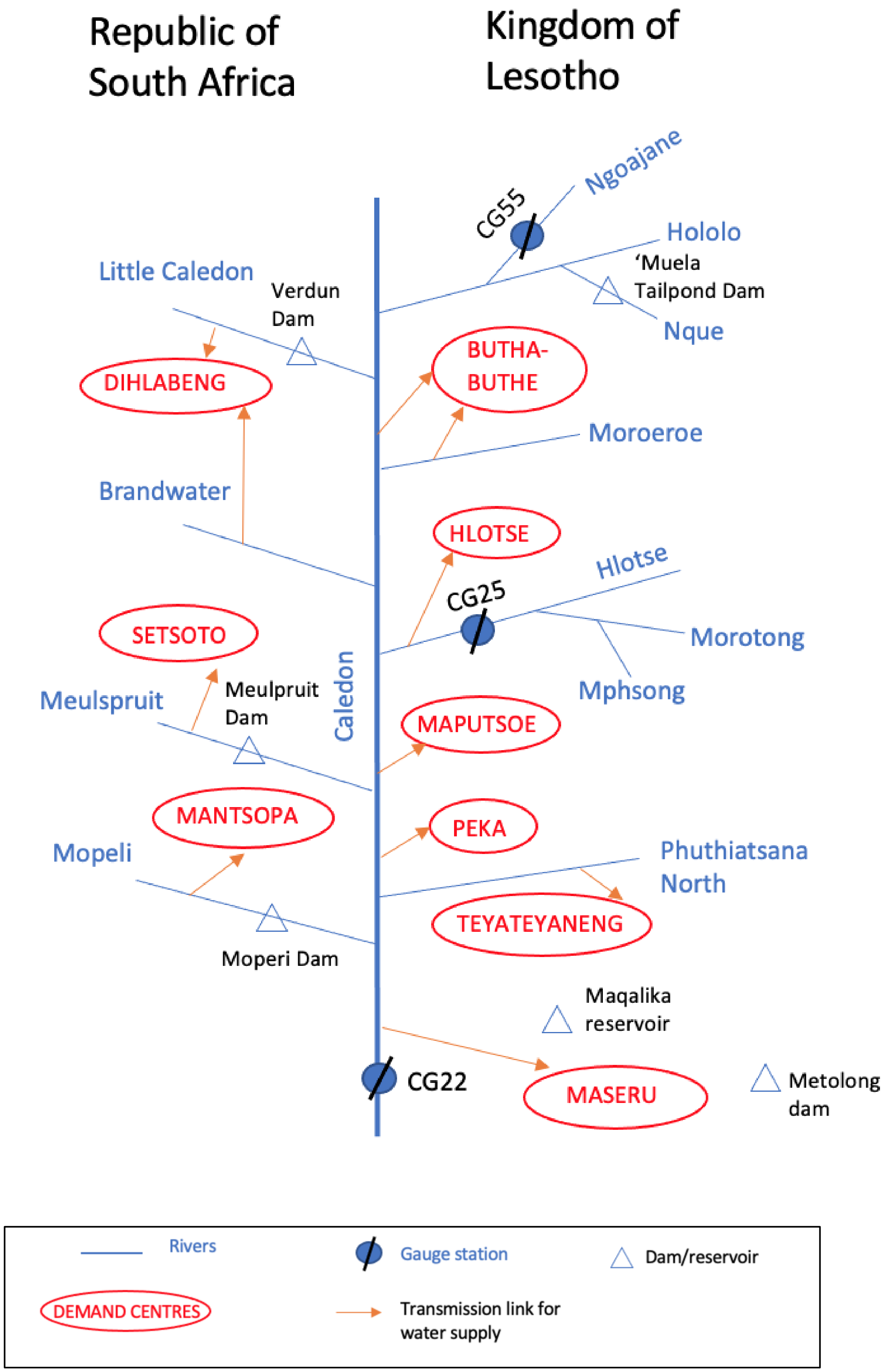
This text shall be included in the report submitted. Data that is collected during the work with the thesis, as well as results and models setups, shall be documented and submitted in electronic format together with the thesis.

Trondheim 15th of January 2021

Tor Haakon Bakken

Tor Haakon Bakken, Professor

Appendix B: Flow chart for river basin configuration, demand centres and reservoirs



Appendix C: WEAP model setups for different scenarios

A total of 8 model setups are attached to the report and submitted to the department at NTNU. The following table provides an overview of the model setups with following screen dumps for illustration.

Scenario	**WEAP model**	**Purpose**
Calibraton and validation	Caledon_v.1.2	Calibration at CG25 and validation at CG55
Reference scenario	Caledon_v.2.2	Estimated withdrawals for reference period
Scenario A	Caledon_v.4.2	Direct abstractions for potable water supply in Hlotse river
Scenario B	Caledon_v.5.1	Direct abstractions for potable water supply and irrigation in Hlotse river
Scenario C1	Caledon_v.6.1	Effect of constant transfer of 0.119 m^3/s from LHWP into Hlotse river
Scenario C2	Caledon_v.6.2	Effect of seasonal transfer of 0.2 m^3/s April-Oct from LHWP into Hlotse river
Scenario D1	Caledon_v.3.5_HP	Effect of reservoir regulation with Hlotse HPP with energy production as first priority
Scenario D2	Caledon_v.3.4_HP	Effect of reservoir regulation with Hlotse HPP, reservoir releases set to meet demands downstream

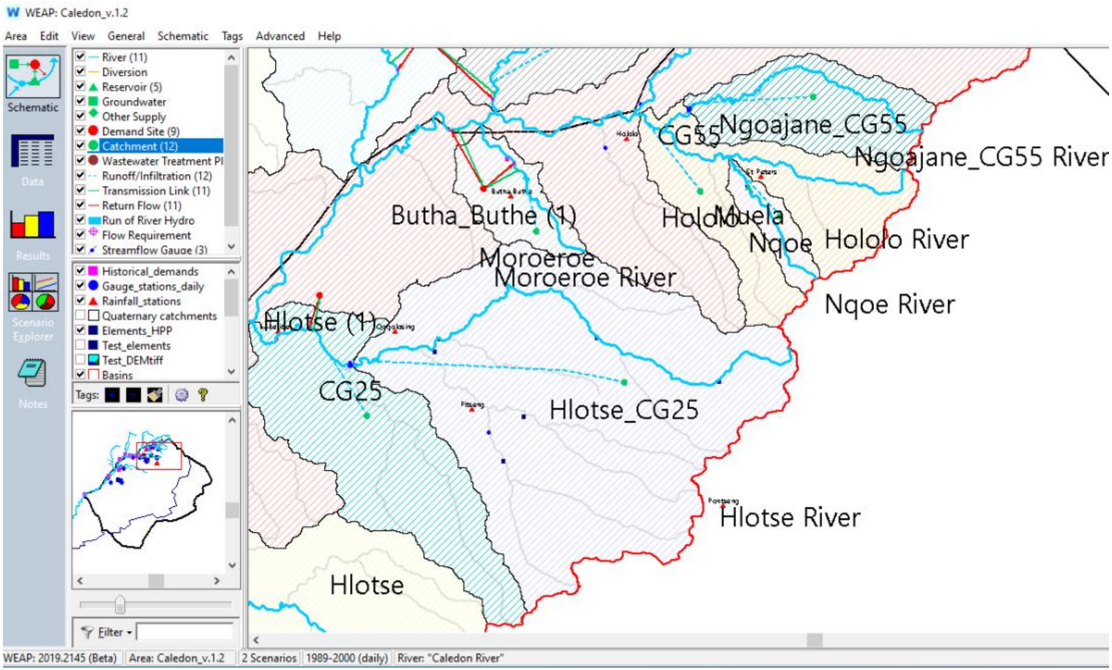


Figure C1 Hlotse_CG25 for calibration and Ngoajane_CG55 for validation

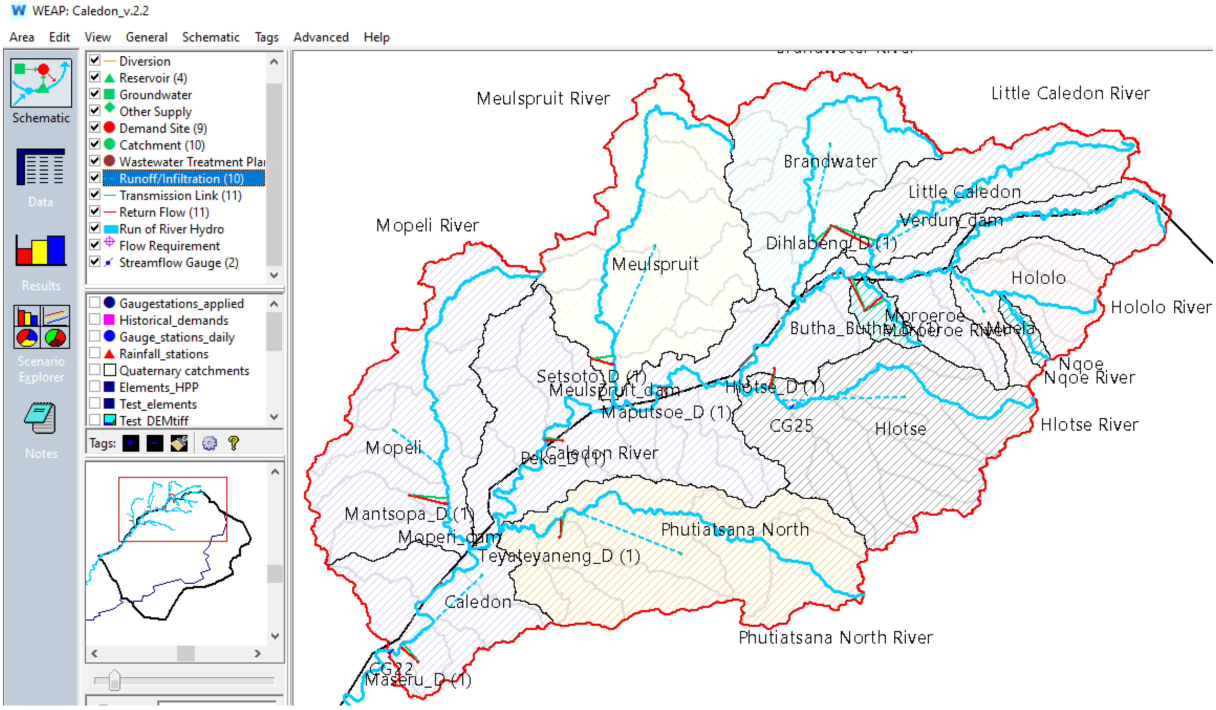


Figure C2 Model setup for Reference scenario

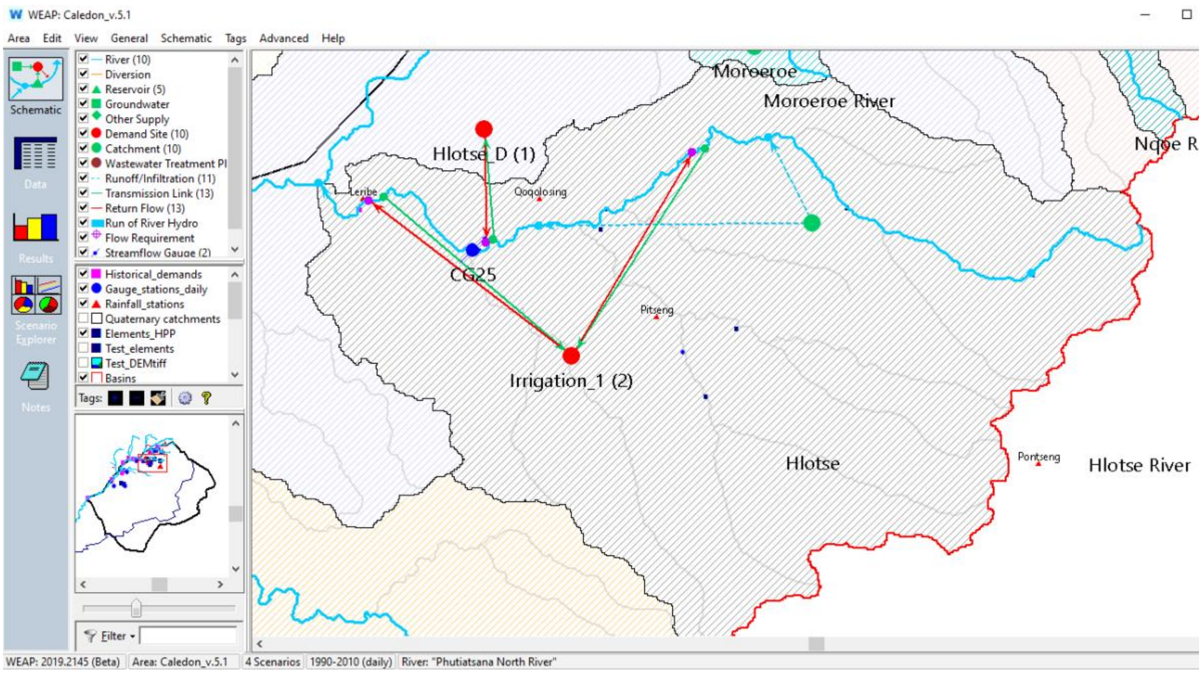


Figure C3 Scenario B with irrigation withdrawals (Irrigation_1) in addition to Scenario A with potable water supply (Hlotse_D)

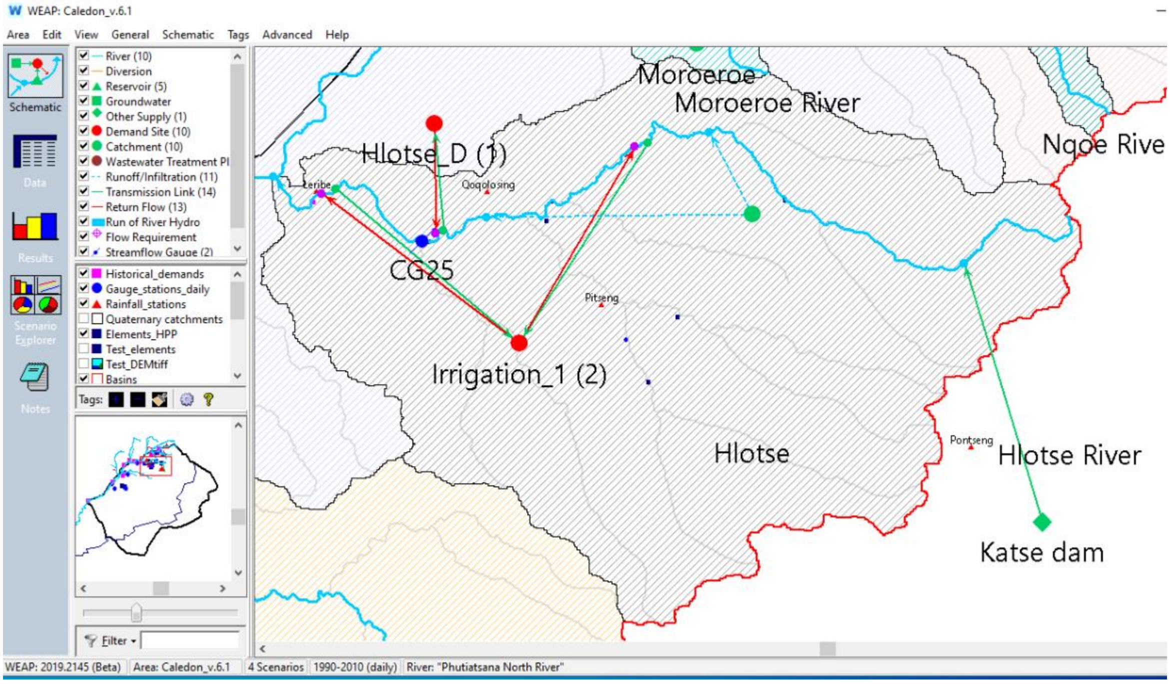


Figure C4 Scenario C with water transfers from Katse dam in the LHWP into Hlotse river

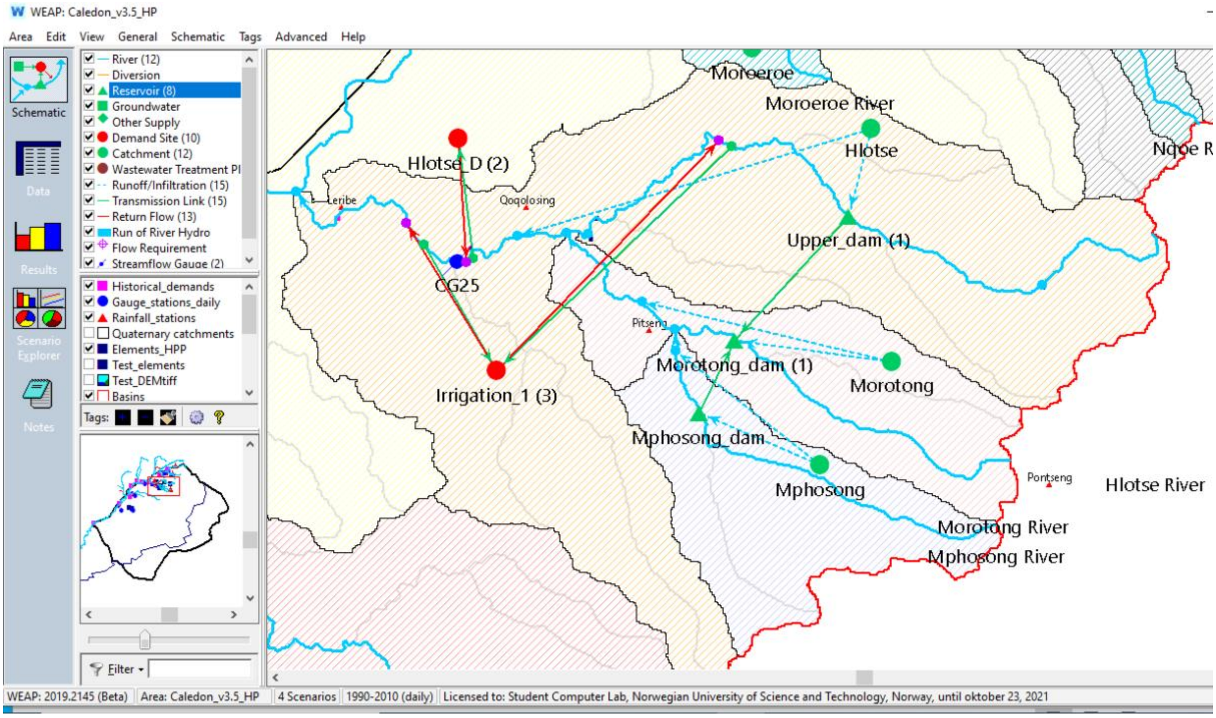
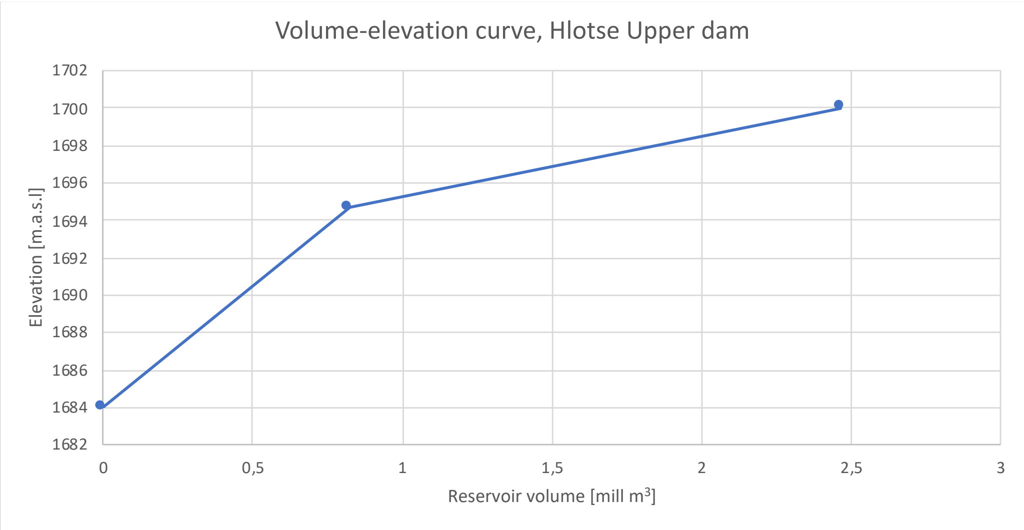


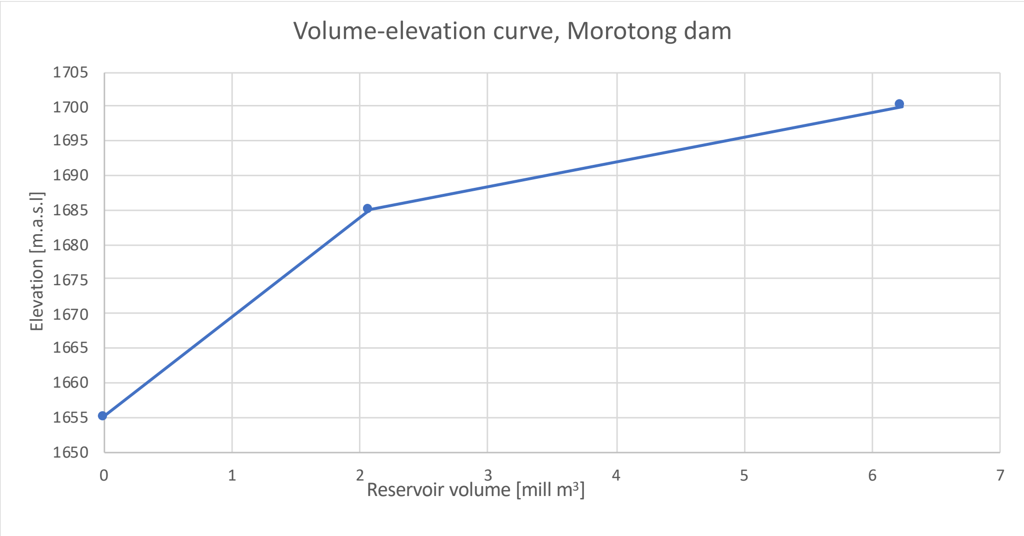
Figure C5 for scenario D with hydropower development with reservoir regulation in Hlotse river and Morotong and Mphosong tributaries

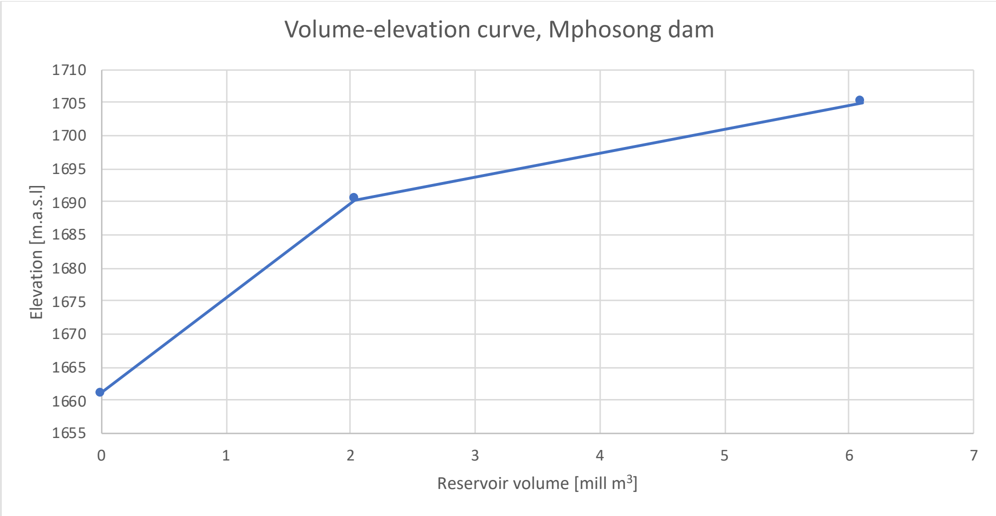
Appendix D: Detailed hydropower and reservoir input data, scenario D

Reservoir characteristics

	Hlotse Upper dam	**Morotong dam**	**Mphosong dam**
Model function	Transfer to Morotong	Hydropower generation	Transfer to Morotong
River/tributary	Hlotse	Morotong	Mphosong
Dam height	19 m	48 m	47 m
Storage capacity	2.467 mill m^3	6.232 mill m^3	6.102 mill m^3
Top of inactive	0.733 mill m^3	1.853 mill m^3	1.814 mill $m^3$3





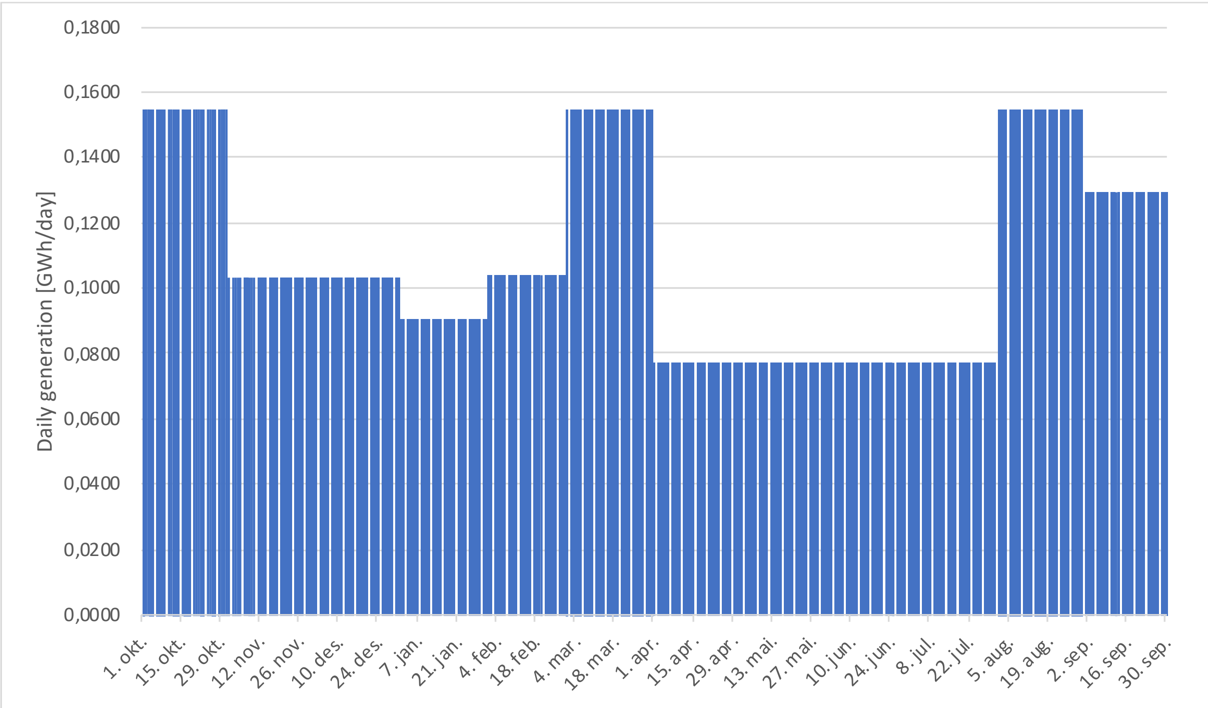


Hydropower characteristics applied for Morotong dam

Max turbine flow	6 m^3/s
Tailwater elevation	1575
Plant factor	100 %
Generating efficiency	69.72%

Net evaporation from the reservoirs

Month	Open water evaporation [mm/month]	Rainfall Princeton [mm/month]	Net evaporation [mm/day]
Oct	114	80	1.1
Nov	125	97	0.9
Dec	145	123	0.7
Jan	139	124	0.5
Feb	113	105	0.3
Mar	98	91	0.2
Apr	68	47	0.7
May	52	17	1.1
Jun	39	13	0.9
Jul	44	7	1.2
Aug	63	15	1.5
Sep	92	26	2.2

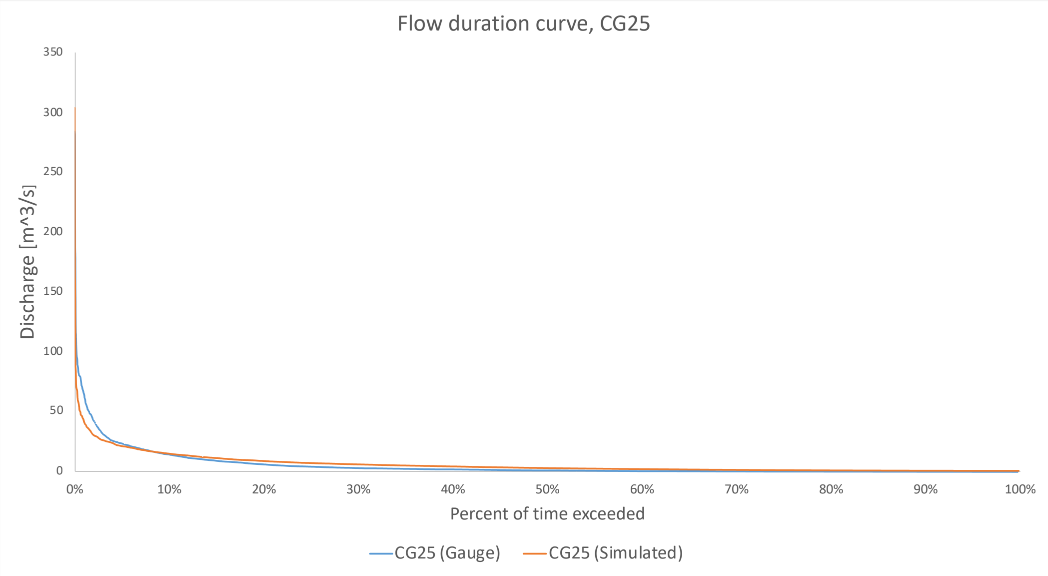


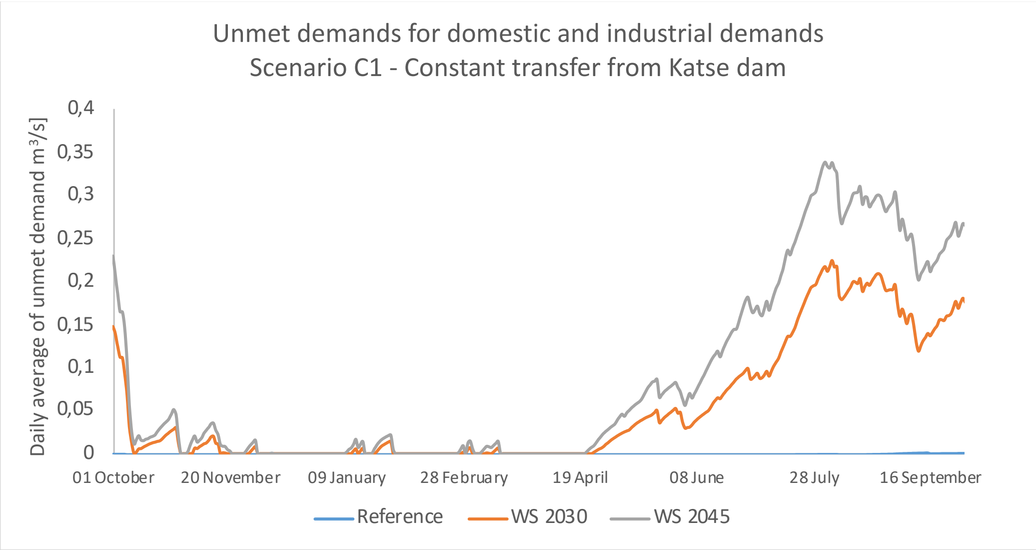
Energy demand for daily generation, Scenario D1

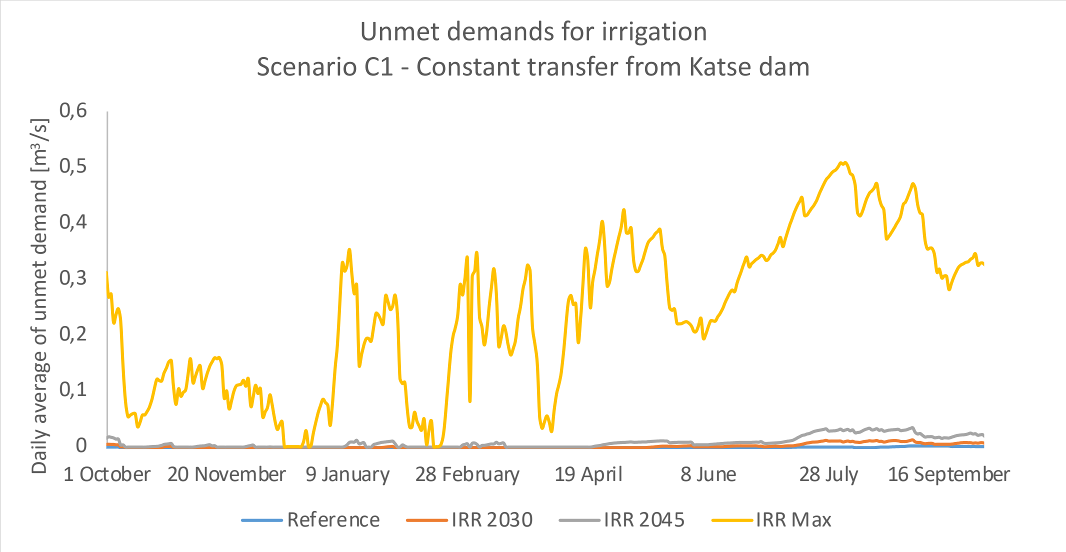
Appendix E: Additional simulation results from the WEAP model

Table E1: PBIAS for each of the years, calibration catchment CG25

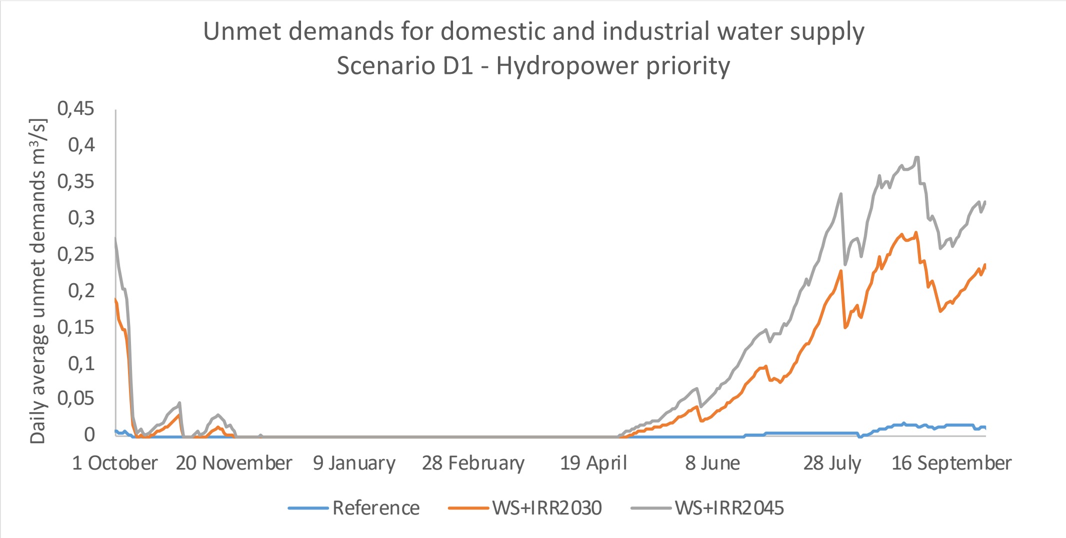
Year	PBIAS [%]
1988/1989	53
1989/1990	-81
1990/1991	-50
1991/1992	-103
1992/1993	-27
1993/1994	-8
1994/1995	-71
1995/1996	1
1996/1997	10
1997/1998	-11
1998/1999	-15
1999/2000	23



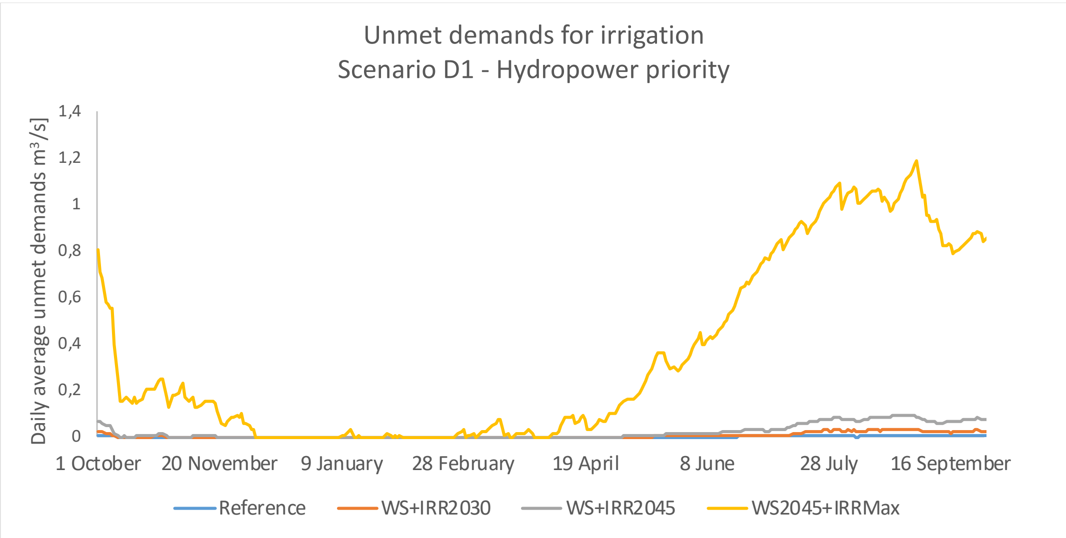




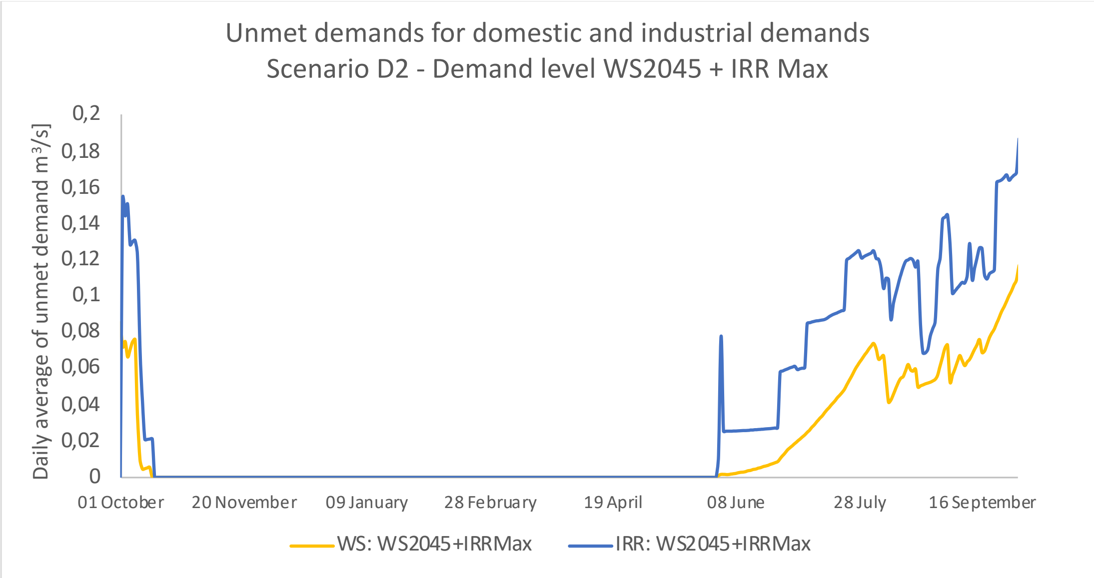
Unmet demands for irrigation
Scenario C1 - Constant transfer from Katse dam
Daily average of unmet demand [m³/s]
0,6
0,5
0,4
0,3
0,2
0,1
0
1 October
20 November
9 January
28 February
19 April
8 June
28 July
16 September
Reference
IRR 2030
IRR 2045
IRR Max



Unmet demands for domestic and industrial water supply
Scenario D1 - Hydropower priority
Daily average unmet demands m³/s]
0,45
0,4
0,35
0,3
0,25
0,2
0,15
0,1
0,05
0
1 October
20 November
9 January
28 February
19 April
8 June
28 July
16 September
Reference
WS+IRR2030
WS+IRR2045



Unmet demands for irrigation
Scenario D1 - Hydropower priority
Daily average unmet demands m³/s]
1,4
1,2
1
0,8
0,6
0,4
0,2
0
1 October
20 November
9 January
28 February
19 April
8 June
28 July
16 September
Reference
WS+IRR2030
WS+IRR2045
WS2045+IRRMax


Unmet demands for domestic and industrial demands
Scenario D2 - Demand level WS2045 + IRR Max
Daily average of unmet demand m³/s]
0,2
0,18
0,16
0,14
0,12
0,1
0,08
0,06
0,04
0,02
0
01 October
20 November
09 January
28 February
19 April
08 June
28 July
16 September
WS: WS2045+IRRMax
IRR: WS2045+IRRMax

NTNU

Norwegian University of
Science and Technology