MODELLING OF WATER DEMAND AND SUPPLY TO DEVELOP FUTURE MANAGEMENT SCENARIOS FOR MOKOLO RIVER CATCHMENT, LIMPOPO PROVINCE

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In the

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At the

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SUPERVISOR: DR RT AKANBI

CO-SUPERVISOR: PROF I DHAU

2025

DECLARATION

I declare that the ‘Modelling of Water Demand and Supply to Develop Future Management Scenarios for the Mokolo River Catchment, Limpopo Province’ dissertation hereby submitted to the University of Limpopo, for the degree of Master of science (Geography and Environmental science) has not previously been submitted by me for a degree at this or any other university; that it is my work in design and in execution, and that all material contained herein has been duly acknowledged.

NKOE EB (Ms) 22/11/2024

DEDICATION

To my extraordinary parents, Isaac and Jellies Nkoe, your boundless love, unwavering support, infinite patience, and guiding wisdom have been my constant companion throughout this journey. I will be eternally grateful for the countless teachings you have bestowed upon my life and the strength I have drawn from your unwavering belief in me.

To my cherished daughter, your pure affection, radiant smile, and warm embrace have been a beacon of joy, inspiring me to persevere and pursue my dreams. May this thesis serve as a testament to you that anything is possible only if you put your mind to it.

To my dearest friends, Oscar and Priscilla, your steadfast prayers, unwavering encouragement, and inspiring words have been a source of constant motivation. Thank you for always believing in my potential and inspiring me to strive for excellence in all that I do and to always be guided by faith.

With profound gratitude and love, I dedicate this dissertation to each and every one of you.

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ABSTRACT

Effective planning and integrated management of water resources in a rapidly changing environment under the influence of climate change and anthropogenic activities relies on consistent monitoring of changes in a river basin from these diverse impacts. The identification of the root causes of changes in river basins will inform the development and use of appropriate interventions. In the Mokolo River Basin of Limpopo, a comprehensive modelling study was conducted to evaluate water demand and supply dynamics using the Water Evaluation and Planning (WEAP) framework. This study involved manual calibration of the catchment, yielding calibration results characterised by a coefficient of determination (R^2) of 0.80 and a Nash-Sutcliffe Efficiency (NSE) of 0.55, alongside validation results of $R^2 = 0.70$ and NSE = 0.61. These metrics indicate a fair level of model performance, suggesting that the WEAP model can effectively simulate the hydrological processes within the basin. The analysis revealed that water demand was adequately met for the baseline year of 2010, indicating a stable supply-demand equilibrium during this period. However, projections for the future, specifically from 2025 to 2045, indicate a significant challenge in meeting water demand, particularly within the mining and industrial sectors. This anticipated unmet demand highlights the pressing need for strategic water management interventions in the basin. Five management scenarios were therefore implemented to address these issues, focusing on reducing water use across irrigation, domestic, and industrial sectors, while also considering inter-basin water transfers as a viable solution. The results of these scenarios demonstrated that implementing such measures could substantially alleviate unmet demand, accentuating the importance of integrated water resource management strategies in the face of increasing water scarcity.

KEY WORDS

Modelling Water demand and supply, future management scenarios, Mokolo River, Limpopo province, WEAP model,

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LIST OF ACRONOMYS

ABM- Agent Based Modelling

ANNs- Artificial neural networks

BMP- Best Management practices

CBWM- Community Based Water Management

CMIP6 - Coupled Model Intercomparison Project Phase 6

CNN- Convolution Neutral Network

DWS - Department of Water and Sanitation

EU- European Union

ESM - Ecosystem Service Models

GDP- Gross Domestic Product

GCRNN - Graph Convolutional Recurrent Neural Network

GIS - Geographic Information System

HRU- Hydrological Response Units

IDP - Integrated Development Plan

IoT - Integration of Smart Technologies

IWRM - Integrated Water Resource Management

LRS - Limpopo Reconciliation Strategy

LSTM - Long Short-Term Memory

LWMA - Limpopo Water Management Area

MBR - Mokolo River Basin

MCWAP - Mokolo Crocodile River Water Augmentation Project

MODFLOW- Modular Finite Different Flow Model

NSE - Nash Sutcliffe Coefficient of Efficiency

RRI- Rainfall-Runoff-Inundation

SDM- System Dynamic Modelling

SARIMA-Seasonal Autoregressive Integrated Moving Average

SAWS - South African Weather Services

SSA - Singular Spectrum Analysis

SSP - Shared Socioeconomic Pathway

SVMs support vector machines

SWAT - Soil and Water Assessment Tool

TOPMODEL - Topography-based Hydrological Model

TSR - Time Series Regression

UN- United Nations

USDA- Unites State Department of Agriculture

WEAP - Water Evaluation and Planning System

WMA - Water Management Area

WRC - Water Research Commission

WRR - Water Resources Research

CHAPTER 1: INTRODUCTION

1.1. Background

Water is one of the most indispensable natural resources (Ahmed et al., 2024), required to sustain human health, economic development, and environmental sustainability (Zhang and Yu, 2018). Despite being an essential resource, there is inadequate supply of this resource to meet all needs, due to its inherent value and expanding demand. Freshwater makes up around 2.5% of Earth's water, with groundwater and glaciers accounting for 98.8% of the total (Kikkas and Kulik, 2018; Mishra, 2023). This demonstrates the global scarcity of freshwater. Despite the perception that water is a scarce resource, the amount of water needed for different purposes has grown significantly over the years, leading to challenges in meeting the competing needs of water globally (Belhassan, 2021).

This is partly due to substantial financial and physical limitations of supply development. Water is used for numerous purposes in the modern world, such as domestic, agricultural, industrial, and ecological uses (Dolan, 2021). However, in many countries, the lack of water resources has become one of the factors limiting social and economic sustainable development (Wang and Yang, 2015). Keeping the supply and demand of water in balance has become more complex. Therefore, it is essential to manage this vital resource in an integrated manner by proactively planning and projecting future water demands and supply capabilities across several sectors while considering the effects of population and economic growth (Hamlat et al., 2024).

The world's population is growing rapidly; if this growth rate is sustained, the global population is estimated to reach more than 9 billion people before the middle of this century (Molotoks, 2021). Due to this unprecedented growth, a significant increase in water withdrawals is also projected. Most global scholars agree that a third of the global population would face water scarcity because of high water consumption rates brought on by socioeconomic factors and climate change (Awotwi et al., 2019).

Climate change continues to affect the global climate system's temperatures, which has led many nations to no longer view the availability of water as a continuous trend due to variations in rainfall patterns, changes in runoff, floods and droughts. (Zhang et al., 2020). The impact of climate change on the hydrological cycle is expected to lead to an increase in evaporation, which may lead to variations in precipitation patterns.

These impacts may also result in decreases in runoff, soil water, drought and flood frequency and intensity (Ahsan et al., 2023). It is widely acknowledged that climate change has a substantial impact on the productivity of several economic sectors, such as domestic, agricultural, and industrial sectors. In river basins, it causes variations in the amount and variability of rainfall, which in turn affects the yearly runoff. These modifications could worsen the growing gap between supply and demand for water, which is made worse by variables like population expansion and economic growth. According to Heidari et al. (2020), the combination of climate change and growing population may cause a change in the relationship between water supply and demand in river basins, which could result in either temporary or persistent water shortages. The effects of climate change on water resources, therefore need to be assessed at regional and basin levels to enable the planning and management of water resources to address future challenges (Abbas and Bailey, 2022).

Over the years, natural and human-induced activities in land use have led to modifications in the hydrological cycle. (Tena, 2019). In recent decades, most rivers around the world have shown notable changes in their annual runoff, which could eventually result in a water deficit (Asghar et al., 2019; Shanafield., 2021) According to Adgolign (2016), water stress in a watershed is a condition that evolves over time; it is not an isolated incident. The use and development of water resources have already progressed beyond a critical point in many regions of the world, resulting in environmental issues such as shifting river flows (Zhou et al., 2019).

In Africa, several rivers have experienced significant changes in their flow patterns due to climate change. The Blue Nile River is one of the most critical examples, with projections indicating a decrease in streamflow due to increased evaporation and changing precipitation patterns (Barnes, 2017; Roth et al., 2018). Similarly, the Zambezi River has shown altered flow regimes, which can be attributed to both climate variability and human activities such as dam construction (Setegn et al., 2011; Barnes, 2017).

In South Africa, the Limpopo River has also been affected, with changes in precipitation and evaporation rates leading to significant fluctuations in streamflow (Love et al., 2010). The Mokolo River has changed from a perennial to non-perennial river, mainly due to rapid evaporation, high water abstraction, and in-stream dams being built (Seaman et al., 2013). These examples illustrate the widespread impact of climate change on South Africa's river systems, necessitating urgent action to address the challenges posed by these changes.

The Limpopo province is a semi-arid province in South Africa. The province experiences high temperatures and unpredictable rainfall; extreme drought is a serious issue impacting the province's agricultural economy (Mosase and Ahiablame, 2018; Shabalala et al., 2019). South Africa has nine water management areas (Department of Water and Sanitation, 2016). The Limpopo Water Management Area (LWMA) is one of the nine WMA servicing the northeastern part of South Africa. There are various catchments within the Limpopo province which fall under the Limpopo Water Management Area, namely Matlabas, Mokolo, Lephalala, Mogalakwena, Sand and Nzhelele (DWS, 2016). The Mokolo River is one of the most developed river catchments within Limpopo province. The main tributaries of the Mokolo River include the Grootspruit, Klein Sandspruit, Heuningspruit, Malmanies, Poer se Loop, and Rietspruit (DWS, 2003). The Mokolo River merges the flows of these tributaries at its northern discharge into the Limpopo Basin (Lombaard, 2015).

There are many activities within the catchment area, including sand mining, coal power plants, coal mines, lodging establishments, wastewater treatment facilities, petrol stations, and agricultural activities. Most of these activities are driven by water that is sourced from the Mokolo dam (DWS, 2016). However, there is a limited amount of spare yield available for future allocations for the anticipated surge in economic development in the Mokolo dam, due to the current water infrastructure and water use (Howard, 2018)

Most of the Mokolo River's basin is located within the Waterberg Coalfields. This area has huge potential for economic development as almost half of the South African in-suit coals are found in the area (Birkholz, 2018). Therefore, significant projects are planned for the area (DWS, 2016), and the water demand in the area is expected to increase significantly in the upcoming years as a direct result of these projects. However, the area around the Mokolo River has a restricted supply of water (Howard, 2018). Due to this limitation in water availability, a realistic analysis of the Mokolo-Crocodile water augmentation project (MCWAP) was carried out in 2010 by the Department of Water and Sanitation (DWS) to determine how future water demand may be satisfied. The study revealed the need to augment the supply of water at the Mokolo Dam to meet future water requirements. The gap between water supply and demand in the Mokolo Dam showed that there is a need for an in-depth understanding and management of water supply and demand in the Mokolo River area. In this kind of area, decision-makers will require an approach that enables them to create a shared vision for the future of water resources, anticipate unforeseen circumstances, and adjust to constantly changing obstacles. This can be achieved through the use of hydrological models.

The understanding of the historical and present conditions of a basin's water resources is aided by hydrological models (Moges, 2021). The Water Evaluation And Planning (WEAP) is a modelling and planning tool for water resources and was developed by the Stockholm Environment Institute in 1988 (Sieber and Purkey, 2011). The model operates on the basic principle of water balance, and it can be applied to single watersheds, municipal systems and complex transboundary river basin systems (Moncada et al., 2020). The WEAP model allows the user to develop and analyse various scenarios, such as potential climate change impact, variation in population growth, assumption in water demand, infrastructure and regulation (Sieber and Purkey, 2015). The WEAP model is widely utilised by many researchers and managers in various countries. Many policymakers and scholars throughout the world use the WEAP model extensively for management decisions (Thiam, 2022; Khalil,2018; Delavar,2020). In Africa, WEAP has been used for water use research, effects of climate change, hydrological modelling and the implications of population increase on water resources (Nang and Seyam, 2023). Studies on assessing and managing water resources have advanced significantly in recent years (Qin et al., 2019). Meanwhile, in South Africa, the WEAP model has also been used, but very few studies focus on the analysis for water demand management (Akanbi et al 2021).

1.2. Problem statement

Water resource availability is declining as socioeconomic activities and climate change impacts increases (Awotwi *et al*., 2019). Global population expansion combined with the effects of climate change, agricultural irrigation, industrialisation and urbanisation are putting tremendous pressure on the limited water resources that are currently available (Silva et al. 2020). Due to these key factors, the global water demand continues to rise causing many countries to experience water shortages (Salehi, 2022).

South Africa is considered a semi-arid country, and its annual average rainfall is estimated to be half of the global annual average, leading to growing water limitations (Gxokwe et al., 2022). The country's population is growing, but most of its water supply is not. Therefore, insufficient water is needed to meet present needs (Matlakala and Kallon, 2020). This issue is not different in the Mokolo River basin (MRB) of the Limpopo water management area; the river catchment's water supplies are mainly used for irrigation and industrial purposes, leaving people in rural areas to rely on groundwater (Marcatelli, 2020). However, the groundwater in the area tends to dry up from time to time, leaving rural communities to depend on water tanks (DWS, 2016).

The inability of the catchment to supply adequate water for domestic purposes indicates that there is a gap between water demand and supply in the Mokolo River. According to the Lephalale local municipality (IDP, 2022), the Mokolo dam will not be able to meet its water demand in the future due to increasing demands and development plans earmarked for the area. These issues show that there is a great need to understand what the current demands are in the catchment, identify possible constraints in water assurance and determine gaps in the Mokolo system's capacity to meet the present and future demands in the catchment. The study utilised the Water Evaluation and Planning Model (WEAP) to simulate water availability in the Mokolo River catchment, water demand, and water supply and identify gaps in supply as well as develop possible future management scenarios for the catchment. The WEAP model is the model of choice in this study because it is widely used in conducting these types of analyses. It is seen as a prime example of an integrated water resource management tool since it connects water supply and demand and environmental requirements (Agarwal et al., 2019).

1.3. Study rationale

The Mokolo River Basin is the most developed catchment area in the Limpopo province, yet it is currently experiencing a water deficit (The Lephalale local municipality, 2022). The extensive reduction in river quantity over the years has been linked to intensified human activities such as sand mining and the high abstraction of water (Maeko, 2020). These activities have altered the natural flow patterns of the river by removing sediments from the riverbed (Seaman et al., 2013), and it has disrupted the natural groundwater recharge process (Maeko, 2020). Previous studies in the catchment were to determine the total water yield of the catchment for developmental use (Talanda et al., 2015). There is, however, a gap in research on the present and future water demand in relation to supply in the catchment or studies that have explored plausible future water situation and management scenarios for the catchment.

The WEAP model has been successfully deployed for catchment-level assessment of the current state of water resources. This model identifies potential threats to water quantity and develops strategies to mitigate these threats using integrated water resource management (Salman and Shahid et al., 2021). A lack of water supply could slow down industrial expansion, diminish agricultural production, and stop portable water supplies. In addition, groundwater and in-stream environmental flow are at risk due to the depletion of local water supplies (Sun and Zhou et al., 2021).

Lephalale town is one of the towns in the Waterberg district, which significantly depends on the Mokolo River catchment for its water supply. The current water challenges linked to the Mokolo River are identified in the IDP of the Lephalale local municipality (2022) and they include inadequate bulk water supply, ageing infrastructure, non-availability of groundwater in rural areas and unplanned growth of rural villages. These water challenges show that water availability is a huge problem in the Mokolo area. Therefore, it is vital to try to understand the gap in the current water demand and catchment supply. To overcome the water shortages in river basins, water allocation and management models are important (Yan *et al*., 2018). Water evaluation and planning (WEAP) models are currently used to simulate water resources.

Hamza and Getahun (2022) utilized the WEAP model to assess the amount of water that was available in the Beles basin; the model showed that the amount of water that was currently being used was relatively small. Seddiki and Cherif (2021) modelled water demand using the WEAP and developed scenarios to determine the future water availability in the city of Bechar. The findings of this study demonstrated that water shortage is a problem that can be resolved by putting into practice a fresh approach based on the control of water demand. The WEAP model was selected for this study due to its simplicity and ability to evaluate water resources using a scenario-based system. The WEAP model can also incorporate various hydrological modules in data-limited areas such as the Mokolo River Basin, where minimal available studies focus on the catchment.

1.4. Aim

The study aims to assess water demand and supply for the development of future management scenarios for the Mokolo River catchment, Limpopo Province.

1.4.1. Objectives of the Study

- Determine the current water supply and demand for various water users, such as mining, irrigation, power generation, and domestic use, in the Mokolo River catchment of Limpopo Province.
- Predict the future water demand and supply in the Mokolo River catchment.
- Develop future water demand and supply management scenarios for the Mokolo River catchment.

1.4.2. Research Questions

The following research questions were addressed in the study:

I. What are the current water demand and supply in the Mokolo River Catchment?
II. What are the future water demand and supply in the Mokolo River?
III. What are the plausible future water management scenarios that can be used to manage future water demand and supply in the Mokolo River?

1.5. Scientific contributions

This study's findings help address existing knowledge gaps regarding the interactions between water demand and supply in the Mokolo River watershed. Additionally, the research investigates the potential impacts of population growth, climate change, and irrigation modifications on future water demand and supply. The study's outcomes provide critical insights into water balance challenges within the Mokolo River Basin (MRB), offering a scientific basis for improved water resource management. Furthermore, the study’s projections on future scenarios of water availability and use can inform decision-makers about the sustainable planning and management of the catchment’s water resources. Scientifically, this research contributes to the advancement of hydrological modelling by integrating socio-economic and environmental variables to enhance predictive accuracy. By addressing the limitations in existing studies, it strengthens the understanding of water demand and supply dynamics in semi-arid regions, providing a foundation for future research in water resource sustainability. Given the current paucity of research on modelling water demand and supply in the Mokolo River catchment, this study represents a significant step towards closing this gap.

1.6. Ethical considerations

The proposed study did not require any human or animal subjects; hence, there is no need for ethical approval.

1.7. Dissertation Outline

The dissertation is designed into five sections.

Section 1 (Introduction) consist of the Study background information, problem statement, rational, aim and objectives, research questions, ethical clearance, scientific contribution and a brief outline of the chapters.

Section 2 (Literature review) Related studies and concepts which covers study methods, which comes after this introduction.

Section 3 (Methodology) comprises of study area, research design, data collection approaches, WEAP model set up, catchment simulation, calibration and validation, and research approach and data analysis, the description of the study area and methodology.

Section 4 (Results and discussion) presents the study results, evaluates their limitations, contrasts them with earlier research, and investigates unexpected outcomes. The results include demographic characteristics such as graphs on current water demand and supply, future water demand and supply, inflow to area and unmet demand.

Section 5 (Conclusion and recommendation) The key findings are restated, the research concerns are addressed, theoretical or practical ramifications are highlighted, and potential directions for future study are suggested.

Chapter 2: LITERATURE REVIEW

2.1. Introduction

This literature review chapter focuses on studies that employed interdisciplinary approaches, demand-supply modelling frameworks, and examine the implications for basin-scale sustainable water resource management. The review also analyses recent developments in modelling water demand and supply within river basins, highlighting methodological trends, challenges, and opportunities. This chapter emphasises the assessment of water requirements for various sectors, including agriculture, industry, domestic use, and ecological flow requirements. On the supply side, it examines how natural hydrological processes, climate variability, and anthropogenic interventions such as reservoirs, diversions, and groundwater extractions influence river basin water resources. Water scarcity, governance, and the effects of climate change are just a few of the other global water management issues discussed in this chapter. In light of these, comprehending the dynamics of water availability and demand is crucial for implementing sustainable management practices that balance environmental health with human water requirements.

2.1. Water Demand and Supply Modelling

The water demand is affected by many factors, including population growth, economic activities, and climate conditions. As cities expand, the pressure on water supply systems increases, making it essential to predict demand accurately to ensure efficient water use. Studies show that population growth has a major impact on water demand, making accurate population forecasts important for future water planning (Hiben et al., 2024; Zhou et al., 2023). In addition, industrial and economic activities also influence water use, highlighting the need for models that consider both economic and demographic factors (Zhou et al., 2023; Ren et al., 2022).

Water demand forecasting models can be grouped into two main types: traditional statistical models and modern artificial intelligence (AI) methods**.** Traditional methods, such as regression analysis and time series forecasting, have been used for many years. These models use past data to predict future water demand based on observed trends (Yang et al., 2024; Wu et al., 2020). For example, the autoregressive integrated moving average (ARIMA) model is a common approach that analyses past water usage to predict future trends (Li et al., 2021). However, these models often struggle to capture complex water demand patterns, particularly in rapidly changing environments.

In contrast, AI-based models, including machine learning and deep learning methods, are becoming more popular due to their ability to handle large datasets and detect complex patterns that traditional models may miss. Techniques such as artificial neural networks (ANNs) and long short-term memory (LSTM) networks have shown better accuracy in forecasting water demand by identifying non-linear patterns and time-related changes in data (Wang et al., 2023; Xu, 2024; Kühnert et al., 2021). For example, a study using LSTM networks successfully predicted urban water demand with high accuracy, demonstrating the effectiveness of AI models in improving forecast reliability (Kühnert et al., 2021; Drogkoula et al., 2023). Additionally, ensemble models, which combine multiple forecasting methods, have been found to improve prediction accuracy by reducing errors (Papacharalampous & Langousis, 2022; Xenochristou & Kapelan, 2020).

It is also important to consider environmental factors in water demand forecasting. Climate change affects water resources by changing rainfall patterns and increasing extreme weather events. Forecasting models that include temperature, rainfall, and other climate variables provide more reliable predictions by accounting for these external influences (Zhou et al., 2023; Vonk et al., 2019). For example, research has found that including climate data in demand forecasts significantly improves accuracy, especially in areas affected by climate change (Stelzl & Fuchs-Hanusch, 2023).

Recent advances in data analytics and real-time monitoring have also transformed water demand forecasting. Technologies such as big data analytics, smart meters, and the Internet of Things (IoT) allow for real-time data collection and analysis, leading to more accurate and timely predictions (Wawrzosek et al., 2021; Geelen et al., 2021; Boudhaouia & Wira, 2021). With real-time data, water supply companies can adjust their operations and respond quickly to changes in demand, making the system more efficient (Abu-Mahfouz et al., 2019).

Alongside demand forecasting, water supply modelling is equally important to ensure a balance between water availability and consumption. Supply modelling involves assessing current infrastructure, identifying water sources, and testing different scenarios to find the best management strategies. The Water Evaluation and Planning (WEAP) model is commonly used for this purpose, as it helps to analyse water supply systems under different conditions (Ren et al., 2022; Kulkarni & Varekar, 2024). By combining supply and demand models, water managers can make better decisions about resource allocation and future infrastructure projects.

Water demand and supply management is further complicated by social and economic factors**,** such as water pricing, government policies, and public participation**.** Effective water management requires not only technical solutions but also a strong understanding of social influences on water use. Studies have shown that involving local communities in water planning is important, as public awareness and behaviour play a key role in water conservation (Hiben et al., 2024; Younis et al., 2023). Policymakers must consider these social aspects when designing water management strategies to ensure they are practical and sustainable.

2.2. Challenges in predicting future water availability and consumption

One of the primary difficulties in forecasting water consumption is the ever-changing nature of influencing factors. Yang et al. (2022) emphasise the significance of considering geological context in water consumption predictions, particularly in karst regions, where geological formations can have a profound impact on water availability. Similarly, Jia and Zhang (2024) introduce a grey neural network model designed to capture the complexities and dynamic structures of water use, highlighting the necessity for innovative approaches that account for non-linear relationships within water consumption data. These studies underscore the importance of integrating multiple influencing factors into predictive models to enhance their reliability.

Moreover, climate change presents a substantial challenge to water availability, further complicating forecasting efforts. Fiorillo et al. (2021) discuss how climate variability contributes to fluctuations in water demand, necessitating adaptive management strategies to mitigate the risks associated with supply failures. Supporting this view, Karamaziotis et al. (2020) indicate that effective water consumption forecasting must incorporate both univariate and multivariate influences, including climatic variables. This underscores the necessity of developing models that can dynamically respond to evolving environmental conditions.

In urban areas, rapid population growth and urbanisation further complicate the prediction of water demand. Rees et al. (2020) developed a household typology that integrates property type and size with demographic factors to improve water demand forecasting in London and the Thames Valley. This approach highlights the crucial role of demographic data in refining water consumption predictions. Furthermore, Yousefi et al. (2020) emphasise the importance of accurately simulating hydraulic conditions in urban water distribution systems to ensure that future consumption needs are met. The integration of demographic and hydraulic data into predictive models is vital for sustainable urban water management.

Machine learning techniques have emerged as valuable tools for improving the accuracy of water demand forecasts. The ensemble stacked model developed by Xenochristou and Kapelan (2020) demonstrates how bias correction can enhance forecasting outcomes, showcasing the potential of advanced computational methods in tackling the complexities of water demand prediction. Likewise, the study by Niyongabo et al. (2024) illustrates the increasing use of artificial intelligence techniques for short-term water demand forecasting, a critical aspect of urban water distribution management. These advancements in computational methodologies are instrumental in the development of more accurate and responsive water management strategies.

The temporal nature of water demand forecasting also presents challenges, as different forecasting periods necessitate distinct methodologies. Li et al. (2020) stress the need for adaptable models capable of making predictions across various time scales, from hourly to daily, to meet the specific demands of water utilities. This adaptability is essential to ensure that water supply systems can effectively respond to fluctuations in demand. Additionally, Boudhaouia and Wira (2021) demonstrate how real-time data analysis platforms can facilitate short-term forecasting, thereby improving the operational efficiency of water management systems. The ability to process and analyse data in real time is increasingly critical in managing dynamic urban environments.

Another key challenge in water demand forecasting is the inherent uncertainty associated with future projections. Nawaz et al. (2019) highlight the importance of incorporating uncertainty into demographic and water demand forecasts, suggesting that prediction intervals can provide valuable insights for decision-making. This approach is particularly beneficial for water resource planning, as it enables consideration of multiple scenarios and their potential effects on water availability. Moreover, Geelen et al. (2021) explore burst detection through nowcasting, emphasising the role of accurate forecasting in optimising network management and improving fault detection. Integrating uncertainty analysis into predictive models is therefore crucial in developing robust water management strategies.

The socio-economic context also plays a significant role in shaping water consumption patterns. Economic factors, such as income levels and household characteristics, have been shown to strongly influence water usage (Dias & Ghisi, 2024). For instance, the research conducted by Tuyor and Salapa (2023) on commercial water consumption highlights variations in demand based on economic activities. A thorough understanding of these socio-economic dynamics is essential for devising targeted water management policies that address the specific needs of diverse communities.

2.3. Socio-economic drivers of water demand

Population growth and urbanisation are key drivers of increasing water demand. As urban populations expand, the demand for water rises correspondingly, placing greater pressure on existing water resources. Zhou et al. (2023) highlight the influence of economic development and technological advancements on water use patterns, suggesting that urban areas may experience peaks in water consumption as they grow. The rapid urbanisation in many developing nations often exacerbates this challenge, necessitating innovative management strategies to ensure a sustainable water supply. Oskam et al. (2021) further illustrate how socio-economic inequalities in access to drinking water can intensify these issues, particularly in informal settlements where infrastructure is inadequate.

Agricultural practices represent another significant socioeconomic factor influencing water demand. In many regions, agriculture remains the largest consumer of water resources. Stefanova et al. (2019) argue that socio-economic scenarios substantially impact water resource management in agricultural catchments, with irrigation practices directly affecting water availability. The efficiency of water use in agriculture is closely tied to socio-economic elements such as farmers' education levels, access to technology, and financial resources. Bhatia and Singh (2024) stress the importance of community-based water management programmes in improving water use efficiency in agricultural settings. These initiatives empower local farmers to adopt sustainable practices that optimise water consumption while maintaining productivity.

Governance structures and policies also play a crucial role in determining water demand. Effective water governance facilitates improved management of resources, ensuring that supply aligns with demand. Zhou et al. (2023) argue that coordinated governance approaches that integrate economic development and technological innovation are essential for sustainable water resource management. Similarly, Hejduková and Kureková (2020) highlight that socio-economic factors significantly influence public perceptions of water scarcity and conservation efforts. Their research underscores the need for policies that address these perceptions to encourage sustainable water use.

The relationship between socioeconomic factors and water demand is highly complex. For instance, as urban areas continue to expand, the demand for water increases, often leading to excessive water extraction and environmental degradation. This trend is particularly evident in regions experiencing socio-economic drought, where water supply fails to meet rising demand, resulting in negative societal and economic impacts. Zhao et al. (2019) emphasise that socio-economic droughts are becoming increasingly prevalent as industrial growth and population expansion intensify water consumption, necessitating urgent action to address these challenges.

Technological advancements can also influence water demand by enhancing efficiency in water use. For example, the adoption of water-saving technologies in agriculture has the potential to significantly reduce water consumption while maintaining crop yields. However, the uptake of such technologies is often constrained by socioeconomic factors, including farmers’ income levels and access to financial resources. Yazdanpanah et al. (2022) assert that economic incentives alone may not suffice in encouraging the adoption of water-saving technologies among farmers, as broader socioeconomic conditions play a decisive role.

2.4. Climate change impacts on water availability

One of the most obvious effects of climate change on water resources is the change in rainfall patterns. Maiolo et al. (2017) explain that both the amount of rain and when it falls during the year can greatly affect the balance of surface water and the total amount of water available. Olabanji et al. (2020) support this, showing that less rainfall, combined with a growing population and economy, could cause water shortages in the Olifants catchment in South Africa. These findings stress the need for new strategies to manage water in a changing climate.

To predict future water availability, scientists are now combining climate, hydrology, and water management models. Shao et al. (2023) show that these models can help understand how climate change affects surface water at the basin level by using climate scenarios from the Coupled Model Intercomparison Project Phase 6 (CMIP6). This combined approach helps in planning and managing water more effectively.

The Middle East, especially the Tigris-Euphrates river basin, is already facing serious water shortages due to climate change. Taheripour et al. (2024) discuss how higher temperatures, less rainfall, more irrigation, and conflicts over shared water make the problem worse in this dry region. This situation highlights the importance of cooperation between countries and better water management strategies to deal with climate change.

Climate change not only affects water itself but also has serious social and economic consequences. Graham et al. (2020) explain that as societies and economies change over time, the impacts of water scarcity will also shift. This shows that managing water resources must consider both environmental and economic factors.

In farming areas, the effects of climate change on water supply are even more serious. Emami and Koch (2019) studied the Zarrine River Basin in Iran and found that water levels will drop, making adaptation plans necessary. Samimi et al. (2022) also highlight how future water availability is uncertain in the Middle Rio Grande Basin and stress the need to consider upstream water use when predicting water shortages. These studies show that farmers and water managers must change their strategies to use water more efficiently.

Climate change does not affect all areas in the same way. Khôi et al. (2021) examined the upper Dong Nai River Basin in Vietnam and found that the impacts will vary depending on population growth and economic development. This means that each region needs its own plan to deal with water shortages.

In many places, climate change will worsen existing water problems. Graham et al. (2018) pointed out that different Shared Socioeconomic Pathways (SSPs), which predict future economic and social conditions, can lead to big differences in future water demand. This shows why water policies must consider social and economic changes, not just the physical changes in climate.

Scientists use hydrological models to study how climate change affects water resources. Ray et al. (2023) review the latest developments in these models and highlight that water systems are very sensitive to climate changes. These models are important tools for predicting future water shortages and helping governments and communities plan for sustainable water use.

2.5. Modelling Approaches for Water Demand and Supply

2.5.1. Soil and Water Assessment Tool (SWAT) and Water Evaluation and Planning (WEAP) model.

The Soil and Water Assessment Tool (SWAT) and the Water Evaluation and Planning (WEAP) model are two widely used tools for managing water resources and assessing environmental changes. SWAT is a hydrological model created by the U.S. Department of Agriculture (USDA). It helps predict how land management practices affect water flow, soil erosion, and chemical movement in large watersheds (Saraf & Regulwar, 2024; Basu et al., 2022). The model divides a watershed into smaller sections, called Hydrological Response Units (HRUs), based on land use, soil type, and slope (Saraf & Regulwar, 2024). This division allows for a more detailed analysis of water movement and variations across the watershed. SWAT has been widely used to simulate river flow, sediment movement, and nutrient pollution, making it an important tool for water management (Saraf & Regulwar, 2024; Basu et al., 2022; Saade et al., 2021).

One of SWAT's main strengths is its ability to use various types of data, such as climate, land use, soil properties, and topography, to predict water flow under different conditions (Choudhary et al., 2023). Research has shown that SWAT can assess the impact of land use changes on water quantity and quality in different regions, including agricultural areas in the United States and tropical regions (Saraf & Regulwar, 2024; Basu et al., 2022; Saade et al., 2021). Additionally, the model has been used to study how climate change affects water systems, helping with long-term planning and management (Saade et al., 2021).

In comparison, WEAP is a water resource planning model that focuses on balancing water supply and demand at different scales, from local to regional levels (Choudhary et al., 2023). Unlike SWAT, WEAP combines hydrological data with socio-economic factors, allowing users to study how different management strategies affect water availability and quality. The model considers the needs of various water users, such as agriculture, industry, and households—to simulate how water is allocated (Saraf & Regulwar, 2024; Basu et al., 2022). Because of its flexibility and easy-to-use interface, WEAP is a popular tool for policymakers and water managers.

SWAT and WEAP can be used together to get a full picture of water availability and demand. SWAT provides detailed hydrological simulations, while WEAP models water allocation and policy impacts (Saraf & Regulwar, 2024; Basu et al., 2022). This combination is useful in areas facing serious water shortages due to climate change, population growth, and increasing water demand. Both models have helped tackle major water management challenges. For example, SWAT has been used to predict how climate change affects rainfall and river flow (Saraf & Regulwar, 2024; Basu et al., 2022). Meanwhile, WEAP has been applied to study the effects of changing climate on water supply and demand, helping decision-makers develop better management plans (Saraf & Regulwar, 2024; Basu et al., 2022).

2.5.2. System dynamics modelling

One key advantage of System Dynamics Modelling (SDM) is that it helps to understand how changes in water use affect the system over time. For example, as populations grow and economies develop, the demand for water increases. This can put pressure on water resources, leading to shortages. In response, governments may introduce policies or invest in new technologies to use water more efficiently (Shahsavari-Pour et al., 2023; Deng et al., 2023). By including social and economic factors in water management models, SDM can help predict future challenges and find better ways to manage water (Leão et al., 2019; Wilson et al., 2017).

Recent research has shown that SDM can be used in different parts of the world to solve water problems. In Chengdu, China, SDM was used to balance water supply and demand, showing how economic growth affects water use (Yu et al., 2022). In Rafsanjan City, Iran, SDM helped to predict water shortages, showing that social and economic factors play a big role in how water is used (Shahsavari-Pour et al., 2023).SDM is even more powerful when combined with other models, such as the Soil and Water Assessment Tool (SWAT) and MODFLOW, which help analyse water flow and quality. For example, in Nanchang City, China, SDM was used to study the link between water resources, economic factors, and environmental sustainability (Deng et al., 2023). This type of approach provides a full picture of how water systems work and helps authorities make better decisions. SDM is also useful in rural areas, where water demand is growing due to farming and industrial activities. In the Tarim River Basin from China, SDM was used to study how the local water system responds to rising demand. The results showed that SDM can be adapted to different regions and challenges (Pang et al., 2022).

The use of Artificial Intelligence (AI) and Machine Learning (ML) has improved SDM’s ability to predict water needs. These technologies can analyse past water use and find patterns to make more accurate forecasts (Shu et al., 2024; Li et al., 2021). This is especially useful for managing water supplies in a changing climate, where rainfall patterns and water availability are becoming less predictable.

2.5.3. Agent-based modelling

One of the main benefits of Agent-Based Modelling (ABM) is that it can show the differences between individuals in a system. For example, Mariano and Alves (2020) used ABM to study how different groups work together in managing water in peri-urban areas. Their research showed that ABM can represent different people with unique behaviours and interactions. This helps us understand how individual actions affect the overall water management system. Similarly, Shoushtarian et al. (2022) used ABM to study how farmers decide to reuse water. Their findings show how different incentives can change water demand and supply over time. By simulating how different people use water, ABM can help create strategies for sustainable water use**.**

Including socio-economic factors in ABM is important for making water management models more accurate. For example, Khan et al. (2017) created a model that combines social and economic factors to help manage watersheds in areas shared by multiple countries. This model shows how people's financial situations and other factors influence their water use decisions, making it more relevant to real-world situations. Similarly, Nouri et al. (2019) used ABM to study how different farming methods and policies affect water use in agriculture. Their research highlights why it is important to include economic and social factors when planning how to manage water resources.

ABM is also useful for testing the effects of water management policies. For example, Xiao et al. (2018) used ABM to explore different ways of managing water demand. Their research helps us understand how different rules and policies might affect water use. Likewise, Huber et al. (2019) used ABM to model how climate change and competition between water users impact water supplies. Their study is especially important as water shortages become more common and new ways to manage water are needed.

Combining ABM with other modelling methods can make it even more effective. For example, Farjad et al. (2017) combined ABM with system dynamics modelling to study how land use, climate, and water resources interact. This hybrid approach helps us understand how these different factors are connected. Additionally, Wang et al. (2018) used ABM to simulate how water trading systems work. Their research shows how water can be shared fairly among different users through market-based approaches.

ABM is not just useful for managing water in farms and cities; it can also help us understand how climate change affects water supplies. For example, Ali et al. (2017) developed an ABM to study how changes in climate and population growth affect urban water supplies. This helps planners prepare for future changes in water availability. Similarly, Hyun et al. (2019) used ABM to study how people’s perception of risk affects their decisions about water use. Their research highlights why it is important to understand human behaviour when planning for climate change.

ABM can also help involve different groups in decision-making about water use. For example, Mirzaei and Azarm (2022) used ABM to study how farmers take part in water-saving programs and how they respond to different payment policies. By modelling the interactions between different groups, ABM can help identify potential conflicts and areas where people can work together. This makes it easier to create fair and effective water management plans that everyone can support.

2.5.4. Statistical and Machine Learning Approaches

Time series analysis is a common statistical method used to study water demand data over time. It breaks down past data into different parts, such as trend, seasonality, and random noise, helping to find patterns that can predict future water use. One well-known method is the Autoregressive Integrated Moving Average (ARIMA) model, which is effective in identifying time-based patterns in water consumption (Huntra & Keener, 2017). Some researchers have improved ARIMA by adding extra factors like temperature and rainfall, creating the ARIMAX model, which provides more accurate water demand forecasts (Huntra & Keener, 2017).

Machine learning is becoming more popular because it can handle complex and unpredictable changes in water demand. Models such as Long Short-Term Memory (LSTM) networks and Convolutional Neural Networks (CNNs) have been used to predict urban water demand by learning from past water usage patterns and external factors (Zhou et al., 2022). A study combining CNNs with LSTM networks showed that this approach can predict daily water demand more accurately than traditional statistical methods (Zhou et al., 2022). This proves that AI-driven forecasting can improve water management strategies.

Machine learning is not only useful for urban areas but also for industrial water demand. For example, case-based reasoning has been used to predict industrial water usage, showing that AI methods can work in different sectors (Yang et al., 2017). Other studies have explored ensemble methods, where different models are combined to increase accuracy, showing a move towards more advanced forecasting techniques in water resource management (Wang et al., 2018).

The combination of AI and time series analysis helps create stronger forecasting models. Studies show that mixing statistical models with machine learning methods, such as Support Vector Machines (SVMs) and Artificial Neural Networks (ANNs), improves the accuracy of water demand predictions (Wang et al., 2018). These models are useful for handling sudden changes in water use caused by factors like economic shifts or climate change (Chan & Chin, 2019).

AI also helps identify key factors affecting water consumption. By analysing large amounts of data from smart meters, researchers can see how household size, income levels, and seasonal changes influence water demand (Cominola et al., 2019). This knowledge is useful for designing water conservation policies that target specific usage patterns. Despite its benefits, water demand forecasting faces challenges like data shortages and sudden changes in water use. As researchers, real-time data and adaptive models that adjust to changing conditions are needed (Seyedan & Mafakheri, 2020). One example is the development of dynamic pricing models, where water prices change based on demand predictions to encourage responsible water use (Rougé et al., 2018).

2.6. Factors Influencing Water Demand and Supply

2.6.1. Climatic Factors

Precipitation is a key part of the water cycle, affecting both surface water and groundwater. Changes in rainfall patterns due to climate change can cause more extreme weather, with some areas getting heavy rain and floods, while others suffer long droughts. For example, Kong et al. (2023) explain that climate change affects the hydrological cycle by changing rainfall and temperature, which in turn influences water flow in rivers and streams. These changes can worsen water shortages, especially in places that already struggle with water supply.

Studies suggest that heavy rainfall events will become more frequent and intense due to climate change. Payus et al. (2020) state that rainfall, temperature, and soil moisture are major factors affecting water resources. Some areas may flood, while others may experience long dry periods, making water management more difficult. In dry regions, where people rely on steady rainfall for farming and daily use, these changes are especially concerning (Gramz et al., 2024). Changes in rainfall patterns also affect the timing of water supply. Jiang et al. (2018) point out that climate change can disrupt the seasonal distribution of rainfall, which is important for farming and water storage. If rainfall becomes less predictable, it becomes harder to plan water use, creating challenges for farmers and water managers.

Rising temperatures also have a major effect on the water cycle, particularly through evapotranspiration the process where water evaporates from land, plants, and water bodies. When temperatures rise, evaporation increases, reducing the amount of water available. Wu et al. (2024) explain that higher temperatures can lead to greater water loss, which affects water supplies in cities like Beijing-Tianjin-Hebei. This is a big problem because hotter temperatures also increase water demand, making shortages even worse.

The connection between temperature and rainfall is complex. More rainfall might seem like a good thing, but higher temperatures can cause more evaporation, cancelling out the benefits of extra water. Gramz et al. (2024) show that in dry areas, even a small temperature rise can significantly reduce water levels in rivers and lakes. This proves that both temperature and rainfall must be considered when looking at how climate change affects water resources. Changes in temperature also affect farming. As temperatures increase, crops need more water, leading to higher irrigation demand. Bhatti et al. (2021) stress that understanding how temperature changes affect crops is essential for managing water use in agriculture, especially in areas that rely on irrigation.

The combined impact of changing rainfall patterns and rising temperatures creates serious challenges for water management. Konapala et al. (2020) explain that climate change affects global water supply by altering seasonal rainfall and increasing evaporation. To manage water resources effectively, we need to consider both climate conditions and human activities. In areas where water scarcity is already a major issue, these climate changes can have severe consequences. Nistor et al. (2019) highlight how rainfall and temperature changes are making water shortages worse in Varanasi, India, causing serious problems for local communities. This shows why it is important to develop adaptation strategies that ensure sustainable water use despite the changing climate.

2.6.2. Socio-Economic Factors

Population growth and urbanisation are major factors behind the rising demand for water. As cities grow and more people move to urban areas, water use increases. Zhou et al. (2020) explain that rapid urbanisation in China has boosted economic growth and household incomes, leading to higher domestic water consumption. This trend is not limited to China—many developing countries experience similar patterns where urbanisation results in greater water use due to better living standards and improved water access.

Urbanisation also affects water distribution and management. Amin et al. (2018) highlight that Pakistan’s growing population has led to greater water demand for food production, while challenges such as sedimentation in water reservoirs and conflicts over water resources make management more difficult. This shows how urban growth can create complex challenges for water supply and governance. In addition, urban expansion changes land use, which impacts water availability. Teutschbein et al. (2023) state that as cities grow, the competition for water increases, affecting the water-energy-food-ecosystem (WEFE) balance. The conversion of natural land into urban areas can disrupt the local water cycle, reducing groundwater recharge and changing river flows.

The industrial and agricultural sectors are the largest consumers of water, and their water use depends on economic and social factors. Shu et al. (2024) stress the importance of long-term water demand forecasting for industrial and agricultural use, especially in regions like the Tuojiang River basin in China. Economic growth, new technology, and changing consumption habits drive higher water demand in these sectors.

Agriculture is the biggest user of freshwater worldwide. Xue et al. (2017) explain that human activities, such as irrigation and dam building, can change river flows, affecting water availability for both farming and industry. This can cause conflicts over water, especially in areas already facing water shortages.

The economic value of water in industry also leads to higher demand. Telfah et al. (2018) note that rapid population growth and economic development put more pressure on water resources to meet domestic, agricultural, and industrial needs. To avoid water crises, effective management strategies and sustainable policies are needed to balance different water demands.

Good policies and governance are key to managing water resources in a sustainable way. Leão et al. (2019) discuss how water use will change in the future as people adapt to climate change and economic growth. They emphasise the need for policies that consider both social and environmental factors. Governments also need to address the social and economic factors that shape water demand. Zhu et al. (2023) show that urban growth and economic activity can cause water shortages and pollution problems. This highlights the importance of integrated water management that promotes both sustainability and development. Moreover, tackling water shortages requires cooperation between different groups. Minh et al. (2023) explain that groundwater quality and recharge rates depend on water demand and management practices. Using collaborative governance—where governments, local communities, and businesses work together can improve water management and help societies adapt to climate change.

2.6.3. Environmental and Ecological Factors

River basins are defined by their hydrological, geological, and ecological features, which influence their behaviour and response to both climatic and human-induced changes. Ban and Lettenmaier (2022) studied how river basins in the Western United States respond to seasonal climate warming, showing that factors such as topography and land cover play a key role in streamflow variations. Similarly, Saydi et al. (2020) found that climatic factors were the main controls on runoff in the glacier-fed Urumqi River Basin, highlighting the importance of understanding local climate influences on hydrological processes.

The morphometric characteristics of river basins, such as drainage density, basin shape, and landforms, are crucial in determining hydrological responses. Kumar et al. (2019) emphasise the role of morphometric analysis in understanding how basins react to climate change and hydrological alterations. Additionally, land use distribution within a basin can significantly affect hydrological behaviour. Liang et al. (2021) found that fragmentation of cultivated land in the Huaihe River Basin impacts water management practices, showing the influence of land use changes on hydrological dynamics.

Groundwater recharge and depletion are key components of the hydrological cycle, especially in regions with limited surface water. Groundwater is an essential resource for agriculture, industry, and domestic use, making sustainable management vital. Mao et al. (2021) examined groundwater recharge in the Poyang Lake Basin, demonstrating how stable isotopes can provide insights into recharge processes and reveal the impact of climate variability on groundwater levels. The relationship between groundwater and surface water is complex, influenced by land use changes and climatic conditions. Urbanisation can lead to more impervious surfaces, reducing groundwater recharge and increasing surface runoff (Khaleghi, 2017). This highlights the need for integrated water resource management, which considers both groundwater and surface water interactions. Groundwater depletion is a growing issue, particularly in arid and semi-arid regions, where water demand exceeds natural recharge rates. Pang et al. (2022) examined the Tarim River Basin in China, where agricultural irrigation is causing severe groundwater depletion. This over-extraction threatens water availability and contributes to wetland degradation and biodiversity loss.

Land use changes, driven by urbanisation, agriculture, and industrial activities, have a significant impact on hydrological processes within river basins. Urban expansion increases impervious surfaces, leading to higher runoff and lower groundwater recharge. Tian et al. (2019) investigated land use changes in the Yongjiang River Basin, showing that they contribute to ecological risks and affect water quality and availability. Changes in land use can also alter how river basins respond to rainfall. Imran et al. (2024) found that land use variations influence runoff accumulation in the Hulu River Basin, demonstrating the need for effective land management strategies to maintain hydrological balance. The relationship between land use and hydrology is further complicated by climate change, which can worsen the effects of land use changes on water resources. Wu et al. (2018) showed that shifts in precipitation patterns and rising temperatures alter runoff timing and magnitude, affecting water availability in river basins. This underscores the need for a comprehensive approach that considers both land use changes and climatic factors to ensure sustainable water management.

2.7. Developing and Evaluating Future Water Management Scenarios

One of the significant approaches to managing water resources is the integration of socio-hydrological models that allow for the exploration of various management scenarios. Li et al. 2019 developed an urban socio-hydrologic model for Beijing, which explores the sustainability challenges and potential solutions for urban water management. This model emphasizes the importance of understanding human behaviour in response to perceived water shortages, suggesting that historical data can inform future management strategies. By simulating different management measures, the model provides insights into how urban water demand can be effectively managed while ensuring sustainable supply. In Sub-Saharan Africa, Macharia et al. (2021) highlight the potential for joint energy and water management approaches to conserve resources. Their study outlines six levels of cost and complexity in implementing strategies that not only save water but also reduce the energy costs associated with water supply. This dual focus on energy and water efficiency is essential in regions where both resources are scarce, demonstrating that integrated management can lead to significant savings and improved sustainability. The operation of agricultural reservoirs is another critical area where future scenario management can enhance water supply. Lee and Shin, (2022) propose a strategy for regulating reservoir operations based on water levels, which promotes water supply when storage is adequate and limits it during shortages. This adaptive management approach allows for a more responsive strategy that can adjust to changing climatic conditions and water availability, ultimately leading to more efficient water use in agricultural practices. Deficit irrigation is a management strategy that has gained traction in water-scarce regions. Trout and Manning, (2019) discuss how deficit irrigation can maximize water productivity by adjusting irrigation levels based on crop needs and available water. This strategy not only conserves water but also enhances crop yields per unit of water used, making it a viable option for sustainable agricultural practices in arid regions. The use of multi-source water supply systems is another innovative approach to managing water resources. Zhang et al. (2019) emphasize the importance of inter-basin water transfers, which can provide additional water sources during low-flow years. By diversifying water supply sources, these systems can effectively reduce the risks associated with water shortages and enhance overall water security. Moreover, the integration of smart technologies (IoT) in water management systems has shown promise in improving efficiency and responsiveness. Gonçalves et al. (2020) propose an IoT-based framework for smart water supply management, which allows for real-time monitoring and management of water resources. This technological advancement enables water managers to respond quickly to changes in demand and supply, optimizing resource allocation and reducing waste. In urban settings, the implementation of decentralized water supply systems has been recognized as a critical strategy for enhancing water management. Cole et al. (2022) discuss how decentralized systems can complement centralized approaches, providing flexibility and resilience in urban water management. This dual strategy allows cities to better manage water resources, particularly in the face of climate change and population growth.

The role of policy and governance in water management cannot be overstated. Effective governance frameworks are essential for implementing sustainable water management strategies. For instance, Townsend et al. (2020) highlight the importance of integrating centralized and decentralized governance mechanisms to achieve water sustainability objectives. This integrated approach ensures that all stakeholders are involved in decision-making processes, leading to more equitable and effective water management outcomes. Furthermore, the assessment of water supply systems under the impact of climate change is crucial for future planning. Bhatkoti et al. (2019) conducted a performance assessment of water supply systems in the Washington Metropolitan Area, identifying vulnerabilities and adaptation strategies to mitigate the impacts of climate change and droughts. Their findings underscore the need for comprehensive modelling and simulation approaches to develop effective water management strategies that can withstand future uncertainties.

2.8. Challenges and Limitations in Water Demand and Supply Modelling

The accuracy of water resource predictions depends on good-quality data. Shao et al. (2023) explain that combining climate, water, and management models helps estimate future water availability, especially as the climate changes. However, these models often lack enough data, especially in dry areas where water shortages are more serious. Changes in rainfall patterns and glacier melting make water predictions uncertain. Vinca et al. (2020) show that errors in climate data affect water forecasts, especially in shared river basins like the Indus. Collecting data is even harder in remote or politically sensitive areas, where reliable information is difficult to get.

He et al. (2021) warns that using old or incomplete data can lead to wrong conclusions about water shortages in cities. This shows why it is important to keep collecting new data to make water resource predictions more trustworthy. Growing populations and cities increase water demand, making data even more important. Ochola (2018) explains that more people in Kenya have put pressure on natural water sources, showing the need for detailed data to manage water properly. Without accurate and up-to-date data, governments may find it hard to plan water use fairly. Another challenge is choosing the right method to study water resources. Taye et al. (2018) highlight the need to pick the best climate models to predict how climate change will affect water supplies. Different models can give different results, so it is important to carefully select the best approach.

2.8.1. Model Accuracy and Validation Challenges

It is important to check that water models are accurate because these models help manage water supplies as the climate changes and demand grows. However, making models highly accurate is very difficult.

A major issue is that climate predictions are uncertain. Gumbo and Kapangaziwiri (2021) explain that climate change reduces water supply, making it harder to check if models correctly predict these changes. Differences in rainfall and temperature data can cause errors, so models need regular updates to stay accurate.

Another challenge is that water systems are complex. Jiao et al. (2021) show that water shortages over the last 30 years have affected plant growth. To be accurate, models must include how climate, water, and nature interact. If they miss these connections, they may predict water availability incorrectly, leading to poor management decisions.

Checking if models work well is also hard due to limited data. Olabanji et al. (2020) say that not enough records on river flow and water quality make it difficult to test whether models give correct predictions. This is a big problem in developing countries, where monitoring systems are weak.

Finally, adding social and economic factors makes models even more complex. Kanyako et al. (2023) explain that growing populations and economies make water shortages worse. If models do not include these real-world changes, they may fail to give useful predictions, making it harder to plan for the future.

2.9. Future Research Directions and Policy Implications

2.9.1. Need for interdisciplinary approaches

Managing water resources is complex because it involves many different factors. It connects with various fields such as environmental science, economics, sociology, and engineering. Eltigani et al. (2024) explain that using Integrated Water Resource Management (IWRM) has led to major changes in water management. They highlight the need to combine knowledge from different areas to achieve water management goals successfully. By integrating expertise from multiple disciplines, policymakers can better understand what affects water supply and demand and create more effective strategies.

Water management also plays a key role in protecting the environment, making collaboration between different fields essential. Kalogiannidis et al. (2023) found that effective water management strategies can help conserve the environment. Their study shows that using ecosystem-based approaches and monitoring water quality can improve sustainability. Including ecological perspectives in water planning helps address environmental concerns while ensuring efficient use of resources.

Climate change makes water management even more difficult, meaning adaptive strategies are necessary. Zhao and Boll (2022) argue that a combination of different approaches is needed to manage water supply and demand in response to climate change. Interdisciplinary methods bring together climate science, hydrology, and socio-economic insights, allowing for a stronger response to climate-related challenges. In dry regions where water is scarce, integrated management is even more important. Çadraku et al. (2024) emphasise that IWRM is essential in such areas, where water supply options are limited and require cooperation between different sectors. This includes working together in agriculture, urban planning, and environmental conservation to manage water resources fairly and sustainably.

Flexible and adaptable governance is another key factor in successful water management. Sismani et al. (2024) suggest that adaptive governance, which encourages learning and flexibility, helps handle the uncertainties and complexities of water systems. Cooperation among governments, NGOs, and local communities can improve knowledge-sharing and resource management, leading to better outcomes.

Good management skills are also essential in water resource planning. Zolfaghari et al. (2024) highlight that aligning business management skills with environmental goals is necessary for effective water governance. This means business leaders, environmental experts, and policymakers must work together to balance economic and environmental priorities.

Technology is also transforming water management. Šulyová and Kubina (2022) discuss how smart city technologies can be used alongside IWRM to improve urban water use. Tools like data analytics and remote sensing help experts understand water systems better and make informed decisions on resource allocation and conservation.

Community involvement is another key factor in successful water management. Aquino et al. (2023) stress the importance of including local communities in IWRM planning and decision-making. When communities are actively involved, water initiatives become more effective and sustainable. Local people can also share traditional knowledge that may improve water management practices.

It is also important to consider gender when managing water resources. Mphila et al. (2021) found that involving both men and women in water planning leads to better decisions and social benefits. Gender-inclusive approaches require collaboration between social scientists, gender experts, and water managers to make sure everyone’s needs are met. Managing water resources across national borders requires cooperation between different fields. Kidane and Andarge (2021) highlight the importance of collaboration in shared water systems. They argue that bringing together knowledge from political science, international relations, and environmental studies can help countries manage water fairly and sustainably.

2.9.2. Policy recommendation for sustainable water management

One of the key recommendations for better water management is using advanced techniques to predict water demand. Accurate forecasting helps plan for future water needs and ensures enough supply. Recent studies show that artificial intelligence (AI) models, like Long Short-Term Memory (LSTM) networks, can predict water demand with high accuracy (Shu et al., 2024; Wang et al., 2023). By adopting these advanced forecasting methods, policymakers can better match water supply with demand, reducing waste and improving resource allocation.

Another important strategy is using real-time monitoring systems to improve water distribution. Research shows that real-time hydraulic models help reduce water loss and make distribution more efficient (Abu-Mahfouz et al., 2019). These technologies allow water suppliers to quickly respond to demand changes and detect leaks, cutting operational costs and improving service. Governments should invest in smart water management technologies that use real-time data to improve efficiency.

Besides technology, economic measures like water pricing can help manage demand. Water pricing encourages people to use water wisely and reduces waste (Alamanos, 2021). Studies show that well-designed pricing policies can significantly lower water consumption, especially in cities where demand is growing fast (Nawaz et al., 2019). Policymakers could introduce tiered pricing, where higher usage leads to higher costs, to promote conservation.

Reusing and recycling water is another crucial approach for sustainable water use. Research highlights that treating and reusing wastewater can help conserve freshwater, especially in areas with limited water supply (Sarraf & Deswal, 2023; Zanfei et al., 2023). Governments should support wastewater treatment facilities and introduce rules that allow treated water to be used in farming and industry. This would not only save freshwater but also support a circular economy. Public awareness and education also play a vital role in water conservation. Campaigns can encourage people and businesses to adopt water-saving habits. Studies show that involving communities in water management decisions leads to better and more sustainable outcomes (Younis et al., 2023; Oyebode et al., 2019). Governments should promote public participation in water management to ensure that local communities have a say in decision-making.

Climate change is another major challenge affecting water supply. Governments must consider climate resilience in their water management plans, as changing rainfall patterns and rising temperatures will impact water availability (Hiben et al., 2024; Zhou et al., 2023). This can be done by developing flexible management plans that adapt to climate changes. Additionally, including climate data in water demand forecasts can improve prediction accuracy and help in planning (Stelzl & Fuchs-Hanusch, 2023; Kühnert et al., 2021).

Integrated Water Resource Management (IWRM) is also essential. This approach ensures that water, land, and other resources are managed together to maximise economic and social benefits while protecting ecosystems (Bunney et al., 2021; Carvalho et al., 2019). Policymakers should create policies that encourage cooperation between different sectors and stakeholders to ensure a balanced and sustainable approach to water management.

Investment in research and development is also necessary for improving water management. Governments should fund studies that explore new technologies and methods for predicting, distributing, and conserving water (Zhou et al., 2022; Mumbi et al., 2021). Collaboration between universities, government agencies, and private companies can help develop innovative solutions for water shortages and improve water supply resilience.

Lastly, strong laws and policies are needed to support sustainable water management. Governments must introduce and enforce regulations that encourage water conservation, protect water quality, and ensure fair access to resources. This includes setting water efficiency standards, preventing pollution, and ensuring that all communities, including disadvantaged ones, have reliable access to clean water (Ren et al., 2022; Gheyas et al., 2022). A strong legal framework will promote responsible water use and help protect resources for future generations.

2.10. Chapter summary

In catchments that are increasingly under stress from environmental degradation, population increase, and climate change, modelling water supply and demand is essential to creating successful management scenarios. The effectiveness of water resource management requires a multifaceted approach that integrates policy considerations, institutional frameworks, and scenario modelling. The interplay between these elements is crucial for developing sustainable water management strategies that can adapt to the complexities of climate change and socio-economic pressures. Methods like hydrological modelling, scenario planning, and IWRM offer useful frameworks for comprehending intricate water systems. To guarantee sustainable water resource management in a variety of situations, future research should concentrate on improving data quality, controlling uncertainties, and encouraging stakeholder participation.

Chapter 3: RESEAECH METHODOLOGY

3.1. Introduction

This chapter describes the methodology used to accomplish the study's goal, specifically the set up and use of the Water Evaluation and Planning (WEAP) model framework. The research design, study region, data collection method, calibration and validation, and data analysis methods used are further discussed in this section. A chronological explanation of the methodological events is given down below. This methodology not only offers a quantitative assessment of water availability and distribution, but it also aids in decision-making by visualizing potential future challenges and risk-reduction strategies.

3.2. The study location

The study was carried out on the Mokolo River catchment area, which is located at 23-24^{0}S, 27-28^{0}E (Figure 3.1.) of the Limpopo province of South Africa. The Waterberg's region is the source of the river basin and its tributaries, which rise between 1200 and 1600 meters above sea level (DWS, 2013). The Waterberg district is under the management of the Limpopo water management area (LWMA) and the Crocodile and Marico water management area (Dama-Fakir, 2021).

The Mokolo River is one of the six major catchment areas that form part of the Limpopo management areas, and it is one of the largest water resources in the Limpopo province as it measures up to 8 395km^2 (DWAF, 1996). The total length of the Mokolo River is 66.47 km and it slopes from South to North (Udall, 2018) as most rivers in the district drain towards the northwest direction of the Limpopo basin (Kgabi, 2020). Since the Mokolo catchment is in the south-east area, it receives more rainfall than any other area in the Waterberg (DWS, 2016).

Most rainfall in the Mokolo River is experienced in the summer, meanwhile a little amount of rain is received in winter seasons. The annual rainfall patterns of Mokolo Catchment vary from 400 to 700 mm (DWA, 2010). The flow of the river starts from Alma town and flows for 1.5 km, until the rivers' flow meets the Sand River and the Grootspruit (Maeko, 2020). The river then continues to flow downstream towards the Vaalwater town until it reaches the Mokolo dam. Water is captured into the Mokolo dam before the river continues to flow downstream. The Mokolo River provides less water to downstream consumers because of an excessive demand for water from the

Mokolo Dam (Seaman et al., 2013). There are approximately 61,882 people living in the Mokolo River catchment area (StatsSA, 2011). There are five settlements around the Mokolo River, the two largest being Lephalale and Marapong, with a combined population of 12,376. The Mokolo reservoir serves as the primary source of water supply for industrial, agricultural, domestic, mining, hydropower generation and game farms (Dintsi, 2022). However, the major user of water from the Mokolo dam is the irrigation sector, which uses about 61% of the water, which excludes water from small farm dams, weirs, and run-off river abstractions (Munnik, 2020). The dam can supply most of the existing needs, but in the future, it will need to receive transfers from other WMAs in order to meet the water demands with a high enough supply guarantee. Figure 3.1 below illustrates the study region (Mokolo River), its tributaries, and the flow direction discharging into the Limpopo River.

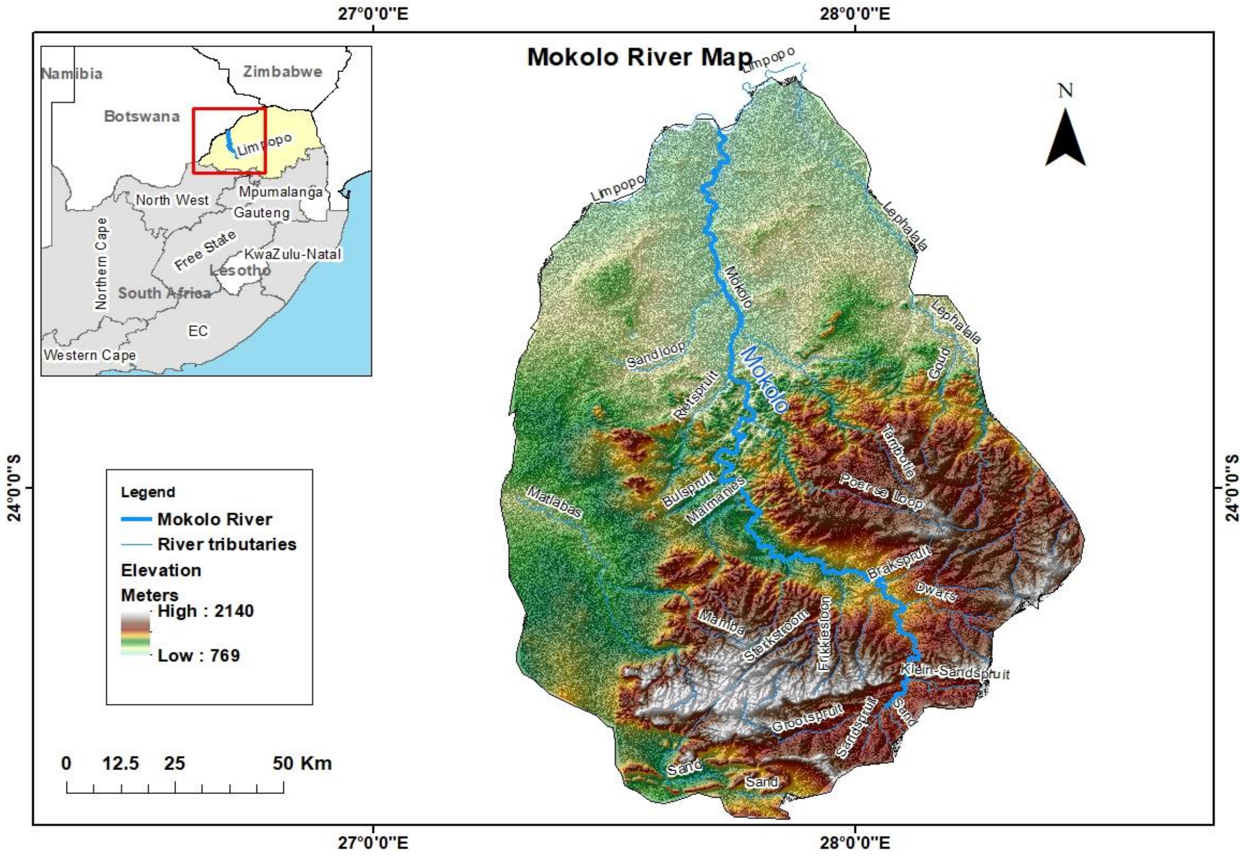


Figure 3. 1: The study area map shows the Mokolo River catchment and its tributaries in the Limpopo province.

3.3. Research design

The research design adopted for this study is a quantitative approach structured around the Water Evaluation and Planning (WEAP) model framework. This approach is selected to provide an empirical and systematic means of assessing water demand and supply within the study area. The quantitative methodology ensures that data-driven insights can be derived, supporting objective decision-making processes (Kumar, 2014). The process involves defining the system's structure, including water sources, demand sites, transmission links, and return flows, and incorporating critical data such as hydrology, climate projections, and demographic trends (Saleem et al, 2021). WEAP also enables a comparative approach where different scenarios can be tested, allowing stakeholders to explore outcomes based on changes in variables like policy interventions, water-use efficiency improvements, or shifts in precipitation patterns. Figure 3.2 outlines the model framework employed to attain the study's objectives.

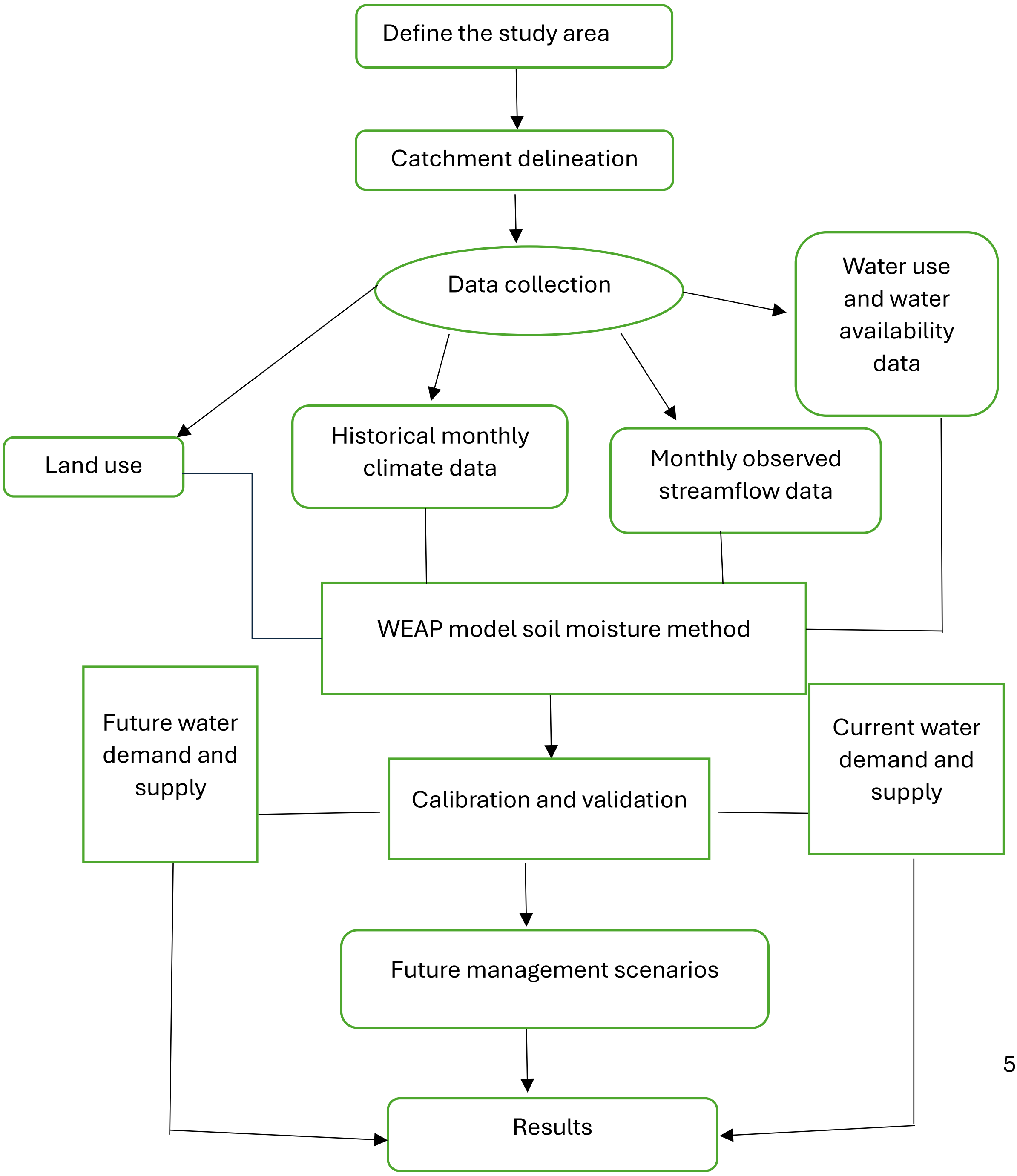


Figure 3.2. The model framework for the Mokolo River Catchment.

3.4. The WEAP model data inputs.

To answer the study's research questions, various secondary data were used to populate and set up the WEAP model to determine the water balance of MRB. The secondary datasets used in this study was collected from a variety of institutions, as shown in Table 3.1. Land use, climate, streamflow, wind speed, temperature, precipitation, and water demand and supply information are all included in the model input dataset. In addition, the model calculated evaporation using cloudiness fraction, average wind speed, relative humidity, and average mean air temperature.

Table 3. 1: A description of the dataset and its sources that were employed in the Mokolo River Basin-WEAP model.

Dataset	**Description**	**Duration**	**source**
Meteorological data	Maximum and minimum temperature, humidity and precipitation	Monthly (1993-2023)	South African Weather Service (SAWS)
	Evaporation is determined by the model based on Climate data entered in the Mokolo Catchment using the soil moisture method.		WEAP (Soil Moisture method)
Hydrology	A4H002 and A4005 Stream flow	Monthly (1993-2023)	Department of Water and Sanitation (DWS)

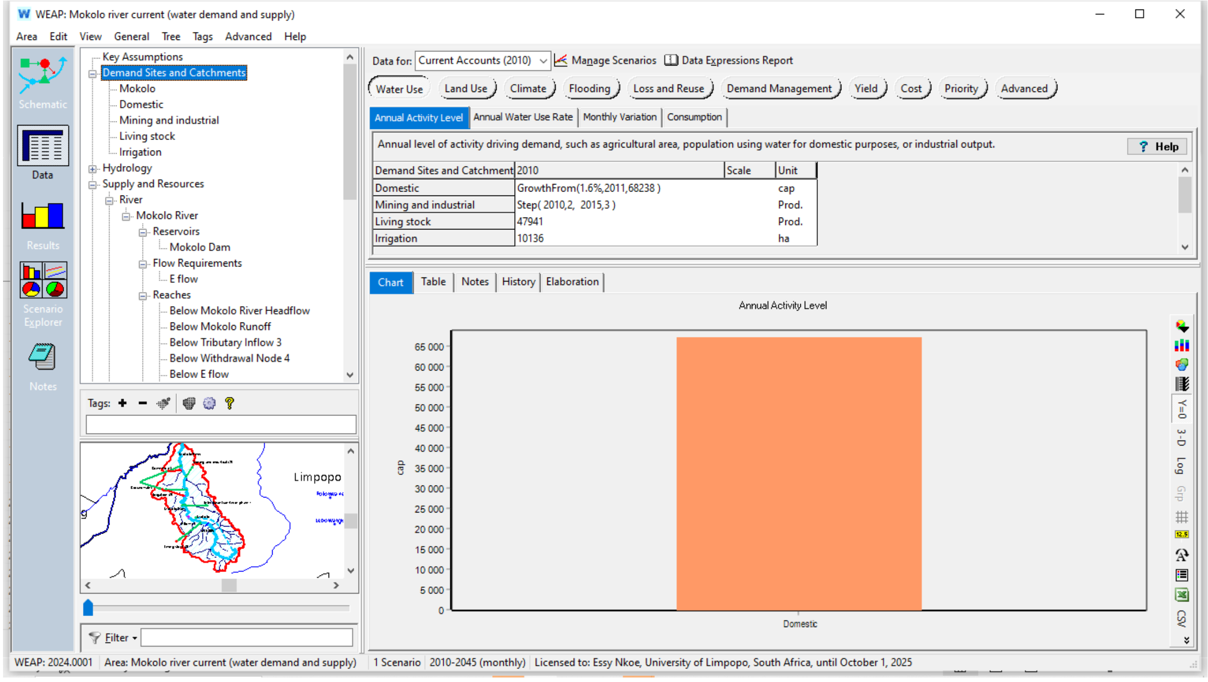
	Reservoir data	Monthly (2010)	Water Research Commission (WRC)
Population & Population growth rate	Census 2011	2011	Socio-Economic Perspectives (P WMA 01/000/00/02914/2)
Water Demand, Supply data, land use and catchment details	Catchment water use for irrigation, industrial, livestock and domestic	Annually (2010)	Limpopo water management reconciliation strategy (P WMA01/000/00/02914/11A)
	Number of Livestock at Mokolo Catchment	Annually (2004)	Internal Strategic Perspective (IPS) vision 1, (PWMA 03/000/00/0404)
	ground water, return flows	Annually (2010)	Groundwater Assessment and Utilisation (PWMA 01/000/00/02914/6) and water requirement and return flows (PWMA 01/000/00/02914/4/3)
Catchment shape file	Shape-file of the Mokolo catchment		QGIS
Projected climate	Precipitation, maximum and minimum temperature	Monthly (2015-2045)	WEAP Coupled Model Intercomparison Project 6 (CMIP6) suite GRDL-ESM4, IPSL-CM6A-LR, MPI-ESM1-2-HR scenario SPP 245 and 370

3.5. Data analysing tools

The analysing tools used to process the secondary data in this study were Microsoft Excel 2016 and WEAP version 2023.02.08. The WEAP model was obtained from the Stockholm Environment Institute through their website weap21.org. Students have a one-year free license to use the model for study, which can be renewed upon request. Microsoft Excel was used to process the meteorological data of the study, and the file was saved in a CSV (comma delineation) file so it can be processed into the WEAP model. The WEAP model software was used to simulate the current and future water demand and supply of the Mokolo River Catchment for the purpose of developing future management scenarios for the Mokolo Catchment.

3.6. The WEAP model set up

The WEAP model was viewed from five different perspectives: schematic, data, results explorer, notes, and scenarios explorer (SEI, 2015). The schematic map was used to create the study area, and then the obtained secondary data (meteorological data, stream flow data, population, land use, and water use) was given as input into various branches of the model such as demand sites, water resources and hydrology. The result view showed the results in various charts and tables. The notes were where the appropriate data and assumptions was established, and lastly the scenario explorer view was where the preferred charts were then grouped. A snapshot of the data view is presented in figure 3.3.



Data for: Current Accounts (2010)

Annual level of activity driving demand, such as agricultural area, population using water for domestic purposes, or industrial output.

Demand Sites and Catchment	2010	Scale	Unit
Domestic	GrowthFrom(1.6%,2011,68238)		cap
Mining and industrial	Step(2010,2, 2015,3)		Prod.
Living stock	47941		Prod.
Irrigation	10136		ha

WEAP: 2024.0001 | Area: Mokolo river current (water demand and supply) | 1 Scenario | 2010-2045 (monthly) | Licensed to: Essy Nkoe, University of Limpopo, South Africa, until October 1, 2025

Figure 3. 3: The data view of the WEAP model, showing some of the different data requirements of the model.

Setting up the WEAP model for application entails multiple steps, such as problem definition, which specifies the study time frame and spatial boundaries of the study region (Asghar and Iqbal et al. 2019). To model the Mokolo River, the study time frame was created using a WEAP model that starts with the creation of a current account year. The current account represents the basic definition of the current water supply system and forms the basis for the analysis of all scenarios. In this study the current account was chosen to be 2010. The year 2010 was chosen as the baseline year, since it was the year that had all the required data need to perform this study. After creating a current account, the study region was defined according to its geographic boundaries using WEAP catchment delineation mode, the Mokolo River catchment boundary was established. The schematic map that was produced was then further enhanced using a catchment shape file of the Mokolo River catchment region and river network that was created using QGIS. Then water demand-supply system's spatial distribution, time frame, and priority were all described (Gao et al., 2017). The study identified four demand nodes for the Mokolo River: namely irrigation, domestic, livestock and mining and industrial as illustrated in figure 3.5. All four water demand nodes relied on water from the catchment surface, with irrigation and domestic uses also relying on groundwater supplies. The time step for the WEAP model was based on the calendar months of October through September, which corresponded to the hydrological year for this study. The entire Mokolo River was considered as a single catchment in WEAP, based on the hydrological data that was available from the Limpopo reconciliation strategy and other institutions. All water demands and water supply data were entered into the model. The model was then calibrated and validated to ensure adequate representation of the hydrological processes within the WEAP model. Statistical analysis confirming this were adequate. Then the model was then run for results.

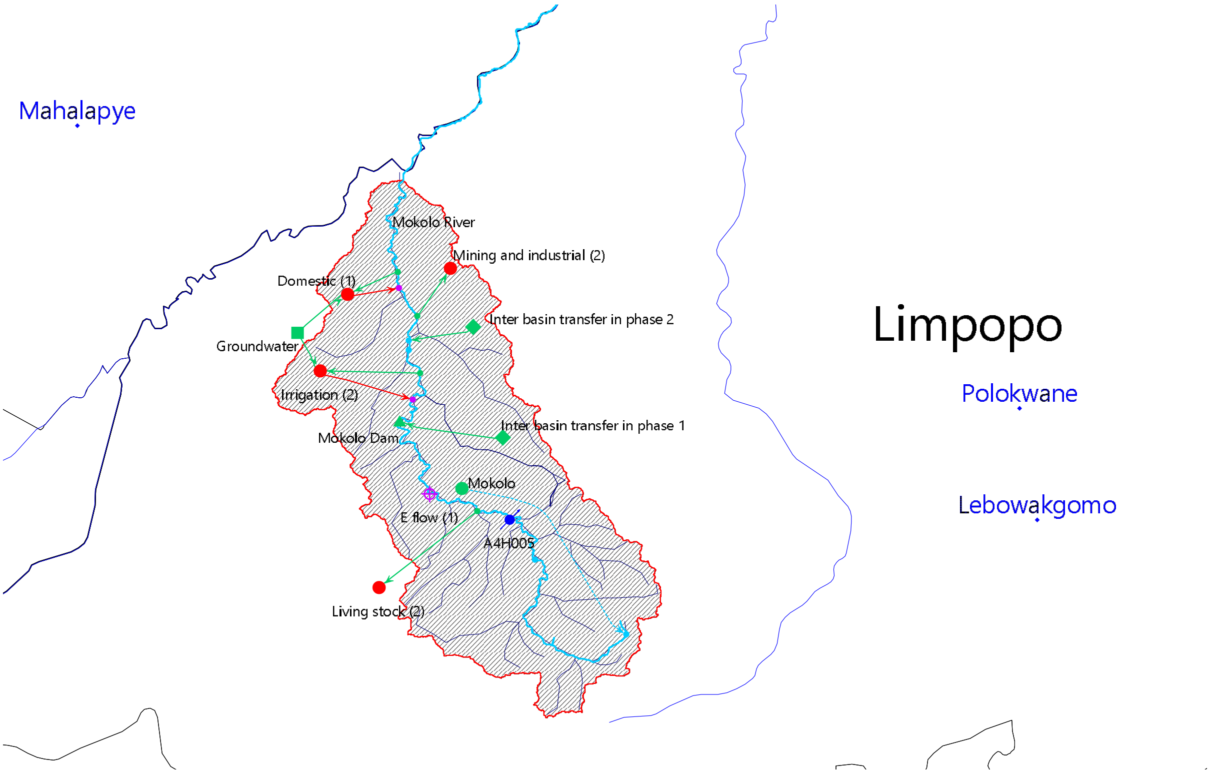


Figure 3. 4: The schematic diagram of the Mokolo River, Limpopo province

3.7. Catchment simulation method

Five simulation methods can be used in WEAP on a day-to-day or monthly basis, and they include soil moisture method, rainfall-runoff method, MABIA method, the plant growth model and irrigation demand only method (Serur, 2022). The Soil moisture method was chosen for this study because it can be used to estimate the actual catchments of water- holding capacity and soil moisture storage (Sieber and Purkey, 2015). This method was used to simulate the hydrological cycle which includes rainfall, evaporation and groundwater recharge. The following mathematical formula was used in the soil moisture methods, and it represented the water balance.

$$Rdj\frac{dz_{1,j}}{dt} = P_e(t) - PET(t)k_{c,j}\,(t)\left(\frac{5Z_{1,j} - 2Z_{1,j}^2}{3}\right) - P_e(t)Z_{1,j}^{RRF} - f_jk_{s,j}z_{1,j}^2 - (1 - f_j)f_jk_{s,j}z_{1,j}^2$$

The following terms are defined according to Hamza and Getahun, 2022. $z_{1,j}$= [1, 0] and it represents the relative soil water storage, P_e is the effective precipitation (mm), Where $k_{c,j}$ is the crop coefficient, *RRFj* is the runoff resistance factor of the land cover, *PET* (t) is the reference potential evapotranspiration. $P_e(t)Z_{1,j}^{RRF}$is the surface runoff, $f_jk_{s,j}z_{1,j}^2$ is the interflow from the first soil layer, fj is the partition coefficient related to the type of land cover, and ks, j is the saturated hydraulic conductivity of the root zone (mm/time). Higher values of RRFj result in less surface runoff. The one-dimensional, two-bucket water accounting approach shown in figure 3.5 is based on empirical functions and is used to explain surface runoff, evapotranspiration, deep percolation, and interflow for basins or sub-basins.

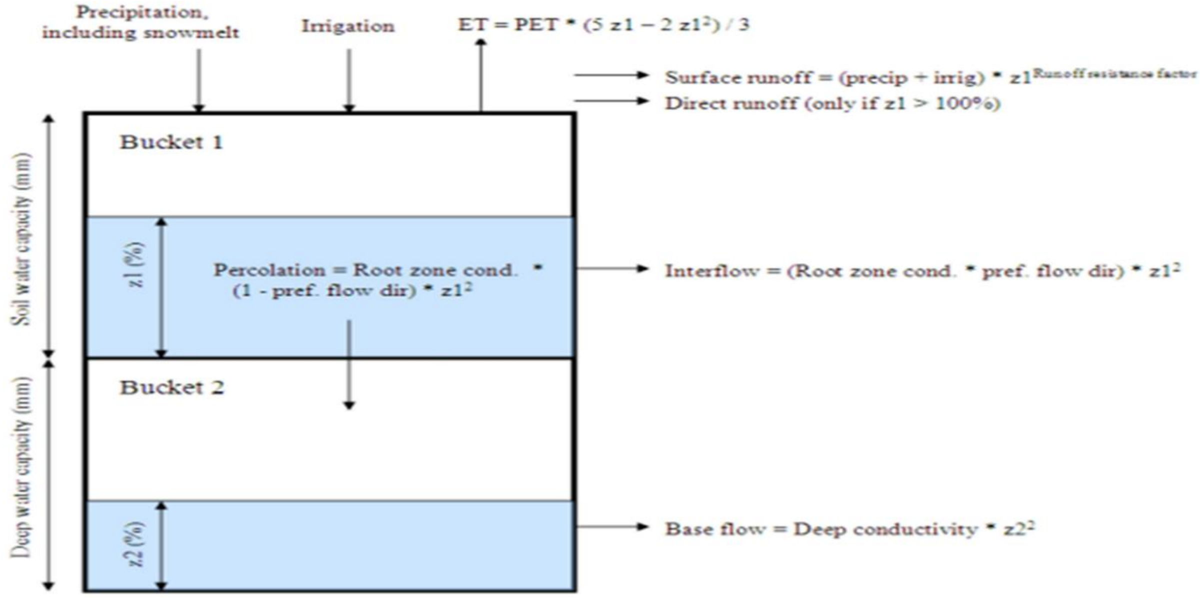


Figure 3. 5: The conceptual diagram and equation incorporated in the soil moisture model (Sieber and Purkey, 2015)

3.8. Model Calibration process.

Model calibration is essential since it verifies the WEAP model's ability to accurately represent the true condition of the water system. The WEAP model can be calibrated either automatically using the PEST approach or manually through the catchment calibration method, which entails adjusting model parameters to reduce the discrepancy between observed and simulated results. This study selected manual calibration. The calibration period spanned from 2010 to 2015, while the validation period extended from 2016 to 2021. Model calibration utilised thirty years of historical streamflow data from DWS and climatic data from SAWS. The model was calibrated via the primary stages outlined in the WEAP 2023 tutorial manual: 1) Collected observed data and selected the model calibration location; 2) compiled observed data and determined the model calibration period; 3) visually assessed the model calibration; 4) adjusted significant parameters and conducted model sensitivity analysis; and 5) optimised the calibration based on statistical and visual evaluations.

3.8.1. Catchment calibration using the soil moisture method

The primary objective of the model calibration in this study was to identify a set of parameters (within the soil moisture method) that are relevant to the Mokolo watershed and accurately portray the hydrology of the Mokolo River at the A4H005 gauging station. Calibration for the A4H004 gauge station was achieved through trial-and-error optimization of unfixed parameters. The model was run to test and compare changes in simulated and observed stream flow before and after parameter optimization. This step was done continually until the satisfactory parameters were met.

The hydrologic model can be re-calibrated using the WEAP embedded soil moisture approach (Sieber and Purkey, 2015), which incorporates seven soil and land use factors. The values of these are as follows: crop coefficient (Kc), soil water capacity (Sw), deep water capacity (Dw), runoff resistance factor (RRF), root zone conductivity (Ks), deep zone conductivity (Kd), preferred flow direction (f), and initial storage fraction at the start of upper soil layer (Z1) and lower soil layer (Z2) simulations. Table 3.2 shows the initial parameters values and the range in which the parameters can be altered.

Table 3. 2: Initial parameters values and its valid range.

Parameters	Default values	Valid range
K_c	1	0 -∞
SWC	1000mm	0 -∞
DWC	1000mm/month	0 -∞
RRF	2	0 -∞
RZC	20mm/month	0 -∞
DC	20mm/month	0 -∞
PF	0.15	0 -1

3.8.2. The model Performance evaluation

The quality of the model was evaluated using the study of Khan and Kundai (2022). The output of the model was compared to the observations for validation. The observed data in a watershed simulation can be fitted by using various performance measure models. The effectiveness of the Nash-Sutcliffe model and the coefficient of determination (R^2) will be employed in the study to validate results, and the following equations are used to define them.

$$R^2 = \left[\frac{\sum_{i=1}^{n} (Y_i^{sim} - \bar{Y}^{sim})(Y_i^{obs} - \bar{Y}^{obs})}{\sqrt{\left(\sum_{i=1}^{n} (Y_i^{sim} - \bar{Y}^{sim}\right)^2 \sum_{i=1}^{n} (Y_i^{obs} - \bar{Y}^{obs})^2}} \right]$$

The Y_i^{sim} represent the ith simulated streamflow, Y_i^{obs} indicates the ith observed streamflow, $\bar{Y}^{sim}$ is the mean of simulated streamflow and $\bar{Y}^{obs}$ is the mean of observed streamflow (Leong and Lai 2017).

$$NSE = 1 - \frac{\sum_{t=1}^{T} (Q_m^t - Q_0^t)^2}{\sum_{t=1}^{T} (Q_0^t - \overline{Q_0})^2}$$

The $\bar{Y}^{obs\ is}$ the ith observed streamflow, $\bar{Y}^{sim}$ is the ith simulated streamflow, $\bar{Y}^{obs}$ is the mean of observed streamflow (Leong and Lai 2017).

3.8.3. The statistical parameters and its validation criteria.

The statistical parameters and their validation requirements for this hydrological model are presented in Table 3.3. The observed and simulated streamflow was compared by assessing the model's accuracy using NSE and R2 values.

Table 3. 3: Nash Sutcliffe Efficiency Values and Correlation coefficient criteria and its interpretation (Sourced from Moriasi *et al*, 2007).

Correlation coefficient	**Interpretation**	**Nash Sutcliffe Efficiency**	**Interpretation**
$0.7<R^2<1$	Good correlation	NSE≥0.8	Very good
$0.4<R^2<0.7$	Acceptable relationship	NSE≥0.5	Accepted
$0.2<R<0.4$	Zero correlation	NSE≥0.3	Ignored

3.9. Data Analysis Methods

3.9.1. Objective 1: Current water demand and supply

The 2016 draft of the Limpopo reconciliation strategy included the Mokolo River reconciliation strategy and other relevant sources, such as the National Department of Water and Sanitation (DWS) and Statistics South Africa. This is where the water use data, population, and population growth rate were gathered. Although the LRS was published in 2016, the data collected from the reconciliation strategy was based on evaluation data from 2010. This study therefore used the 2010 data to set up the WEAP current account year, which is the year with the most complete sets of data required to populate the model. The required meteorological data was collected from the South African Weather Services (SAWS). The hydrological data used to achieve this objective was obtained from DWS. The data had to be pre-processed into a format that could be used by the WEAP model. Details such as meteorological data, stream flow data, population, land use, water allocations by sectors in the catchments, and return flows were used to populate the model and simulate the current water demand and supply of the river catchment using the WEAP model.

II Current water demand

The WEAP model used the water use data to simulate the basin's water demand by determining the annual activity levels, water usage rates, and consumption patterns. This study modelled four demand-consumptive consumers in the basin: domestic water demand, livestock water demand, industrial water demand, and irrigation water demand. A growth rate key assumption was created, which was used in the domestic annual activity level to account for the growing population in the catchment. The growth rate in the used was 1.66% (DWS, 2016), which was sourced from the LRS. The mathematical expression called a step function in WEAP was used in the annual activity level to account for the expansion that will take place in 2015 in the mining and industrial sector. The yearly time series wizard in WEAP was also used to show the changes that took place from 2010 to 2016 for the water use rate per unit within the mining, industrial, and domestic sites. Irrigation and livestock were assumed to be constant throughout the years, as the LRS has capped allocation to these water user sectors. The simulated streamflow from the Mokolo basin supplies water to the basin's water demand. The necessary requests for water are distributed according to priority. The priority index in WEAP is a number between 1 and 99, where a lower number denotes a higher priority and vice versa. Domestic was given first priority compared to the other demand sites. This priority rule in WEAP is helpful in representing a water rights system and is useful in times of water scarcity to ensure that higher priorities are fully met before lower priorities are taken into consideration (Sieber and Purkey 2011).

III Current water supply

Water resources such as precipitation, surface water, reservoir and groundwater were also defined within the model. To achieve this, A4H005 streamflow gauge and Mokolo reservoir data were collected from the Department of Water and Sanitation. Groundwater data was collected from the Limpopo reconciliation strategy, this however presented some challenges due to limited data availability. All these data were used to populate and setup the supply and resources within the WEAP model. A lower priority of 99 was assigned to the Mokolo dam. This was done in order for the reservoir to fill only if water was left over after all other higher priority demands had been met. Then the model was run using current account data to simulate the water yield based on the defined water resources. The results of the simulation were examined to determine the total yield from the catchment.

3.9.2. Objective 2: Future water demand and supply

I. Future water demand

WEAP Linear forecasting method was used to forecast future water demand in the catchment based on time series of historical data and population growth such as water use data (Sieber and Purkey, 2015). This method assumes that there is a linear relationship between historical data and future outcomes. The method used the historical water use patterns to extrapolate into the future by fitting a linear regression model to the historical data so that the model is able to estimate future water demand (SEI, 2015).

II. Future water supply

The catchment's future supply capacity was determined using the WEAP Rainfall-Runoff (soil moisture method) runoff computation, integrating future global warming and rainfall variation scenarios. Future temperature, precipitation, and wind speed can be forecasted using General Circulation Models (GCMs). Three different future climate models from the sixth phase of the Coupled Model Intercomparison Project 6 (CMIP6) suite were used in this study. These models were GRDL-ESM4, IPSL-CM6A-LR, and MPI-ESM1-2-HR, all of which were part of the WEAP model. These three CMIP6 models offer extensive climate simulations worldwide and over extended durations, facilitating the assessment of internal climate variability and the statistical reliability of trends (Xu et al., 2021). Also, they have integrated multiple Shared Socioeconomic Pathways (SSPs) to predict diverse future radiative forcing scenarios. This aids in comprehending how prospective climatic alterations are contingent upon social trajectories and mitigation initiatives (Deepa et al., 2024). Models like IPSL-CM6A-LR exhibit enhanced climatology and increased climate sensitivity relative to earlier iterations, perhaps resulting in more precise warming estimates (Boucher et al., 2020). These models were selected using a number of factors, such as the presence of both historical runs and future scenarios, the inclusion of several parameters including precipitation, maximum and lowest temperatures, and availability at a monthly time step. As a sub-model of climate change prediction, these characteristics were deemed crucial for this study. The plausible effects of climate change on the Mokolo catchment supply capacity were estimated from 2015 until 2045. The CMIP6 scenarios used for the MRB were the shared socioeconomic paths (SSPs) SSP245 and SSP370, which were accessible within the WEAP model. The impact of climate change on surface water and groundwater resources in 2015–2045 was evaluated under the SSP245 and SSP370 emission scenarios. The results were displayed as a trend line on a graph, which will represent the predicted water supply for the period 2015-2045.

3.9.3. Objective 3: Future Management scenarios

Scenarios are built into the WEAP model to try and address the ‘what if’ questions (Sieber, J. and Purkey, 2011). A reference management scenario was first generated, representing the study’s current year which is the year 2010. The current year provides a foundation for further analysis of the present condition and comparison with alternative simulated scenarios (Ayt Ougougdal., 2020). This year (2010) was chosen because it has the most recent data required to populate the model. To enhance the understanding of future water situations in the Mokolo River, different scenarios was developed in the model to simulate different socioeconomic situations like population increase, irrigations and industrial area reduction. Thereafter, different possible management scenarios that examines the effect of employing water conservation measures for domestic demand and an increase in inter-basin transfer into the catchment was examined. In the past, Lévite and Sally et al. (2003) used the WEAP model to test various management scenarios in the Olifants River, South Africa. This approach was therefore adopted for the Mokolo River catchment.

i. Supply-demand side management scenarios

Management scenarios were implemented using supply-demand side management scenarios. The following plausible management scenarios were developed for the study area. (Scenario development assumptions are based on the Limpopo reconciliation strategy, 2016)

Reference scenario: Water supply and demand in the Mokolo watershed were examined in the first baseline scenario created for this study. This scenario, which assumes that all other influencing factors, like water usage and climate change, stay constant, reflects the actual state of water resources with a population growth of 1.66%. The current accounts are chosen to serve as the base year for the model, and all data is incorporated into these accounts to create the scenarios. In the years following the current accounting year, the scenarios look at possible changes to the system. Future projections of the current situation (2010) are made for the years 2015–2045. Water usage was expected to rise in accordance with a population growth rate of 1.74% if irrigation systems remained unchanged.

Scenario 1: Under this scenario, the adoption of water-saving agricultural practices and a decrease in unauthorised irrigation water usage were found to result in a 15% reduction in irrigation water consumption under this scenario. Rainwater collection and drip irrigation were two techniques that farmers employed (Asghar et al., 2019), and they greatly aided in this decrease but other measurements remained unchanged from the reference scenario.

Scenario 2: This scenario predicted a 5% decrease in industrial water use, assuming that future water management in the basin will result in the adoption of new technologies and practices. That industry will be incentivised to develop more efficient processes and recycling systems, resulting in a significant reduction in total water usage.

Scenario 3: This scenario assumes that basic municipal water usage has declined by 23% as a result of the implementation of water conservation measures and demand management approaches. Public awareness efforts and incentives for reduced water use were critical in accomplishing this goal. It is also anticipated that the population growth rate will drop, as projected by the LRS.

Scenario 4: According to this scenario, plans for inter-basin transfer from a different catchment were made in 2030. By moving excess water from resource-rich areas to resource-poor ones, this calculated action sought to increase the reliability of the water supply.

Combined Integrated Management Scenarios

Scenario 5: This scenario assessed the combined effects of the four preceding management scenarios, demonstrating a significant impact on total water use. This scenario employed the merging of demand-side management strategies with supply-side management methodologies.

3.10. Conclusion

This chapter has presented the methodological framework designed to assess both current and projected water demand and supply in the study area using the WEAP (Water Evaluation and Planning) model, with a focus on developing management scenarios that target reductions in water demand across irrigation, domestic, and industrial sectors. The methods were chosen to provide a systematic and reliable foundation for evaluating how demand-management strategies could alleviate water stress and promote sustainability within the catchment. This methodological approach sets a strong foundation for the analysis and results in the following chapters, where the effectiveness of these scenarios will be examined, offering valuable implications for sustainable water management practices in the Mokolo region.

Chapter 4: RESULTS AND DISCUSSION

4.1. Introduction

This section presents the findings from the modelling of water demand and supply to develop future management scenarios for Mokolo River Catchment, Limpopo Province. Outcomes relating to the current and future water demand from the Mokolo systems, supply dynamics, inflow to the area, and supply under future projections under the Climate Model Intercomparison Project Phase 6 (CMIP6) under Shared Socioeconomic Pathways (SSP) 245 and 370. The results also include assessments of management scenarios aimed at reducing water use in irrigation, domestic consumption, mining, and industrial activities.

4.2. Calibration and validation

The WEAP model was calibrated by entering monthly meteorological data, land use, latitude and streamflow from A4H005 gauge station which is situated on the Mokolo river catchment. Thereafter, the soil parameters were set at their default settings in order to carry out the initial calibration. The initial calibration based on the default parameter values showed that the model was not calibrating well. The main aim of calibration was to find the best-fit parameter values that accurately reflected the system's behaviour in the real world, by iteratively adjusting the parameters until the simulated streamflow and the observed streamflow for the designated period matched as closely as possible (Abera and Ayenew, 2021).

The soil parameters were adjusted through trial-and-error method to find a good fit between the meased and simulated streamflow within the reference account in the WEAP model. Running the model on a separate set of data and contrasting the simulated and actual outcomes is the process of validation (Khalil, 2018). If the observed data closely resembles the simulated results, the model is calibrated. The statistics analysed from the simulated outputs produced by the WEAP model and observed flow data at the A4H005 gauge station were used to extensively examine the efficacy of the model's performance. Figure 4.1 shows a graphical comparison of the simulated streamflow and the annual total observed streamflow for the years (2010–2015) for calibration and (2016–2021) for validation.

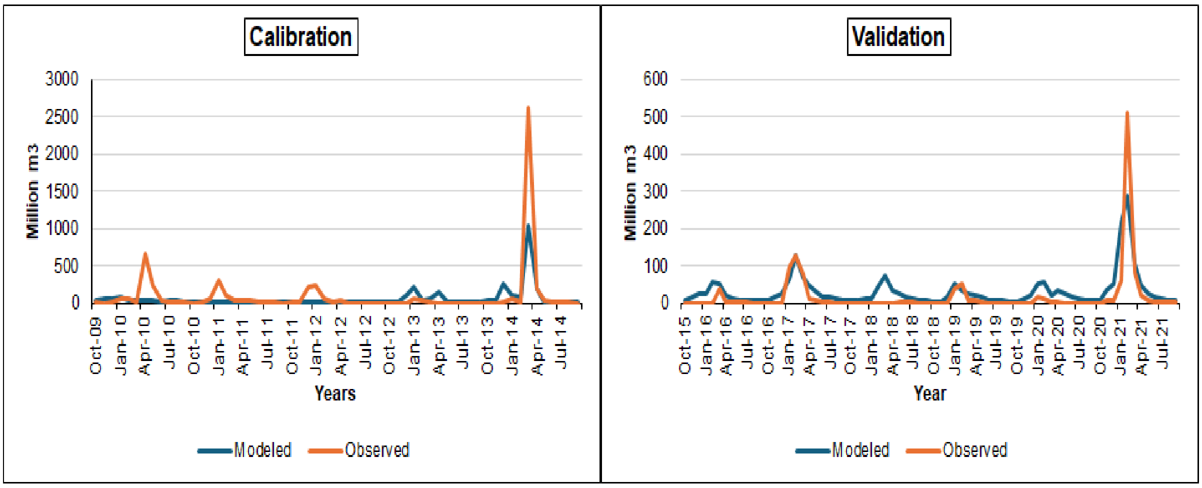


Figure 4. 1: Showing the observed and simulated streamflow for the Mokolo River at A4H005 gauge station

4.3. Model performance evaluation

The performance efficiency of the WEAP model was tested using two statistics from the simulated output and the measured streamflow data. The coefficient of determination (R^2) and the Nash-Sutcliffe model were the two statistical measures employed for performance evaluation. Table 3.1 was used to assess the acceptability and feasibility of the model. For the Mokolo River Basin, the simulated and observed runoff for the calibration period was 2010–2015, and it was validated for the period 2016–2021 as displayed in Figure 4.1, respectively. The Monthly hydrograph of the simulated and observed streamflow data shown in Figure 4.1 demonstrated a satisfactory agreement for the calibration period with an R^2 of 0.80 and an NSE of 0.55. A satisfactory agreement between the measured and simulated streamflow was also revealed for the validation periods with an R^2 of 0.70 and NSE of 0.61 (Table 4.1).

Table 4. 1: The statistical evaluation performance of the Mokolo model.

Gauge stations	**Statistics parameters**	**Calibration**	**Validation**
A4H005	R	0.89	0.84
	R^2	0.8	0.7
	NSE	0.55	0.61

4.4. Objective 1 results: Outcome of the current Water demand assessment

The WEAP model was utilised to simulate water demand in the Mokolo River Basin (MRB) based on annual activity levels and water usage rates. Four key demand sites were identified within the basin: domestic, irrigation, livestock, and mining and industrial. Among these, domestic water demand was given the highest priority, as reflected in Table 4.2.

Table 4. 2: The demand sites and its priority level for demand prioritisation.

Demand sites	Demand priority
Domestic	1
Irrigation	2
Livestock	2
Mining and industrial	2

This study assumed that domestic water demand would increase over time due to population growth. Similarly, mining and industrial water demand was projected to rise every five years due to industrial expansion, given that the Mokolo River's location is within the Waterberg Coalfields, (an area central to coal mining and power generation). This assumption aligns with the reconciliation strategy (2016). In contrast, irrigation and livestock water demand were assumed to remain constant throughout the study period. Figure 4.2 shows a gradual increase in total water demand from 2010 to 2023.

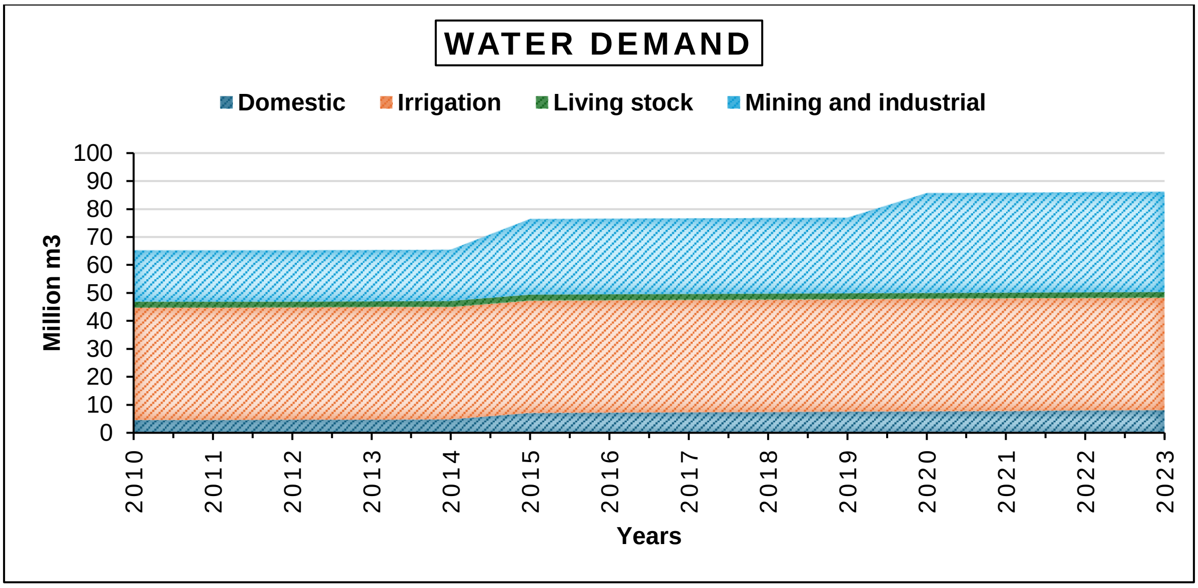


Figure 4. 2: The current water demand (2010-2023) within the Mokolo River basin is presented in this plot.

There is a gradual increase in water demand in the Mokolo River basin from the study's current account year until the end of the simulation period in 2023. The total annual water demand in 2010 of just above 65 MCM steadily increased to a total of almost 80 MCM in 2023. The 15 % increase shows how population and industrial increase have an impact on water demand. The highest increase in demand from the basin is from the mining and industrial sectors. This sector doubled, increasing from 18 Mm³ in the baseline year to 36 Mm³ in 2023. The basin's water consumption remains substantial, despite its limit. The basin receives the least demand from the domestic and livestock sectors. This trend highlights the significant growth in water demand over the study period, particularly in the domestic and industrial sectors.

4.5. Current water resource availability and supply from the Mokolo River basin.

In the WEAP model water enters the system or basin from many sources, including rivers, groundwater, catchment precipitation, local reservoirs, and other local supply sources including ponds, lakes, which is captured by the model as inflow to the area (Nivesh *et al*., 2023). The Mokolo catchment receives water from a variety of sources, including Mokolo reservoir and ground water and local diffuse dams (DWS, 2016). The annual total inflow to the Mokolo catchment was estimated to range between 3813.31 Mm³ in 2010 and 4142.07 Mm³ in 2023, as shown in Figure 4.5. A decline in inflow was observed between 2013 and 2016, with the lowest inflow recorded in 2019 at

2150.54 Mm³. This reduction is attributed to 2019 being an exceptionally dry year, as identified using the WEAP water year method. The reduced inflow during these years significantly impacted water availability in the basin. For example, unmet irrigation demand ranged from 39 Mm³ to 37 Mm³ between 2015 and 2019, as displayed in Figure 4.3. Furthermore, Figure 4.4 reveals unmet demand across all sectors between 2016 and 2020, indicating the severity of water shortages during this period. These findings align with similar studies conducted in other basins using WEAP. For instance, Nyingi, (2024) analysed the Athi River Basin and found that periods of low precipitation caused significant reductions in inflow, leading to unmet demands for agricultural and domestic use. Similarly, Kumar et al., (2021), in their study of the Ganga Basin in India, reported that low inflow years, often associated with drought conditions, resulted in substantial deficits in water availability. Both studies highlight the sensitivity of water demand and supply to variability in inflow, validating the trends observed in the Mokolo catchment.

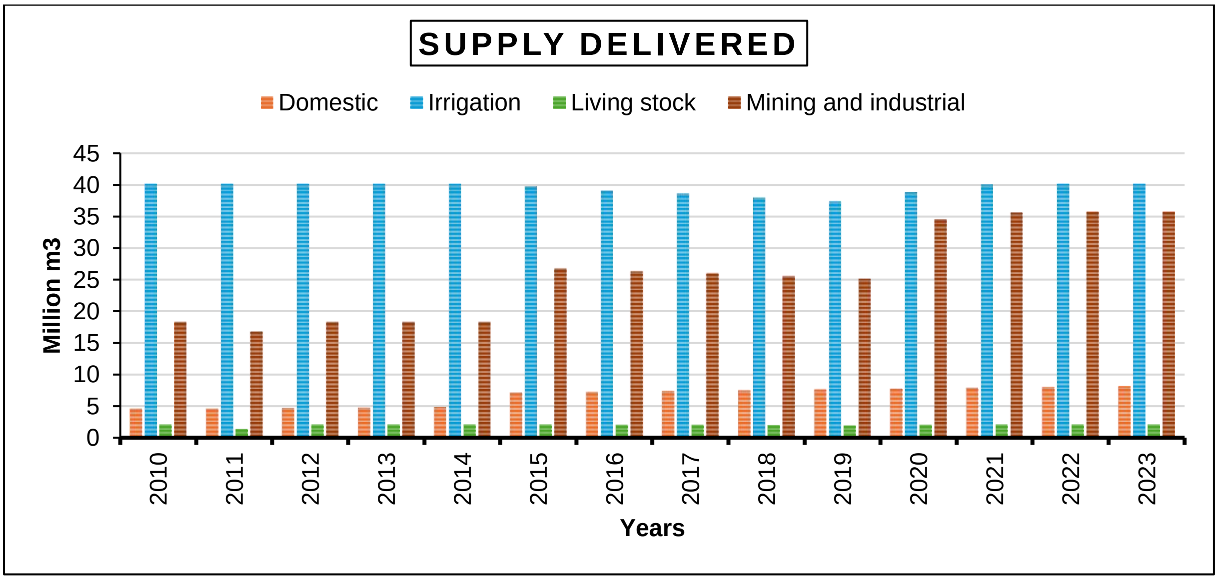


Figure 4. 3: The supply delivered to various demand sites within the Mokolo River

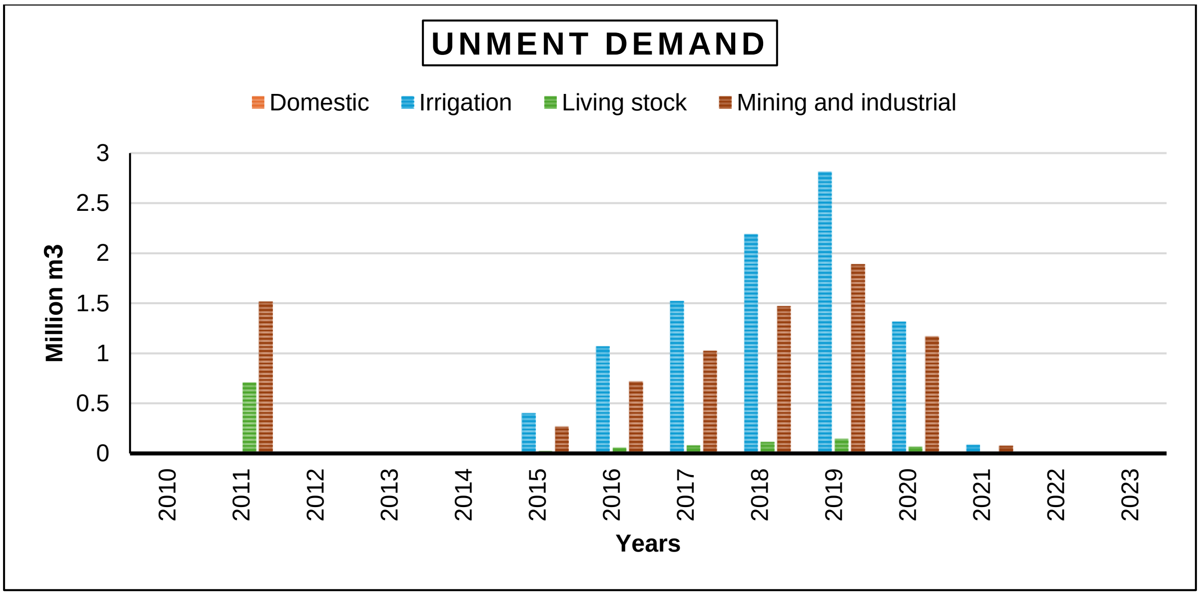


Figure 4. 4: Unmet demand for observed years in the Mokolo basin.

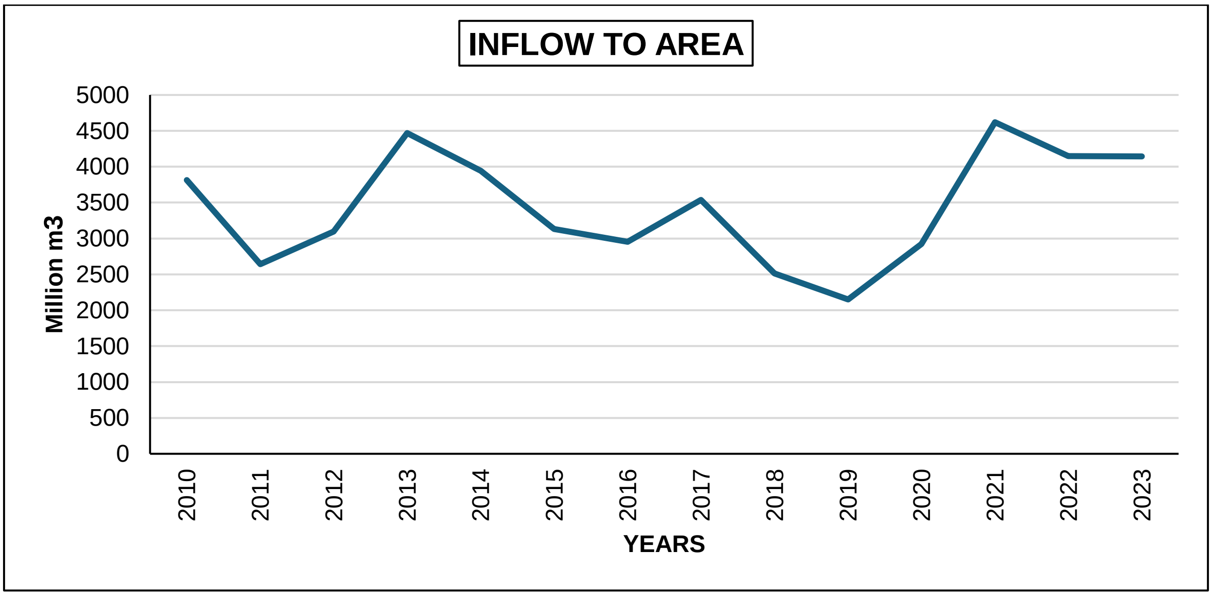


Figure 4. 5: Inflow to area for observed years within the Mokolo catchment.

4.6. Objective 2 results: Outcomes for future water demand and supply under SSP 240 and SSP370

4.6.1. Future projections on water resource availability

Future water demand projections are essential for effective water resource planning and management, particularly in the face of population growth, urbanization, and climate variability (Saleem et al., 2021). The linear forecasting method, is a widely used and straightforward approach, estimates future water demand based on historical trends, assuming that changes occur linearly over time. In the WEAP model, future demand was projected using baseline year data, with the assumption that water demand patterns would follow historical trends. The projection period began in 2015, utilizing future climate data from three models under CMIP6 already programmed into WEAP, and downscaled to the study area by the model. The results, presented in Figure 4.6, indicate that irrigation and livestock water demands are expected to remain constant at 40.16 Mm³ and 2.11 Mm³, respectively. In contrast, domestic and mining and industrial water demands are projected to increase over time, modelled in WEAP using a step-function mathematical expression. Mining and industrial water demand is forecasted to rise significantly, from 27 Mm³ in 2015 to 110 Mm³ in 2045. Similarly, domestic water demand is projected to grow from 7 Mm³ to 12 Mm³ over the same period. The total water demand for the catchment is expected to increase from 76 Mm³ in 2015 to 164 Mm³ in 2045. This substantial growth in mining and industrial demand will make it the largest water consumer in the catchment, surpassing irrigation, which was the dominant sector in the baseline scenario. The observed trend of increasing industrial water demand overtaking agricultural demand underscoring the importance of adaptive water resource management to address changing consumption patterns. (Bryła, 2021). These results remain constant under the three Models.

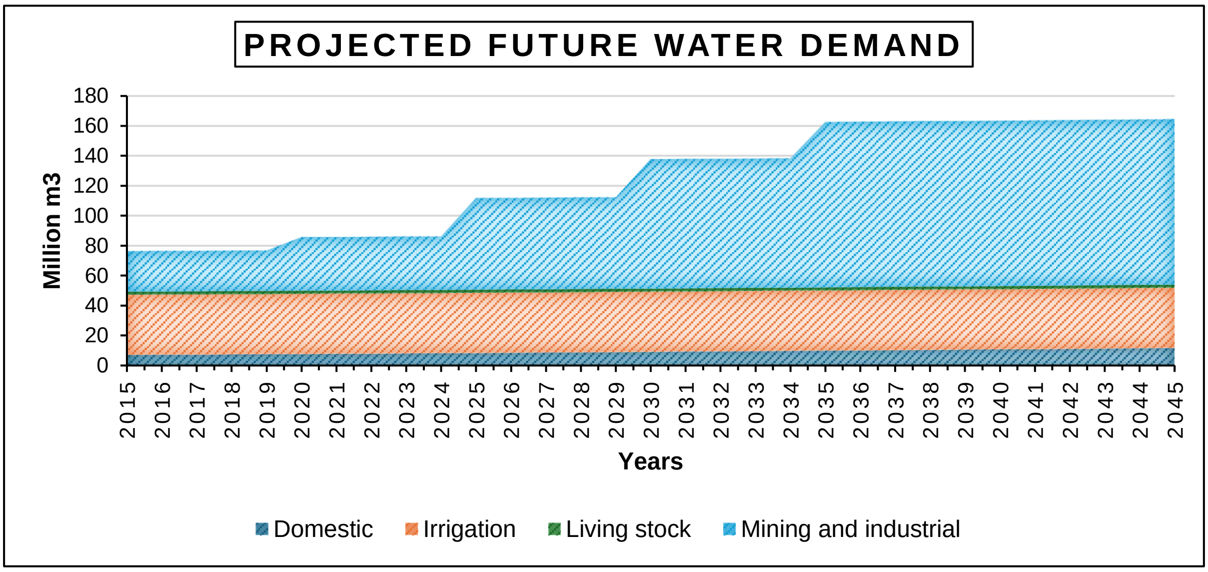


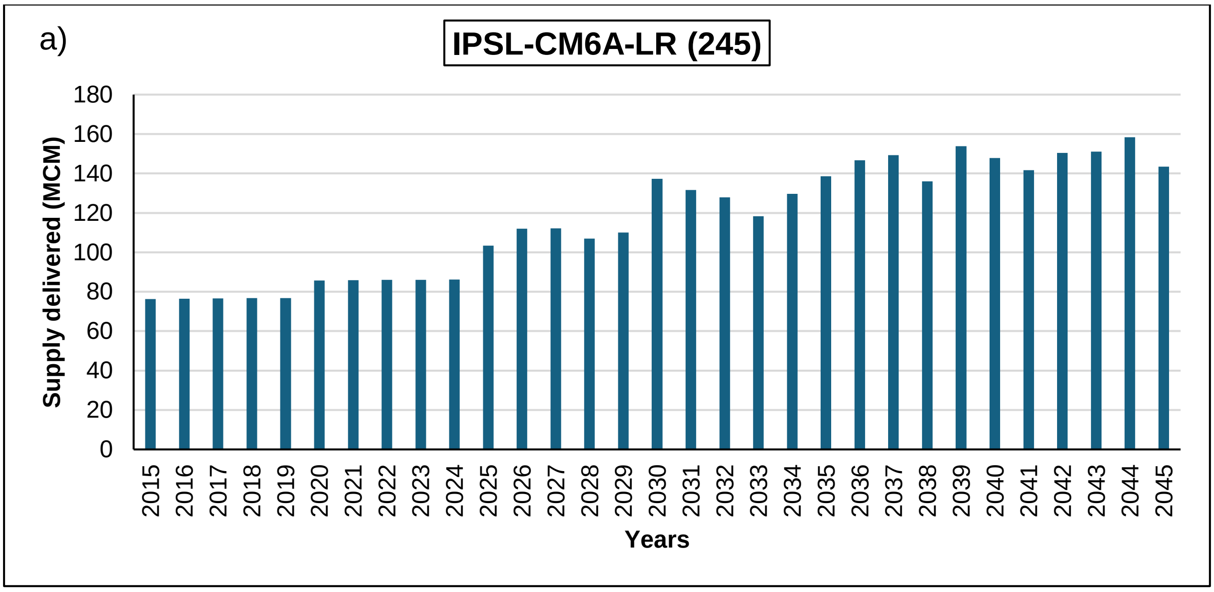
Figure 4. 6: Projected Future water demand for the Mokolo catchment.

4.7.1 Future projections of water demand consumption.

Global climate models (GCMs) are recognized as essential tools for simulating long-term climate projections in a dynamic environment, facilitating the assessment of future climate variables (Gouda et al., 2018). This study employs downscaled data from three models within the Coupled Model Intercomparison Project Phase 6 (CMIP6), specifically, IPSL-CM6A-LR, GFDL-ESM4, and MPI-ESM1-2-HR, under two Shared Socioeconomic Pathways (SSP245 and SSP370) to analyse the impacts of evolving climatic conditions on water demand and availability from the period 2015 to 2045.

I) Water supply with SSP245

Future water availability was estimated utilizing monthly climate data from SSP245 corresponding to the aforementioned GCMs. The performance of IPSL-CM6A-LR and MPI-ESM1-2-HR in terms of water supply across various sectors demonstrated comparability. In the baseline year of 2015, the IPSL-CM6A-LR model projected a water supply of 76 million cubic meters (Mm^3), which is anticipated to increase to 144 Mm^3 by 2045. In contrast, the MPI-ESM1-2-HR model also began with a supply of 76 Mm^3 in 2015 but is expected to rise to 134 Mm^3 by 2045. Notably, both IPSL-CM6A-LR and GFDL-ESM4 models forecasted peak water supplies in the years 2039 and 2044, likely attributed to increased precipitation during these wet years. The GFDL-ESM4 model consistently indicated the highest projected water supply, ranging from 86 m^3 to 150 m^3 in the years 2039, 2042, and 2044. Overall, these findings suggest that the IPSL-CM6A-LR model provides the most favourable water delivery estimates among the models analysed. A study by Rodrigues, (2024) similar to this study focused on the impacts of climate change on water availability indicates that significant changes in hydrological cycles are anticipated, which will exacerbate existing challenges related to water scarcity. This study utilized multiple GCMs to project future scenarios that align with findings regarding increased demand and reduced supply.


a)
IPSL-CM6A-LR (245)
Supply delivered (MCM)
0
20
40
60
80
100
120
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160
180
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2016
2017
2018
2019
2020
2021
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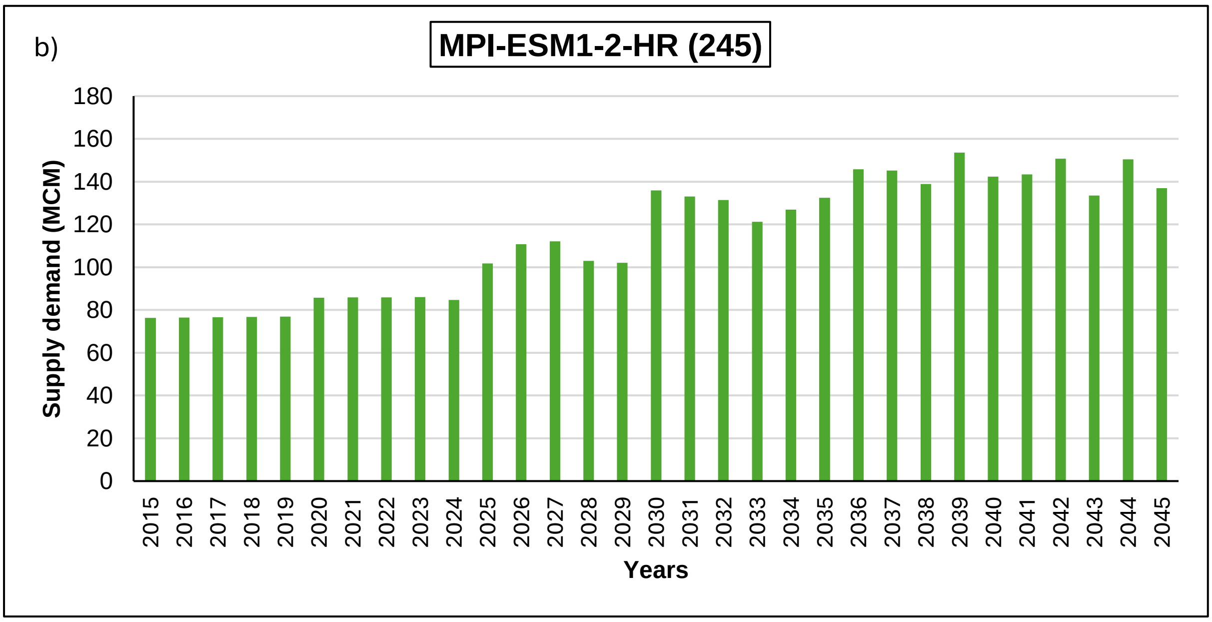
b)
MPI-ESM1-2-HR (245)
Supply demand (MCM)
0
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40
60
80
100
120
140
160
180
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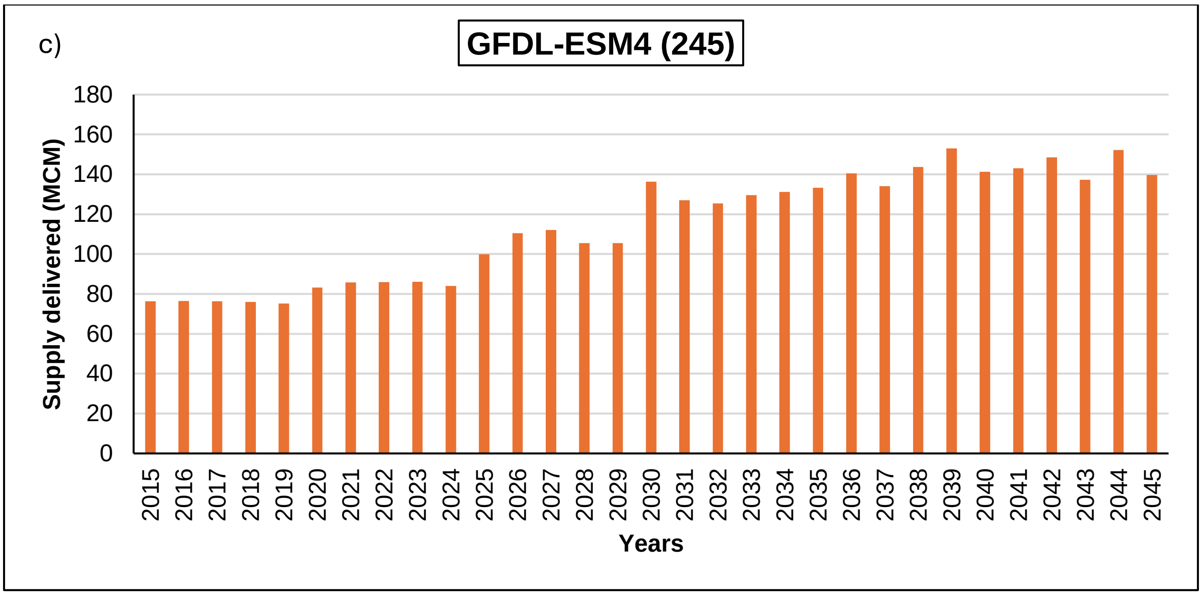
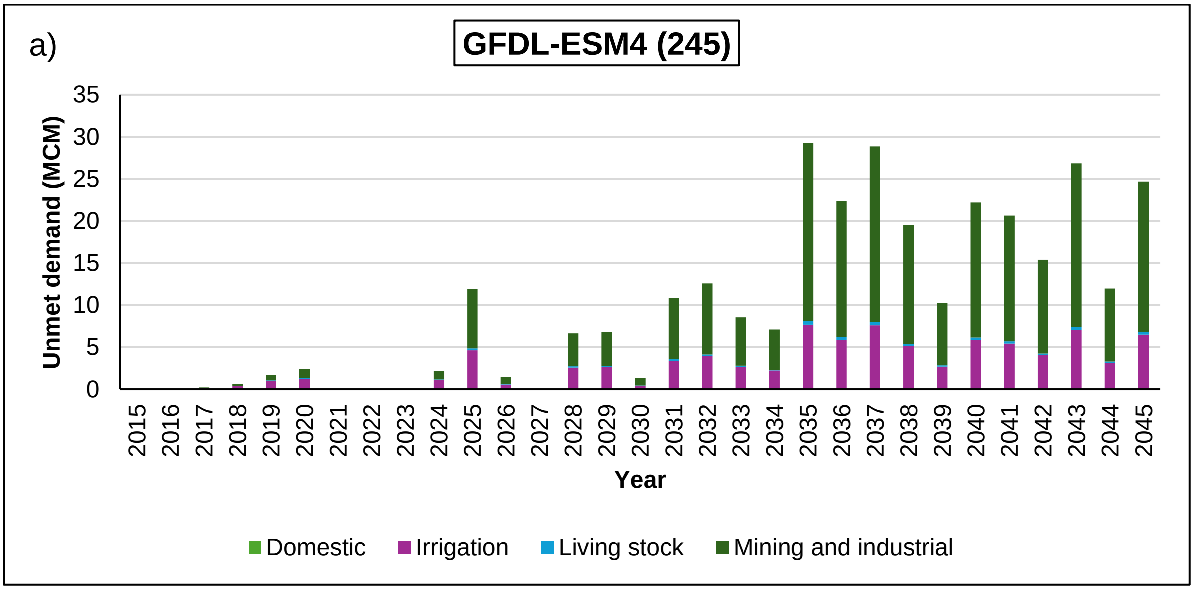
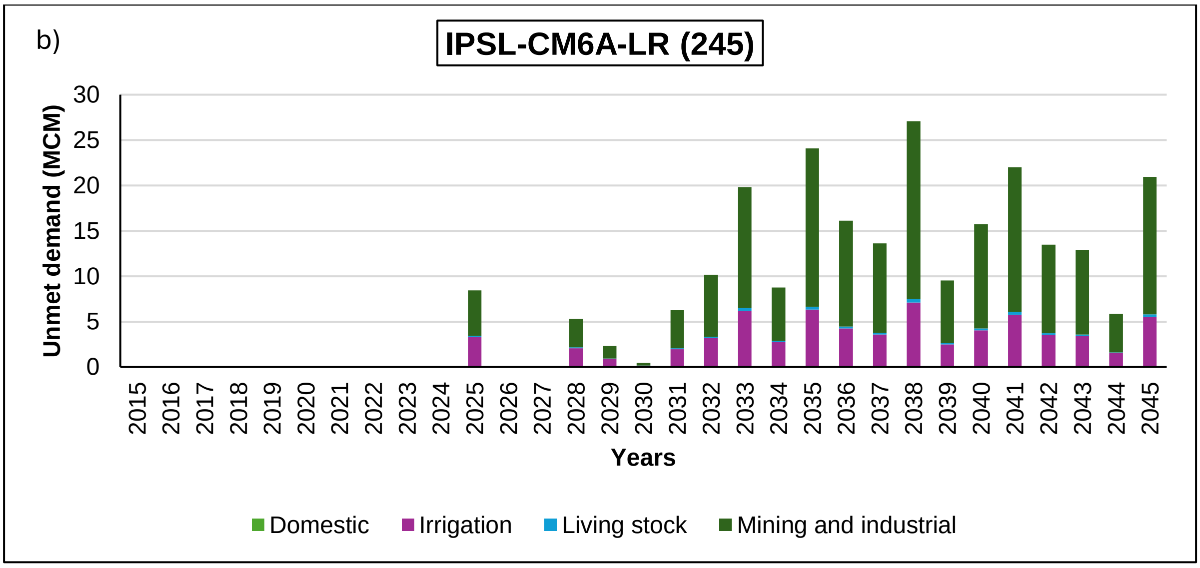


Figure 4. 7; The supply delivered comparison of the three CMIP6 model (a) IPSL-CM6A-LR, (b) GFDL-ESM4, and (c) MPI-ESM1-2-HR under SSP245 shown by plot a, b, c above indicates an increasing delivery of supply in the basin.

II) Unmet demand with SSP24

The results presented in Figure 4.8 illustrate the unmet demand outcomes derived from three distinct models under the Coupled Model Intercomparison Project Phase 6 (CMIP6) utilizing the Shared Socioeconomic Pathway 245 (SSP245). The analysis indicates that Model 1 (IPSL-CM6A-LR) exhibited unmet demand for the majority of the evaluated years. Notably, the years 2035 and 2037 recorded the highest unmet demand, with a shortfall of 23 million cubic meters (Mm^3) in the mining and industrial sectors, followed by an unmet demand of 8 Mm^3 in irrigation. In contrast, Model 2 (GFDL-ESM4) demonstrated the most significant level of unmet demand in 2038, with deficits of 7.25 Mm^3 in irrigation and 17 Mm^3 in the mining and industrial sectors. For Model 3 (MPI-ESM1-2-HR), the years 2035 and 2043 were characterized by considerable unmet demand. Specifically, in 2035, all sectors including mining, industry, livestock, and irrigation experienced unfulfilled demand. In 2043, unmet demand was observed solely within the mining, industrial, and irrigation sectors. The findings suggest that beginning in 2024, none of the models are capable of meeting the demands placed on mining, industry, and irrigation. Furthermore, livestock is similarly affected by unmet demand across all models; however, these deficits are relatively minor compared to those observed in industrial sectors. This indicates that despite the inflow of water into the catchment area, the supply yield remains insufficient to satisfy all demand requirements within the catchment. When comparing the three models the IPSL-CM6A-LR model performed better than the other two models.





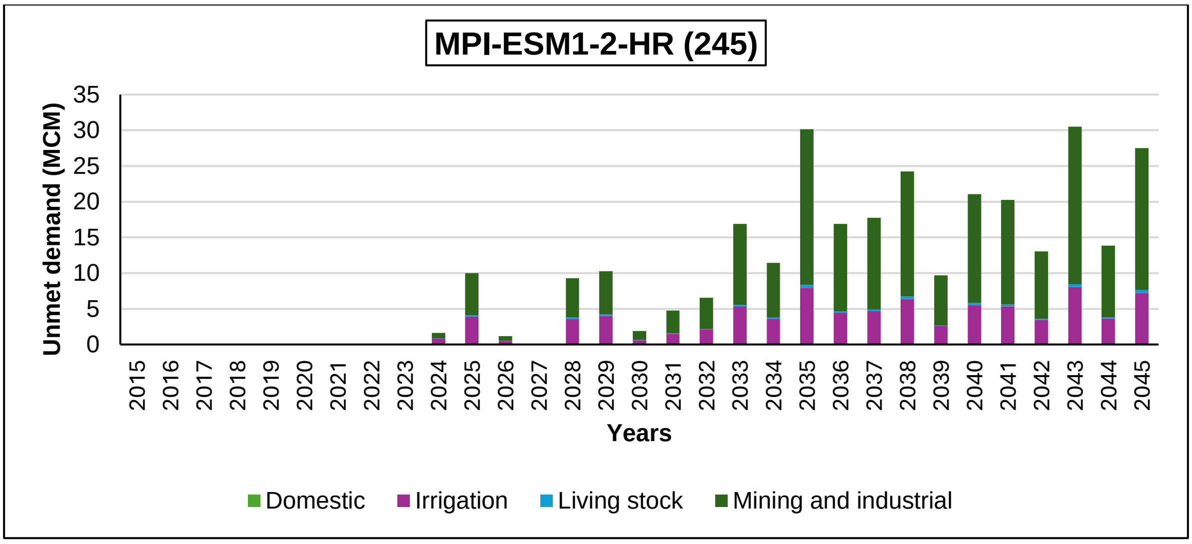
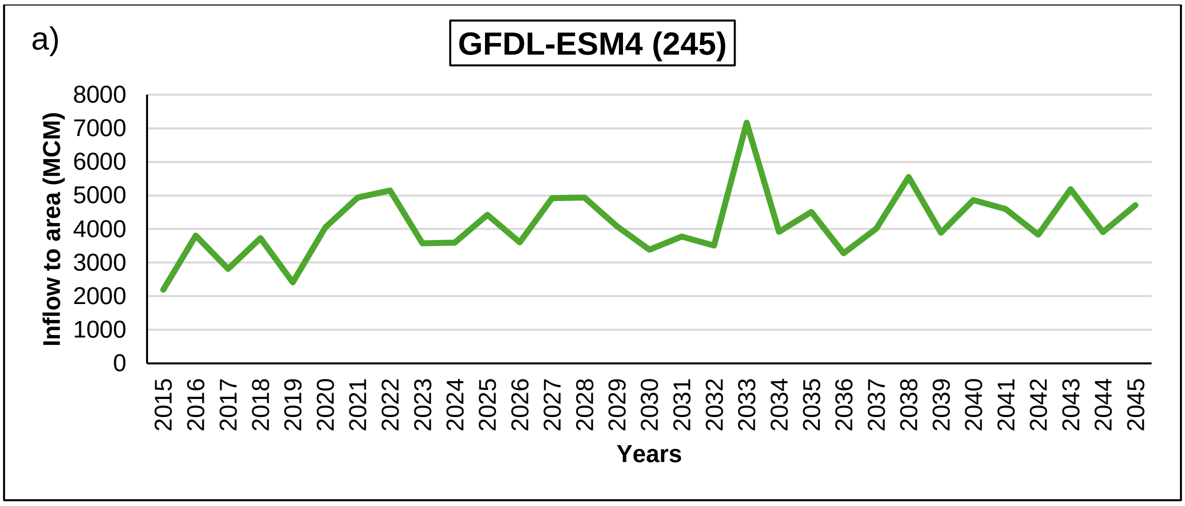
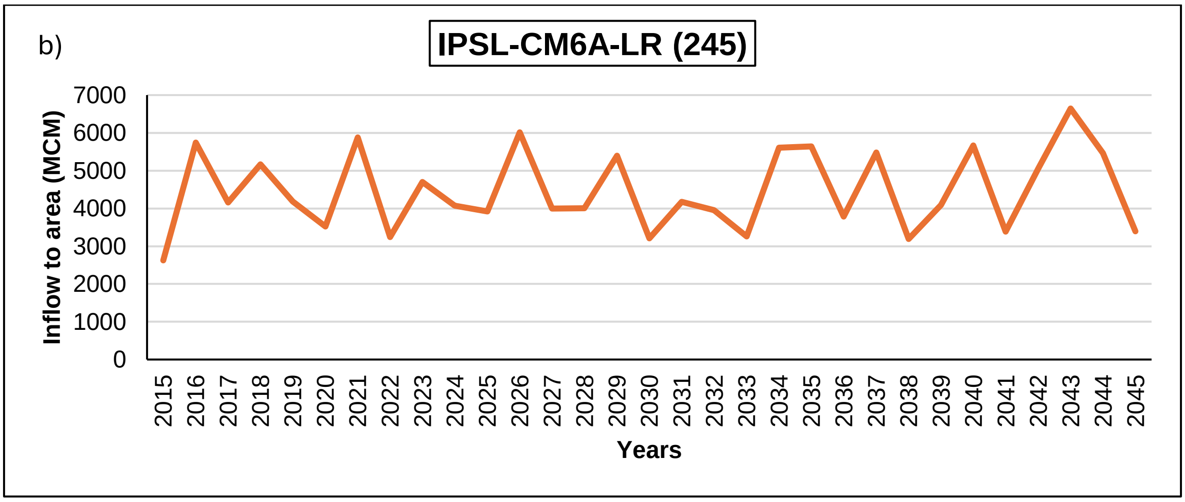


Figure 4. 8: The unmet demand comparison for the three climate models (a) IPSL-CM6A-LR, (b) GFDL-ESM4, and (c) MPI-ESM1-2-HR. under SSP245

III) Inflow to area with SSP245

Figure 4.7 illustrates the inflow to the studied area as projected by three different CMIP6 climate models, encompassing all relevant water sources. Model 1: IPSL-CM6A-LR exhibited an inflow that varied from 2193.42 Mm³ in 2015 to 4714.49 Mm³ in 2045, marking the final year of the prediction period. Notably, the minimum inflow was recorded in 2015, while the maximum inflow occurred in 2033, reaching 7167.63 Mm³. Model 2: GFDL-ESM4 demonstrated a slightly different trend, with inflow values ranging from 2625.33 Mm³ in 2015 to 3395 Mm³ in 2045. The peak inflow for this model was observed in 2043, where it reached 6645 Mm³. Model 3: MPI-ESM1-2-HR showed an initial inflow of 2438 Mm³ in 2015 and projected an increase to 4315 Mm³ by 2045. Similar to the other models, the highest inflow for this model occurred earlier, in 2031, at 6766 Mm³, with the lowest value again recorded in 2015. These results indicate significant variability in projected inflows among the three models, highlighting the influence of climate change on hydrological patterns within the region. The differences in inflow projections underscore the necessity for further investigation into model-specific assumptions and their implications for water resource management under changing climatic conditions.





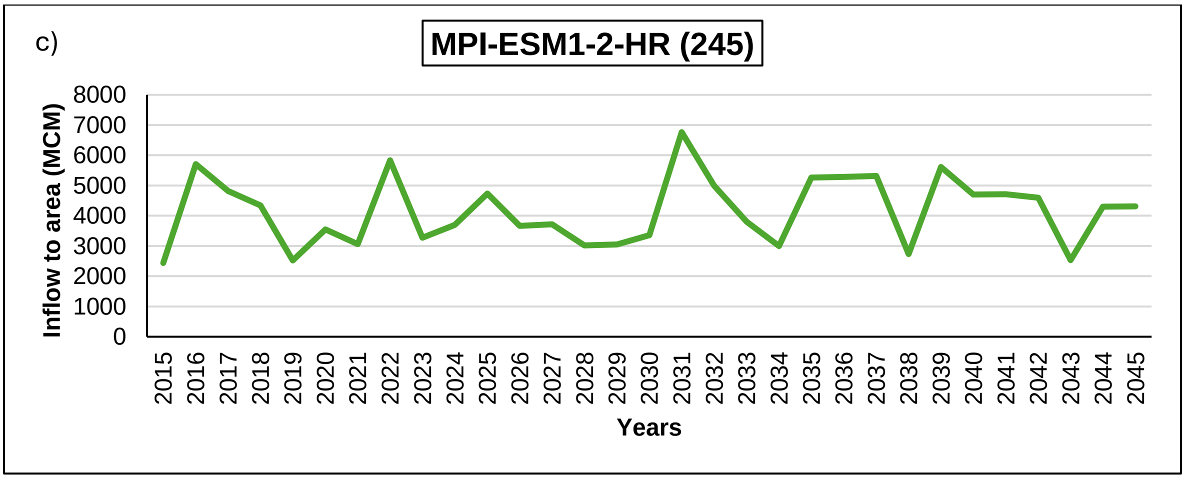
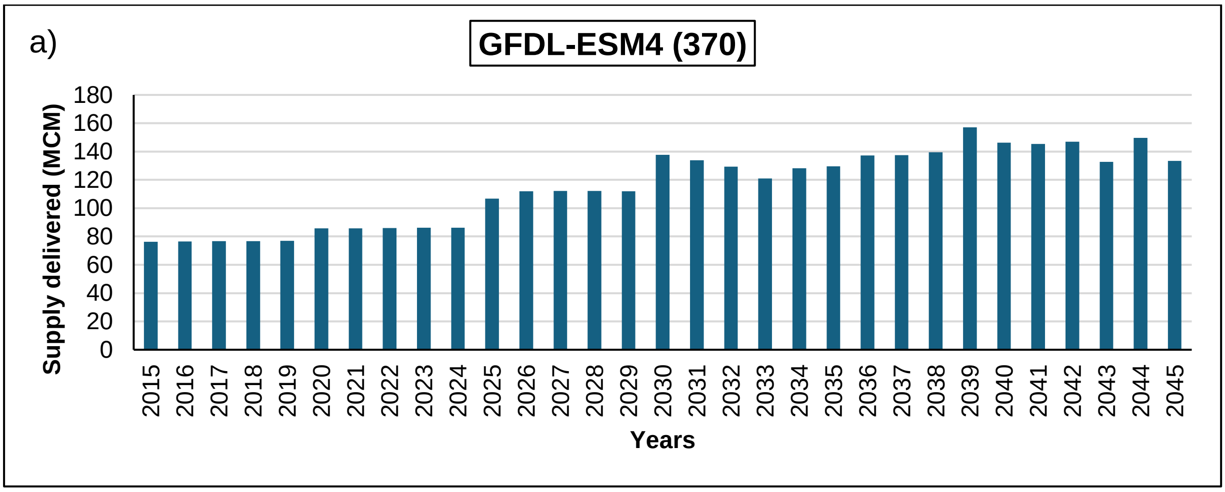
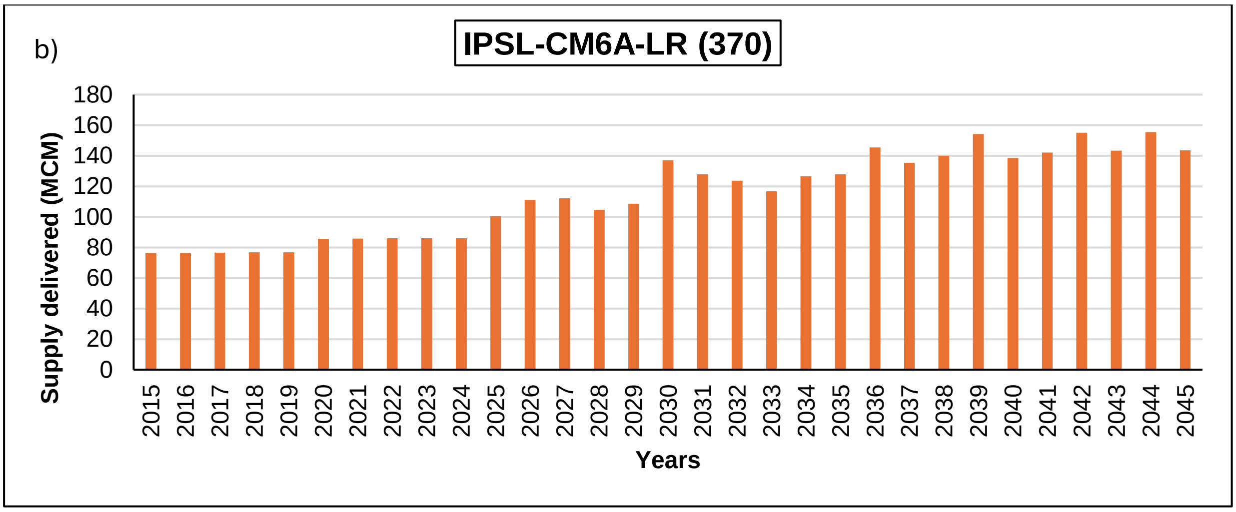


Figure 4. 9: Presents the Inflow to area comparison for the three CMIP6 models (a) IPSL-CM6A-LR, (b) GFDL-ESM4, and (c) MPI-ESM1-2-HR under SSP245.

i) Future water supply under SSP370

Figure 4.7 illustrates the inflow to the studied area as projected by three different CMIP6 climate models, encompassing all relevant water sources. Model 1: IPSL-CM6A-LR exhibited an inflow that varied from 2193.42 Mm³ in 2015 to 4714.49 Mm³ in 2045, marking the final year of the prediction period. Notably, the minimum inflow was recorded in 2015, while the maximum inflow occurred in 2033, reaching 7167.63 Mm³. Model 2: GFDL-ESM4 demonstrated a slightly different trend, with inflow values ranging from 2625.33 Mm³ in 2015 to 3395 Mm³ in 2045. The peak inflow for this model was observed in 2043, where it reached 6645 Mm³. Model 3: MPI-ESM1-2-HR showed an initial inflow of 2438 Mm³ in 2015 and projected an increase to 4315 Mm³ by 2045. Similar to the other models, the highest inflow for this model occurred earlier, in 2031, at 6766 Mm³, with the lowest value again recorded in 2015. These results indicate significant variability in projected inflows among the three models, highlighting the influence of climate change on hydrological patterns within the region. The differences in inflow projections underscore the necessity for further investigation into model-specific assumptions and their implications for water resource management under changing climatic conditions.





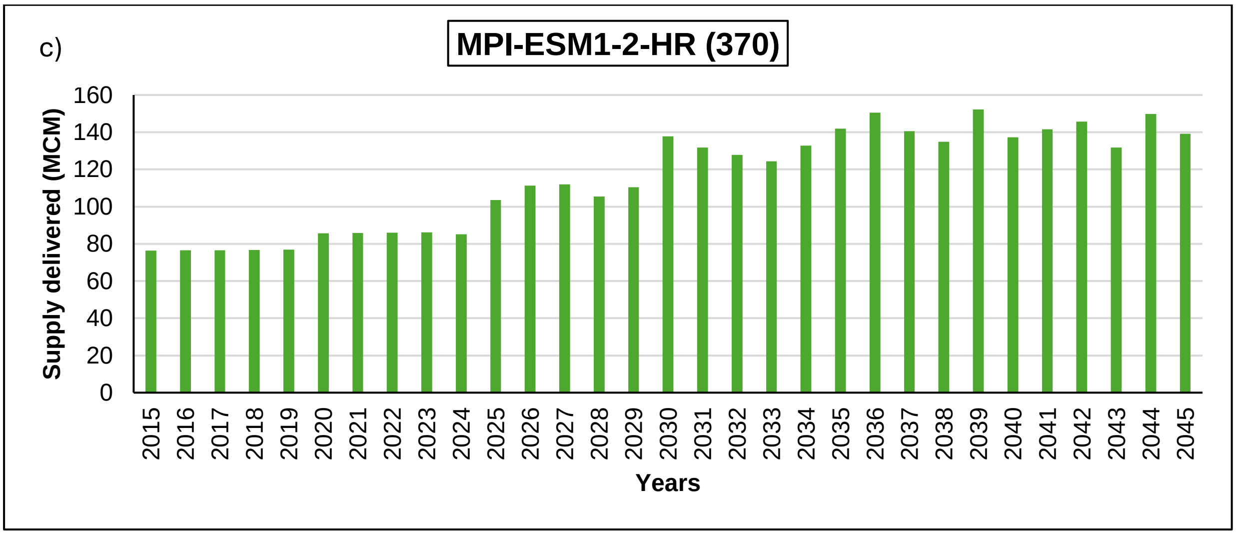
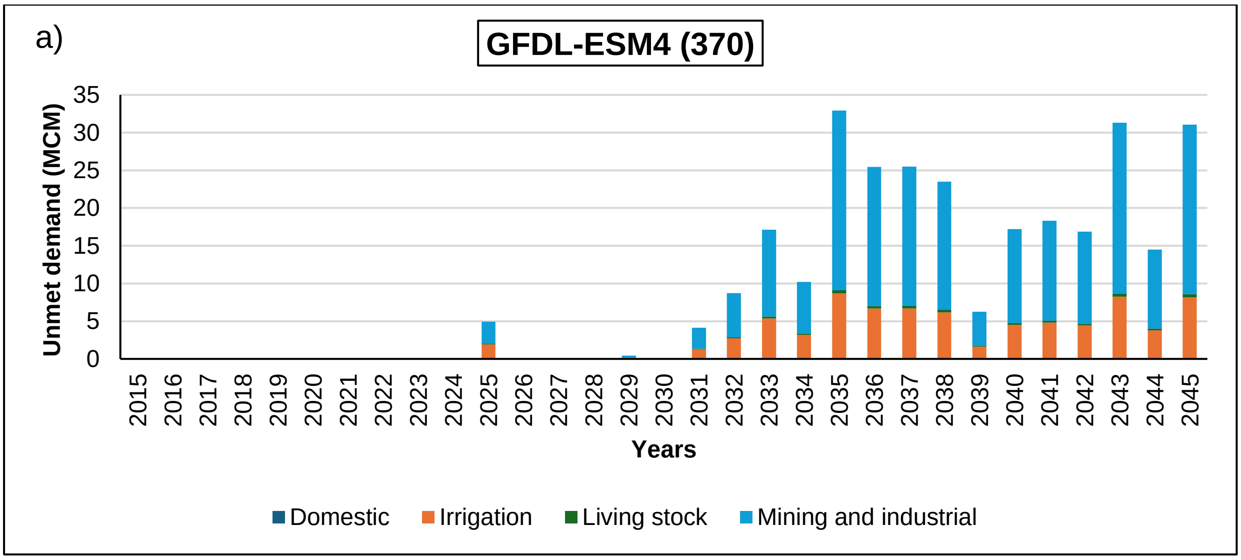


Figure 4. 10: Represents the water supply delivered to various demand sites under different CMIP6 models IPSL-CM6A-LR, GFDL-ESM4, and MPI-ESM1-2-HR with SSP370

ii) Future Unmet demand

Unmet water demand is a significant concern across three primary sectors: irrigation, livestock, and mining and industrial activities in this study. This analysis evaluates the extent of unmet demand as projected by three distinct climate models: IPSL-CM6A-LR, GFDL-ESM4, and MPI-ESM1-2-HR. the results in figure 4.11 displayed the following outcomes. In Model 1 (GFDL-ESM4), unmet demand is evident in the years 2025, 2029, and from 2031 to 2045. During this period, both the mining/industrial sector and irrigation experience considerable unmet demand, while the livestock sector exhibits only minimal unmet demand. Notably, the peak unmet industrial demand occurs in 2035, reaching 23.8 million cubic meters (Mm³), whereas irrigation faces an unmet demand of 8.66 Mm³. The total water requirement across these sectors is estimated at 163 Mm³; however, only 130 Mm³ is supplied. In Model 2 (IPSL-CM6A-LR), the industrial sector experiences an unmet demand of 25 Mm³, while irrigation's unmet demand is recorded at 9 Mm³. This model also highlights that the most significant unmet demand occurs in 2035, with a supply of only 128 Mm³ against a requirement of 163 Mm³. Model 3 (MPI-ESM1-2-HR) reveals that the peak unmet demand arises in 2043, where mining and industrial activities face an unmet demand of 23 Mm³ and irrigation shows an unmet demand of 8.5 Mm³. This model successfully delivers 132 Mm³ instead of the required 164 Mm³. When examining the scenarios under Shared Socioeconomic Pathway (SSP) 370, Model 2 demonstrates the highest levels of unmet demand compared to Models 1 and 3. This trend illustrate the varying impacts of climate models on projected water availability and highlights the critical need for effective water management strategies to address these gaps in supply across different sectors. Based on the above results, model2 (IPSL-CM6A-LR) performed better under the SSP370 scenario.



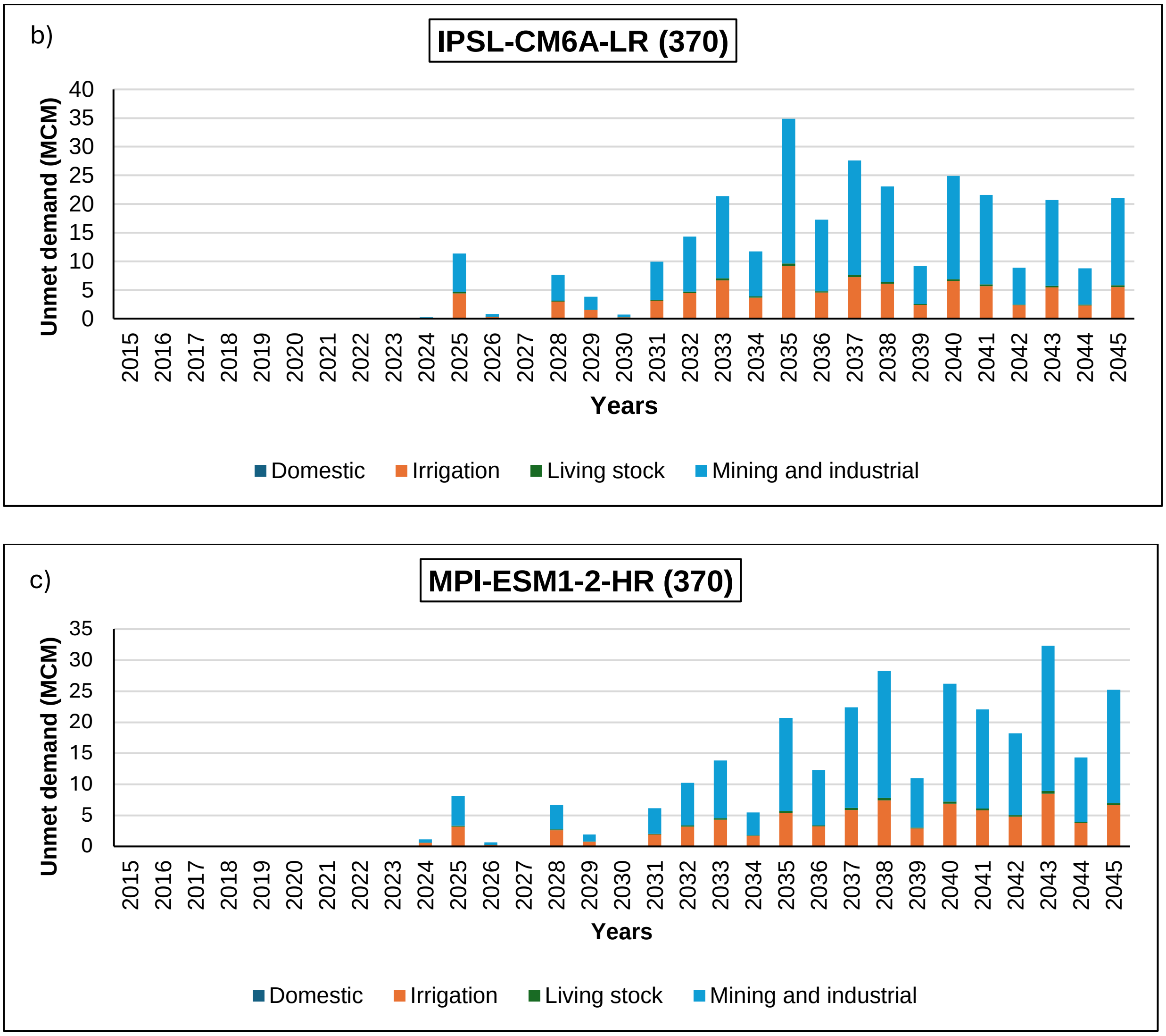
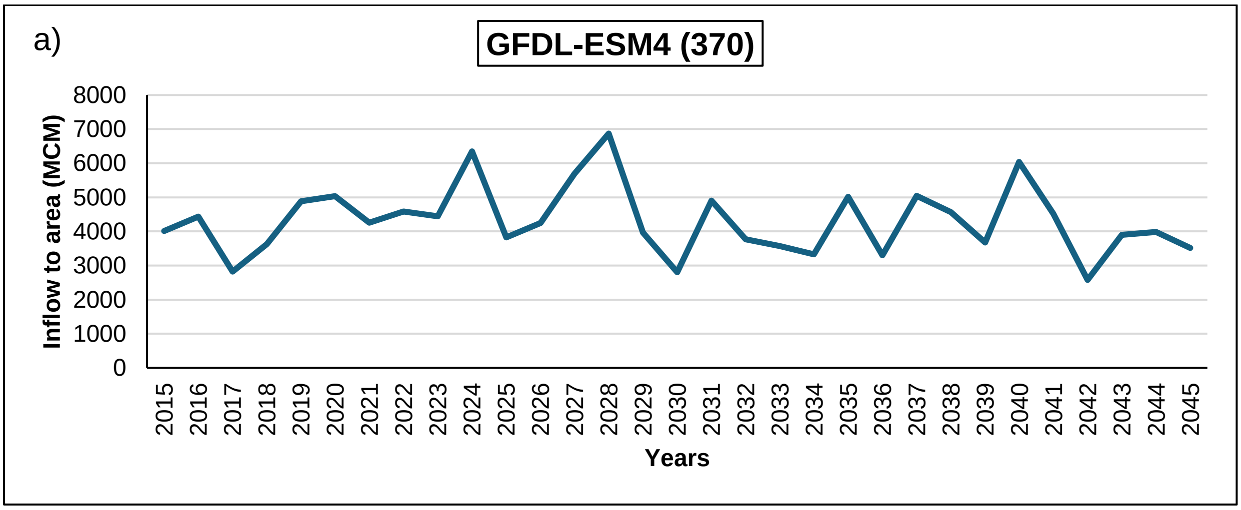
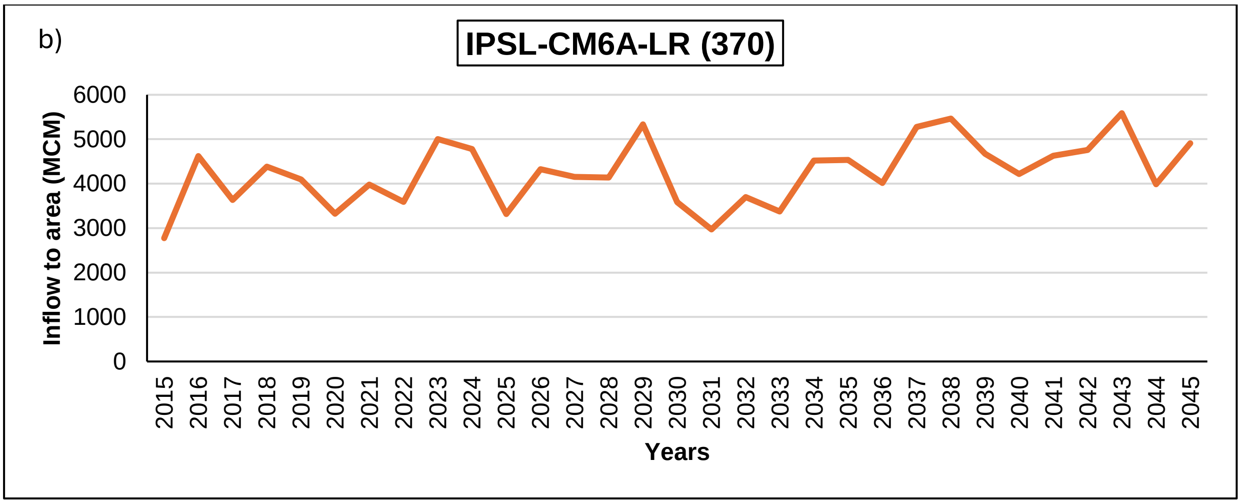


Figure 4. 11: The unmet demand Comparison of the three CMIP6 models under SSP370 shown by plot a, b, c above indicates increasing unmet demand in the basin.

iii) Future inflow to area with SSP370

The availability of water in the Mokolo River is significantly influenced by various meteorological factors, including precipitation, average temperature, wind speed, and humidity. These climatic elements play a crucial role in determining the inflow into the river system, which has exhibited notable fluctuations over the years due to the impacts of climate change. In the context of Model 1 (IPSL-CM6A-LR), the inflow to the Mokolo River has shown a declining trend, decreasing from 4010 Mm³ in 2015 to 3513 Mm³ by 2045. The most significant reduction occurred in 2043, when inflow reached a low of 2579 Mm³. Conversely, the highest inflow was recorded in 2028, with a substantial volume of 6870 Mm³, indicating that this year experienced significantly higher precipitation compared to other years. For Model 2 (GFDL-ESM4), inflow values ranged from 2777 Mm³ in 2015 to 4912 Mm³ in 2045. The peak inflow for this model was observed in 2029, reaching 5334 Mm³. In Model 3 (MPI-ESM1-2-HR), initial inflow was measured at 1791 Mm³ in 2015, with projections indicating an increase to 4807 Mm³ by 2045. The highest inflow under this model occurred in 2021, with an inflow of 5933 Mm³, reflecting variability influenced by climatic conditions. Several factors may contribute to the observed low inflow levels in certain years, particularly in relation to climate change. These include Variability in Precipitation: Changes in rainfall patterns can lead to significant differences in water availability. Years with below-average precipitation result in reduced river flow (Meskelu,2024). Increased Evapotranspiration: Higher temperatures can enhance evaporation rates from both soil and water bodies, further diminishing available water resources. Climate Change Impacts: Long-term shifts in climate can alter hydrological cycles and seasonal distributions of rainfall, resulting in decreased inflow during critical periods (Jiménez-Navarro et al., 2021).





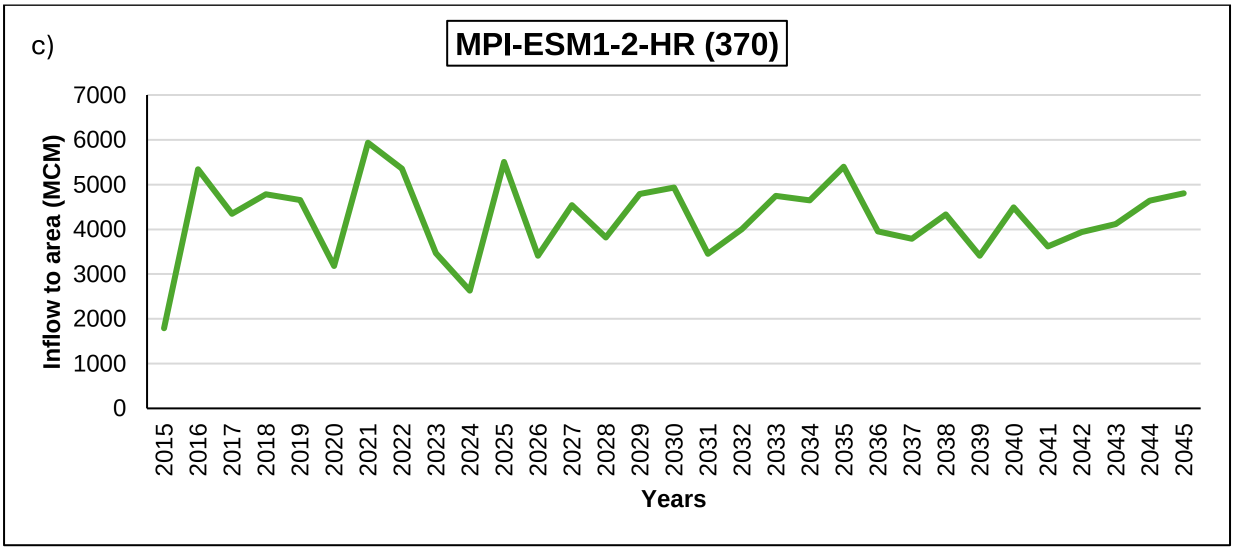


Figure 4. 12: Presents the inflow to area comparison for the three CMIP6 models (a)PSL-CM6A-LR, (b) GFDL-ESM4, and (c) MPI-ESM1-2-HR under the SSP370

4.8. Objective 3 results: Future outcomes of water demand and supply management scenarios

4.9. Reference scenario: Baseline scenario

In this scenario, the model assumes that the current pattern of growth and water use continues, taking into account the impact of climate change and population expansion. A 1.7% growth rate was anticipated based on LRS. Also, it was assumed that there was an inter basin transfer of 13 Mm3 to the Mokolo dam and the startup year was 2015, as indicated in the 2016 reconciliation strategy for the Limpopo province. It was observed that the projected total water demand increased from 86Mm3 at the onset of the simulation to 164 Mm3 at the end of the scenario (Figure 4.13). The population in the Mokolo region was expected to increase due to employment opportunities in mining and industrial sectors, leading to a greater number of individuals relocating to the area for work. Figure 4.14 illustrates the anticipated water supply delivered to demand sites in Mokolo up to the year 2045, with estimates suggesting that supply will fluctuate from 80 Mm³ in 2024 to 130 Mm³ by 2045. The scenario forecasts a significant rise in unmet water demand in most years, as depicted in Figure 4.15. The mining and industrial sectors, along with irrigation, are projected to experience the highest levels of unmet demand due to their substantial water requirements. Conversely, unmet demand within the livestock sector varies annually. This unfulfilled demand is concerning due to the fact that is seen in most years. This suggests that unmet demands for livestock may be attributed to a conversion of irrigation lands into game farms, resulting in an increase in livestock numbers (DWS, 2016).

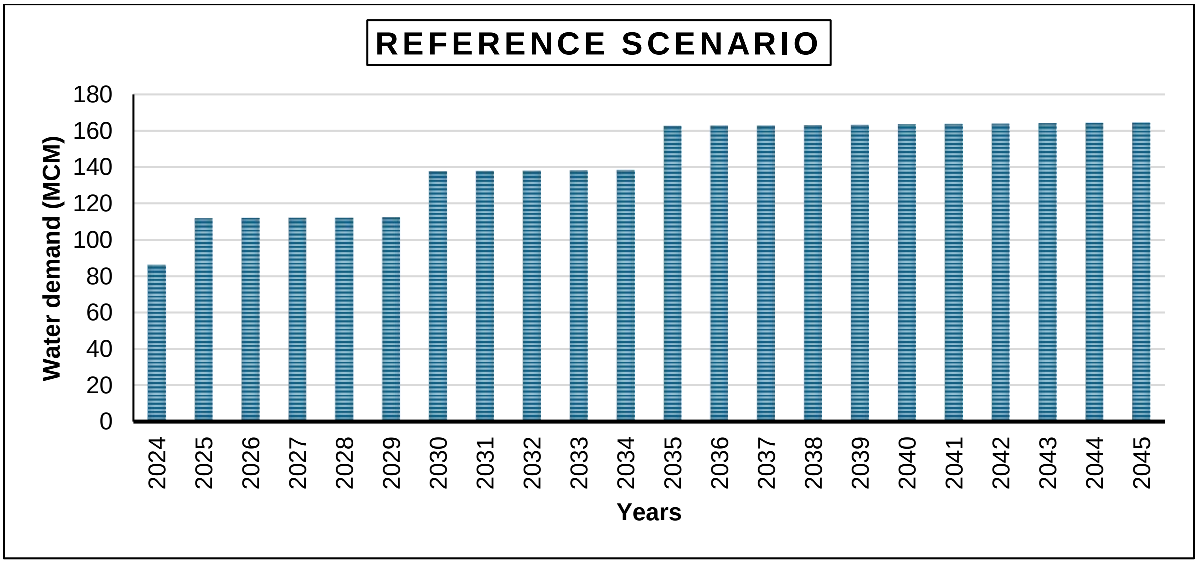


Figure 4. 13: illustrate the water demand for the reference scenario at the mokolo river catchment.

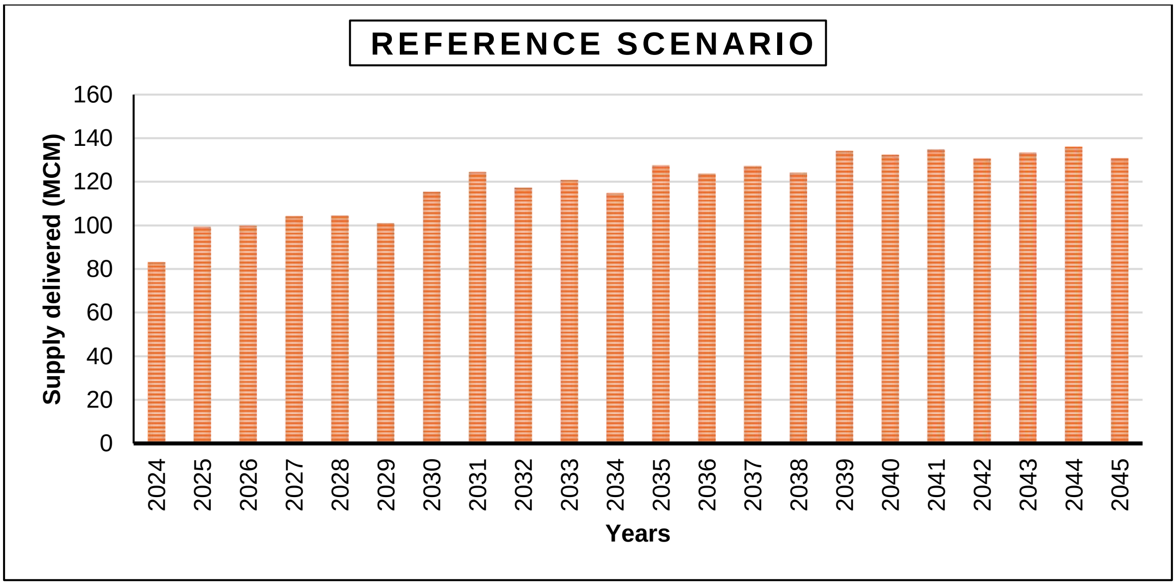


Figure 4. 14: Shows the amount of water being supplied to the various demand sites at the Mokolo River.

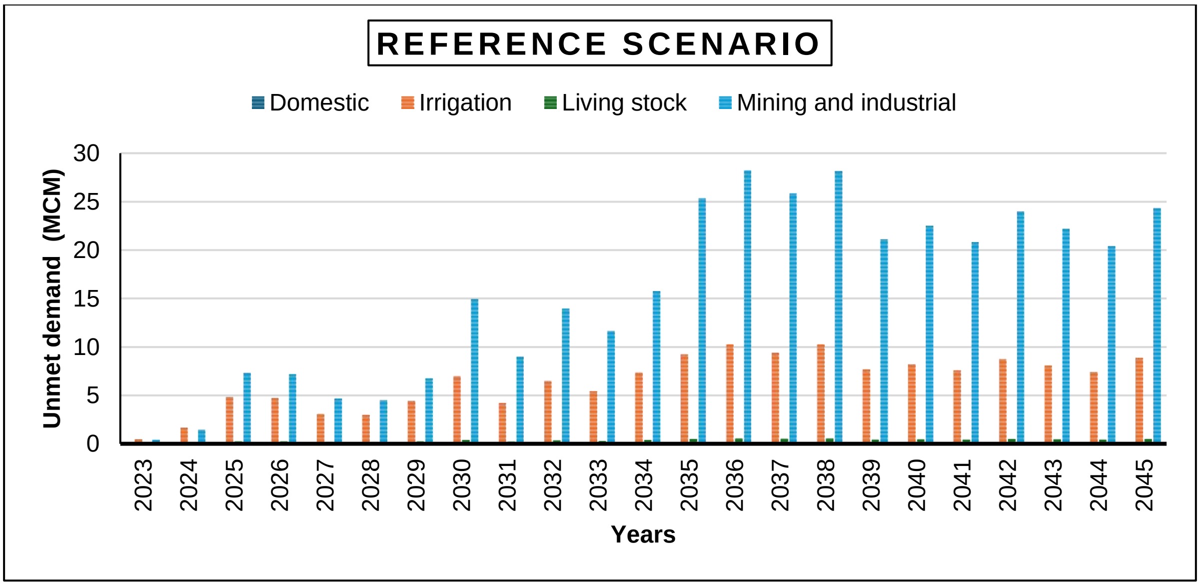


Figure 4. 15: Displays the unmet demand under the reference scenario at the Mokolo River catchment.

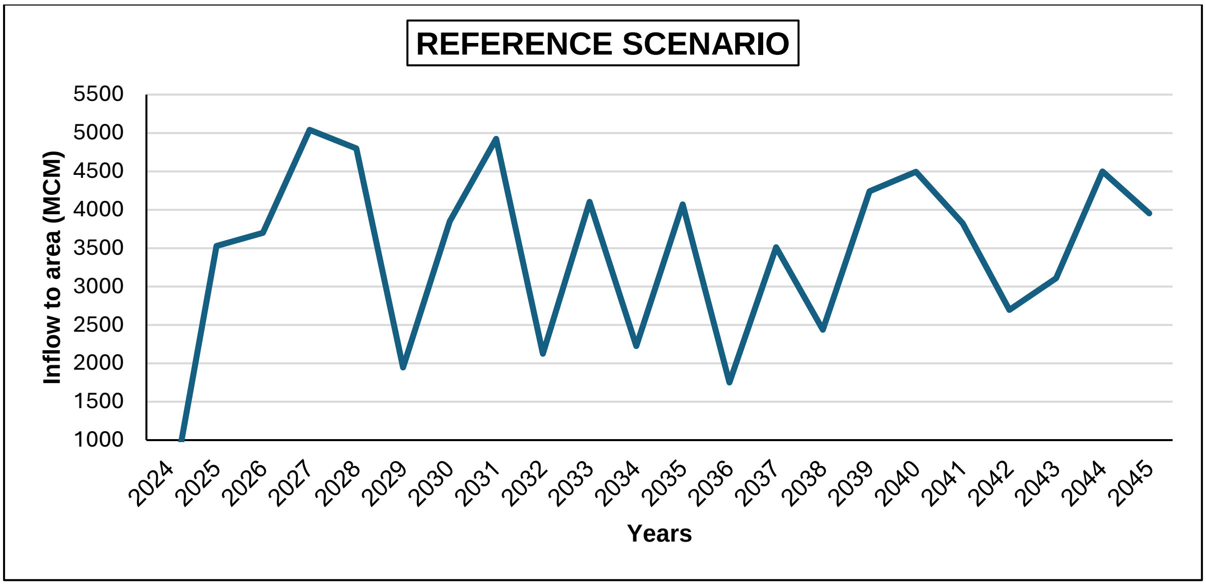


Figure 4. 16: Presents the inflow to area for the refence scenario for the period 2024 to 2045.

Management scenario 1: Irrigation reduction due to advance technology implemented.

The scenario referred to as the Irrigation Efficiency Scenario posits a reduction in irrigation water consumption, projecting a decrease of 15% by the year 2025, attributed to advancements in irrigation technology. As illustrated in Figure 4.17, water demand is anticipated to rise from 86 million cubic meters (Mm³) during the base period to 130 Mm³ by the conclusion of 2045. Notably, there was a decline in demand from 112 Mm³ to 86 Mm³, which is ascribed to the expectation that the irrigation sector will begin utilizing water more judiciously through the implementation of advanced irrigation technologies by 2025. Furthermore, Figure 4.18 indicates that the water supply is expected to fluctuate between 83 Mm³ and 112 Mm³ by 2045. A notable decrease in water supply is projected for the period spanning from 2025 to 2029. This reduction has resulted in unmet demand within the irrigation sector during those years, as depicted in Figure 4.19. Overall, the reduction in irrigation consumption has contributed to a decrease in unmet demand in the irrigation sector when compared to the reference scenario. However, it is important to note that the mining and industrial sectors continue to face significant unmet demand even through irrigation water use is decreased. These findings are in line with a study by Berbel (2018) that evaluated the relationship between irrigation consumption and efficiency using a microeconomic model and found that increasing efficiency would result in a considerable reduction in water use.

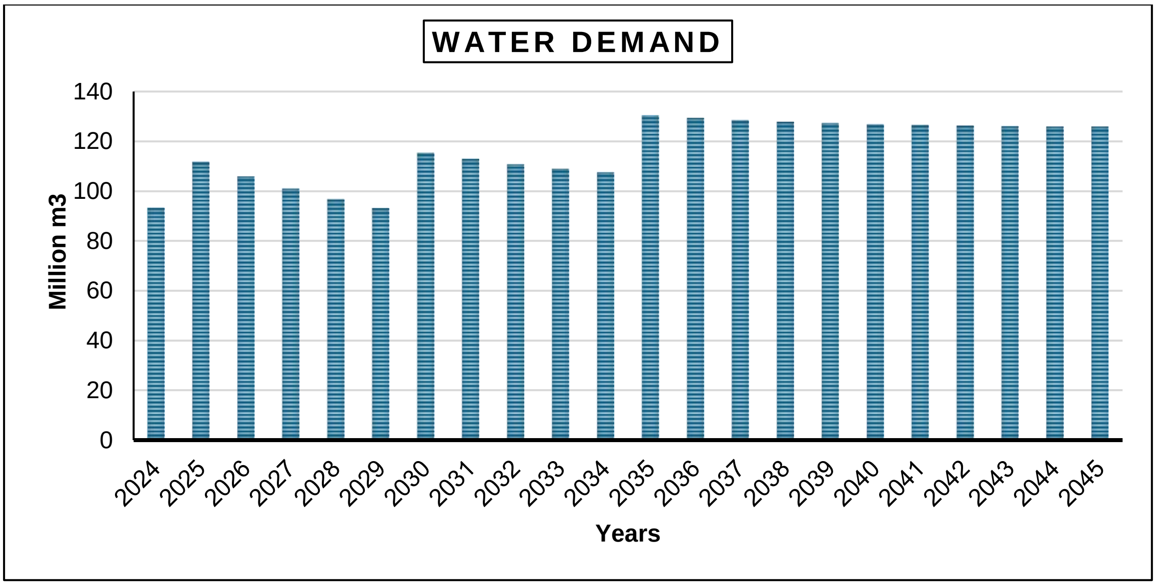


Figure 4. 17: Shows the water demand for the irrigation reduction scenario

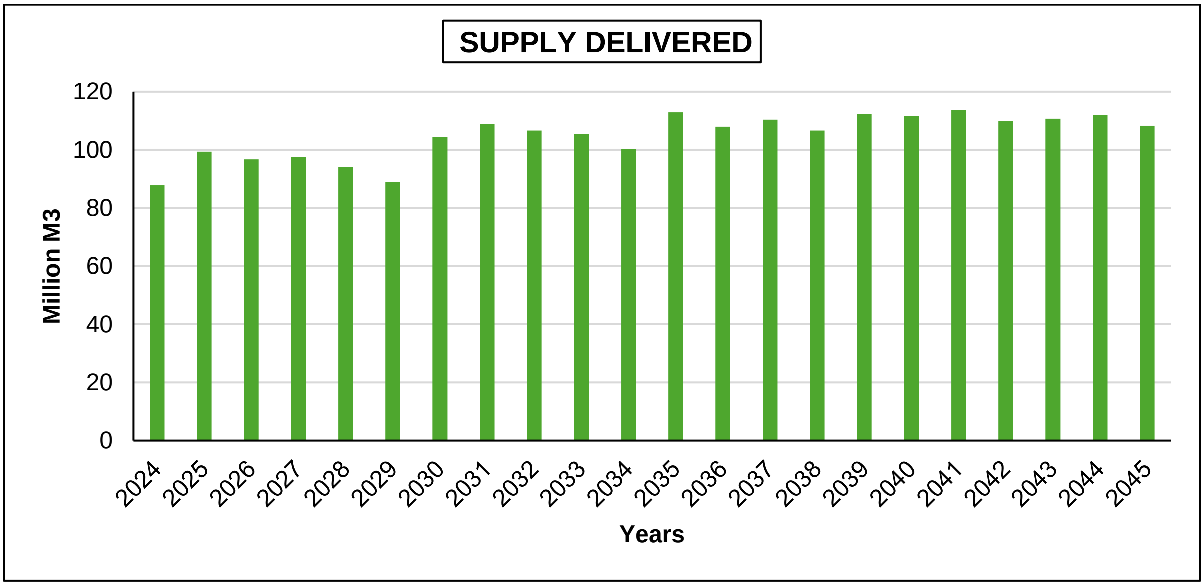


Figure 4. 18: Presents the supply delivered for the different demand site under the irrigation reduction scenario.

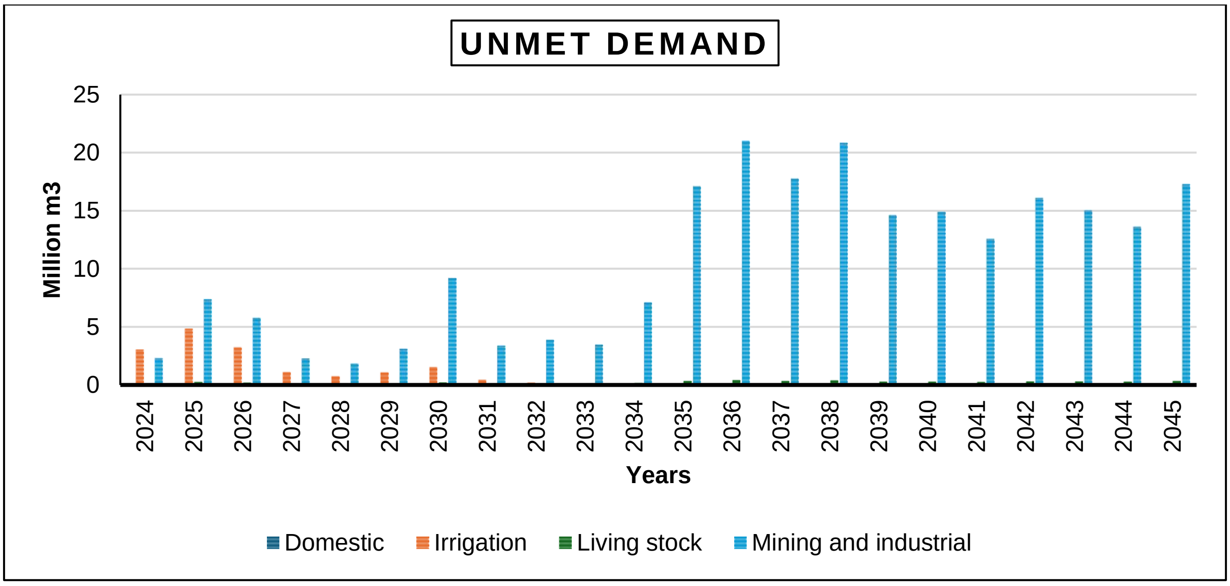


Figure 4. 19: Displays the unmet demand after the irrigation water use has been reduced.

Management scenario 2: Domestic water conservation measures

In the baseline year of 2015, domestic water demand was recorded at 88 million cubic meters (Mm³). This demand is projected to increase to 152 Mm³ by 2045 as shown in figure 4.20. This significant rise highlights the necessity for effective water management strategies to mitigate potential shortages and enhance sustainability. The results in figure 4.22 show that supply deliveries to the basin are expected to fluctuate, starting from 85 Mm³ in 2015 and reaching approximately 121 Mm³ by 2045. This trajectory indicates a potential shortfall in meeting the projected demand, highlighting the critical need for intervention strategies. The results in figure 4.23 further reveals that unmet demand is anticipated to escalate from 3 Mm³ during the base period to a concerning 32 Mm³ by 2045. This increase in unmet demand signifies an urgent call for enhanced water conservation measures and infrastructure improvements to address leakages and inefficiencies in the system. It is important to note that streamflow is predicted to remain consistent with the reference scenario throughout this period. This stability suggests that while demand may increase significantly, the natural water supply may not experience corresponding growth, thereby exacerbating the pressure on available resources. The findings from this scenario highlight a pressing need for comprehensive water conservation measures and proactive management strategies. Implementing effective water-saving initiatives and reducing leakages will be essential in achieving the projected reduction in domestic water demand. Without such interventions, the anticipated rise in unmet demand could lead to severe implications for water availability and sustainability by 2045

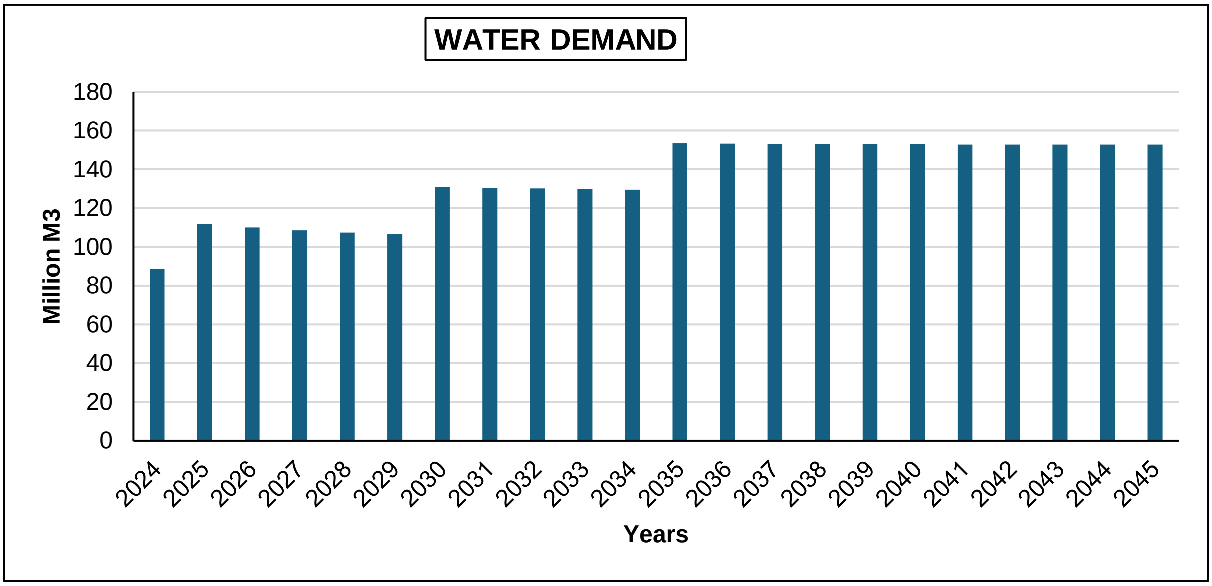


Figure 4. 20: The water demand under the domestic conservation measure scenario is shown in this plot.

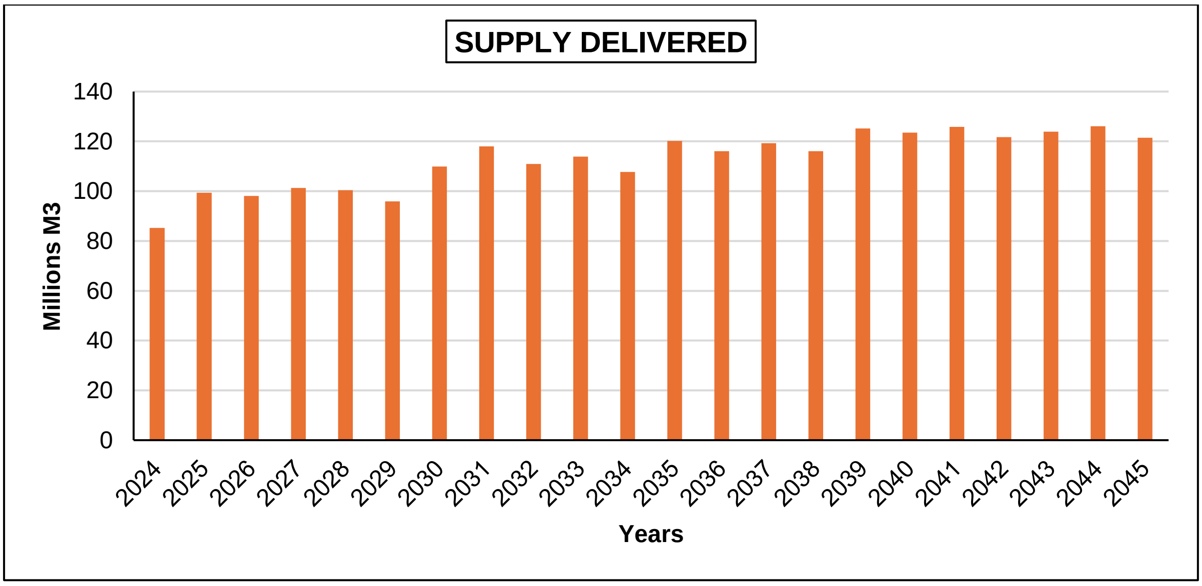


Figure 4. 21: The supply delivered to the demand sites after domestic conservation measures has been implemented

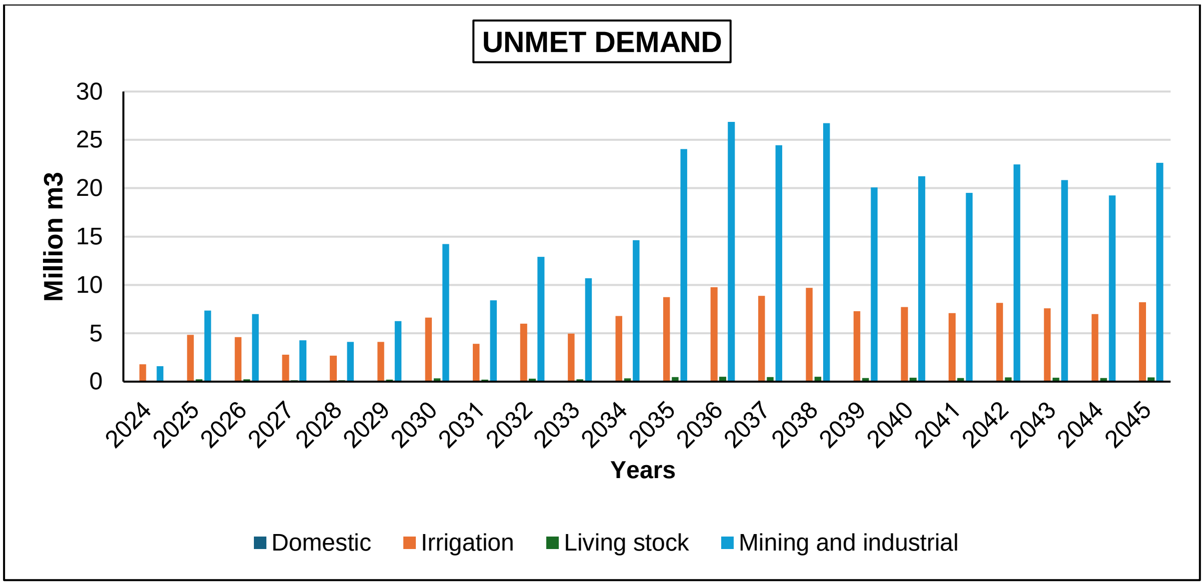


Figure 4. 22: The unmet demand under the domestic water conservation scenario

Management scenario 3: Mining and industrial efficiency improvements due to Advance technologies.

The scenario under consideration examines the implications of implementing water efficiency technologies within the mining and industrial sectors of a river basin. This approach, termed the "incorporation of water efficiency technologies" scenario, indicates a substantial projected reduction in water demand. Specifically, it is anticipated that the adoption of advanced water management technologies will decrease industrial water demand from 112 million cubic meters (Mm³) in 2025 to 94 Mm³ by the conclusion of the scenario period as displayed in figure 4.23. By 2045, the results in figure 4.24 the total volume of water delivered to the basin is expected to reach 92 Mm³, an increase from 84 Mm³ recorded in the base year. However, despite these advancements, the estimated unmet demand for water is projected to rise as seen in figure 4.25. Notably, the peak unmet demand is forecasted to occur in 2036. It is important to highlight that the reduction in water use from mining and industrial activities has a relatively minor impact on overall water supply and unmet demand when juxtaposed with the reference scenario. Consequently, this scenario does not significantly alleviate unmet demand throughout the period from 2025 to 2045

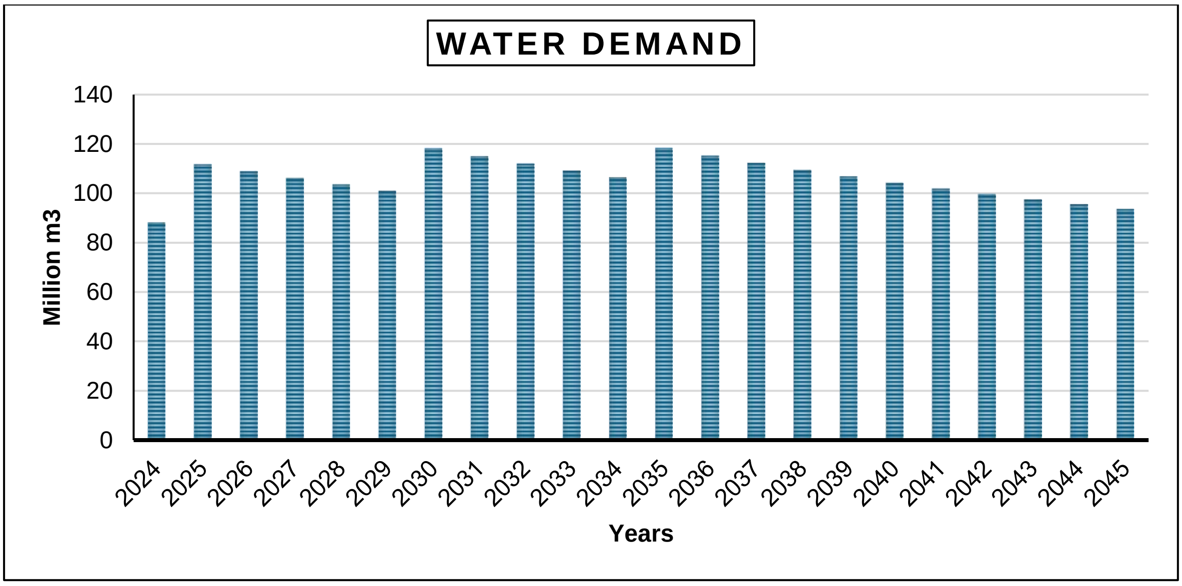


Figure 4. 23: The water demand for the Mining and industrial efficiency improvement due to advance technologies.

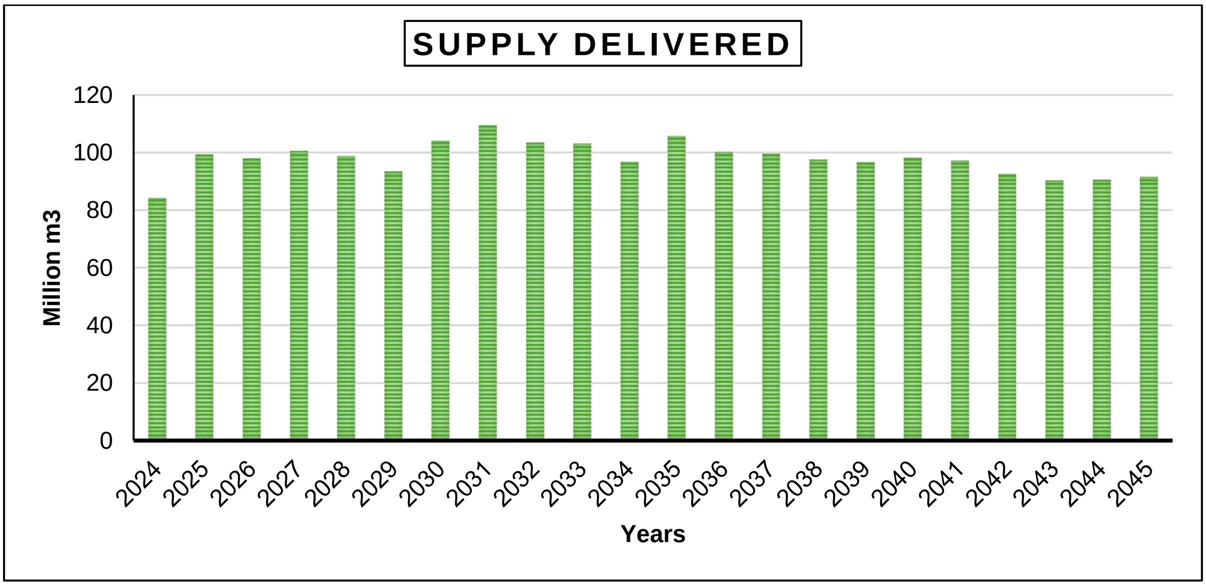


Figure 4. 24: The supply delivered under the industrial efficiency improvement scenario.

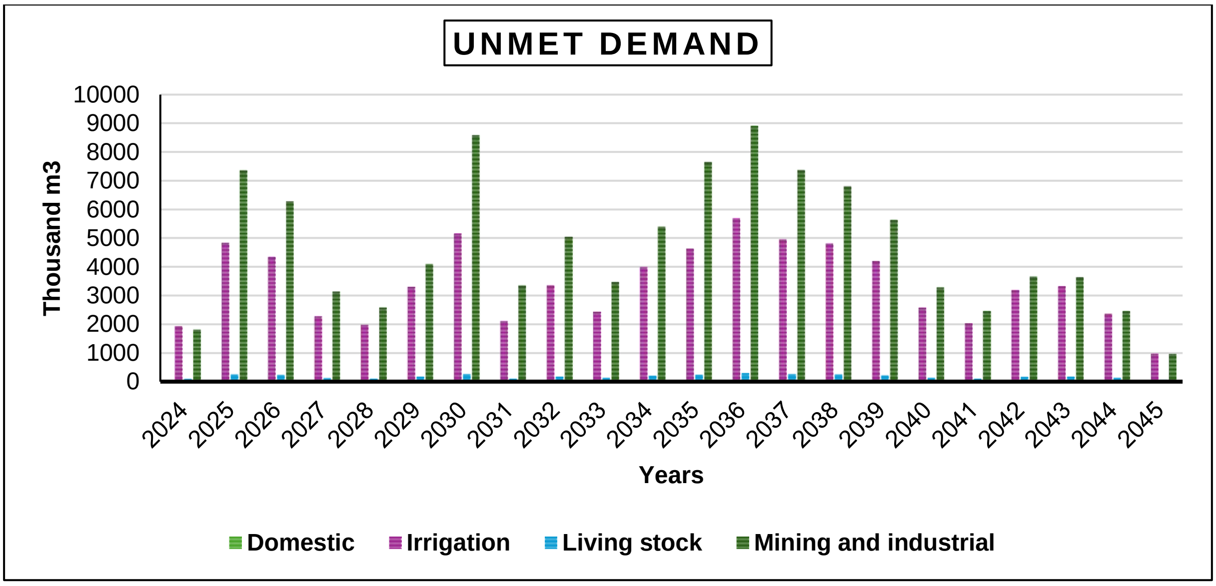


Figure 4. 25:The unmet demand under the industrial efficiency improvement due to technology innovations.

Management scenario 4: Introduction of Inter basin transfer-in from another catchment

The effects of an inter-basin transfer in the Mokolo basin are analysed in this scenario, termed the "increase in supply scenario." This scenario anticipates a transfer of 100 million cubic meters (Mm³) by 2030, which is expected to address the rising demand in the catchment area. As illustrated in Figure 4.26, water consumption is projected to increase from 86 Mm³ to 164 Mm³. Furthermore, future deliveries to the basin are expected to grow from 83 Mm³ in 2024 to 164 Mm³ by 2045, as depicted in Figure 4.27. The estimates suggest that unmet demand will increase between 2024 and 2029 before the additional supply is implemented. The results shown in revealed that inflow to area under this scenario varied for the study period. The inflow at the begin of the period was 143 Mm3and it increased to 4055Mm3 in the last period of the scenario. 4 figure 4.29 Figure 4.28 demonstrates that this extra supply has the potential to significantly reduce unmet demand in the Mokolo catchment compared to three other scenarios. These findings indicate that transferring water supply from another catchment can effectively alleviate unmet demand in the Mokolo basin.

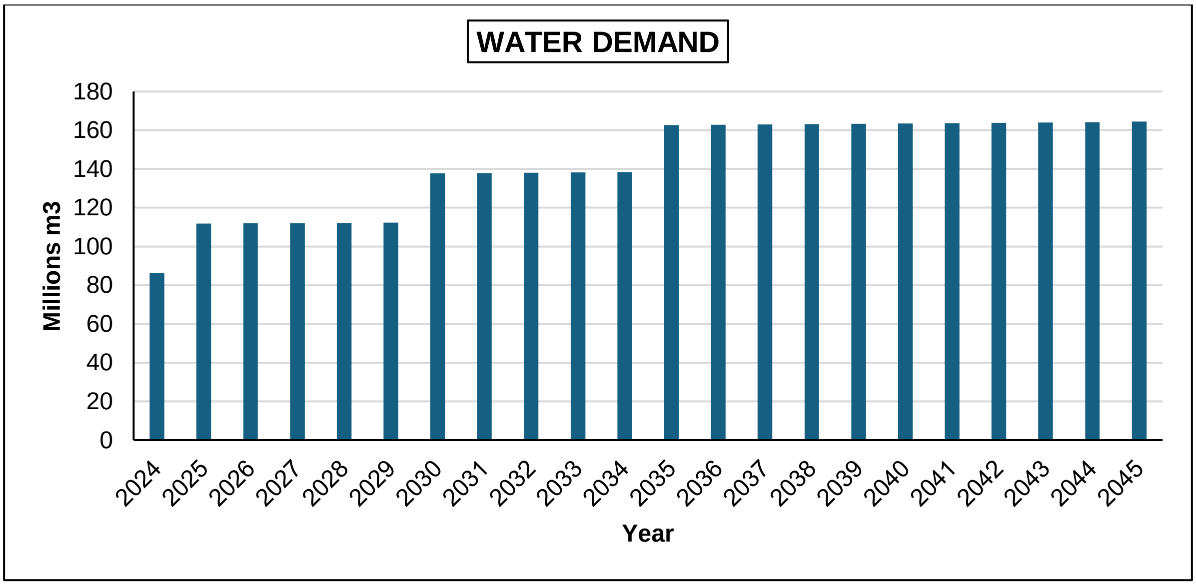


Figure 4. 26: The water demand for the inter basin transfer is shown by the plot above.

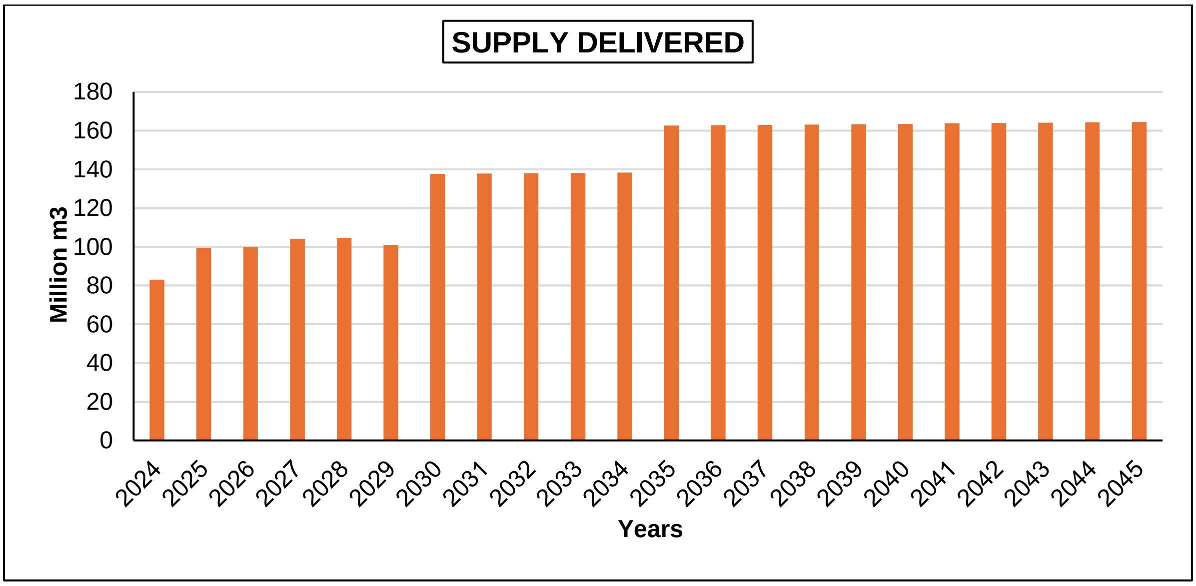


Figure 4. 27: The supply delivered under the inter basin transfer scenario.

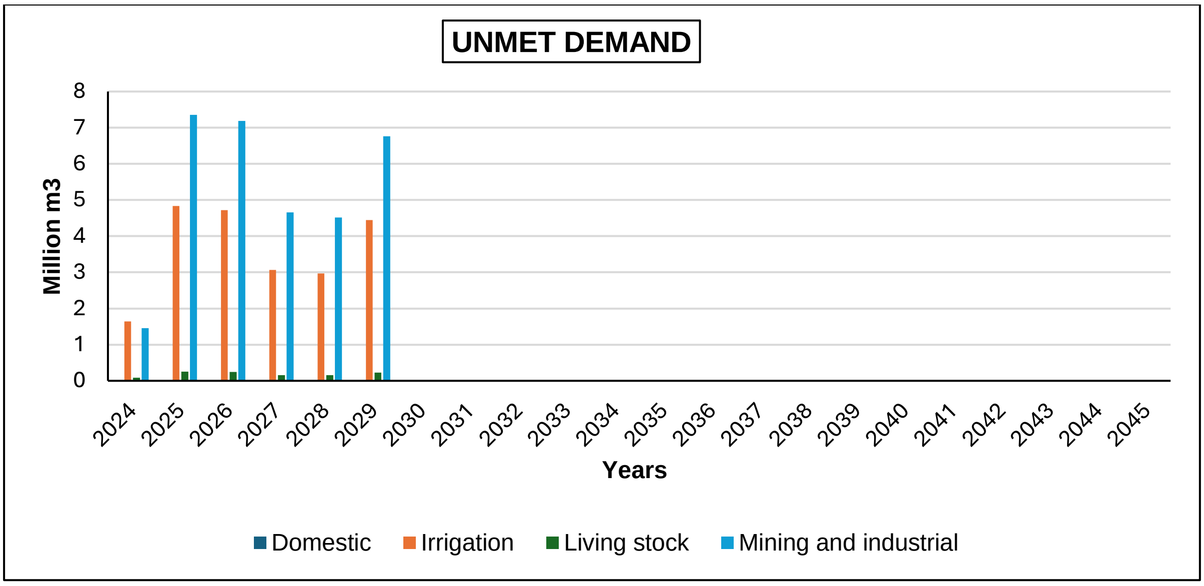


Figure 4. 28: The unmet demand experienced by various demand sites under the inter basin transfer scenario.

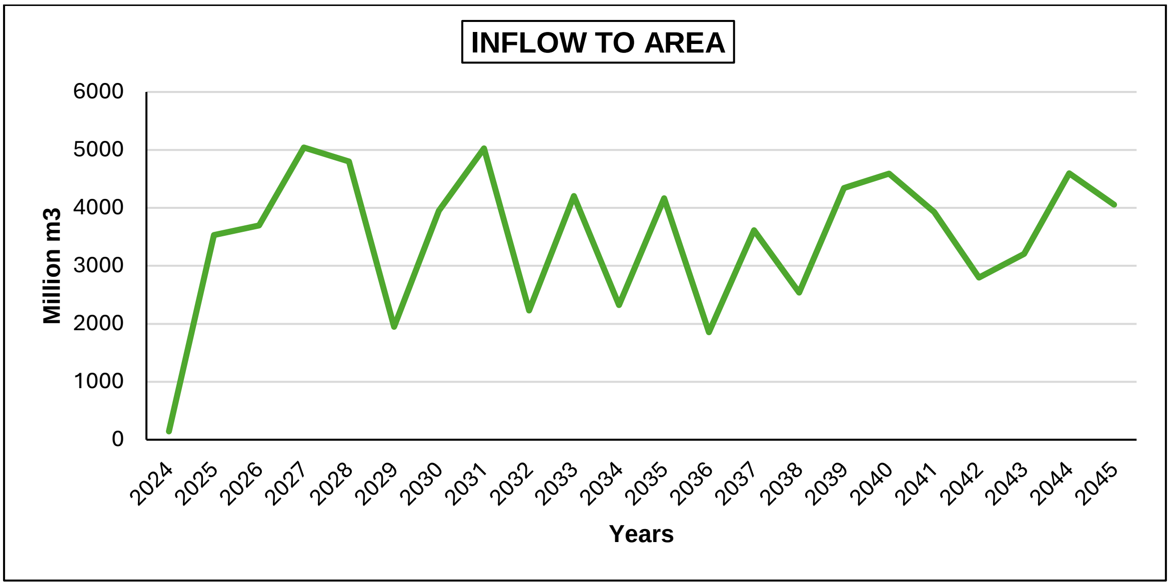


Figure 4. 29: The Inflow to area under the inter basin transfer scenario for the period (2024-2045).

Management scenario 5: Combination of all scenarios

This analysis evaluates the effects of integrating all scenarios to assess their influence on water demand, supply, and unmet demand. The findings indicate that water demand is projected to decrease from 88 million cubic meters (Mm³) in 2015 to 43 Mm³ by 2045, as illustrated in Figure 4.30. Concurrently, the water supply delivered to the basin is expected to decline from 91 Mm³ in 2024 to 45 Mm³ by 2050, as shown in Figure 3.31. This reduction in water supply is attributed to the corresponding decrease in water demand. Figure 4.32 reveals that unmet demand is anticipated to rise in 2025 but will begin to decrease from 2026 through 2029. Following this period, there is no projected unmet demand until the conclusion of the scenario timeframe. These results suggest that the combination of these scenarios effectively reduces unmet demand across various sites within the Mokolo catchment.

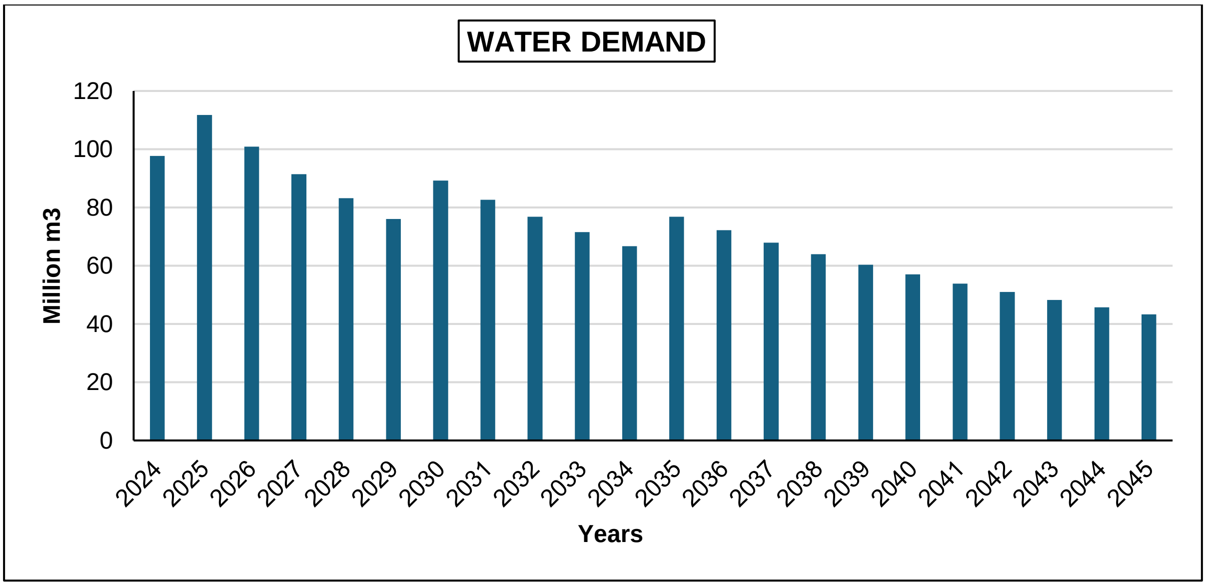


Figure 4. 30:The water demand for the combined integrated management strategy.

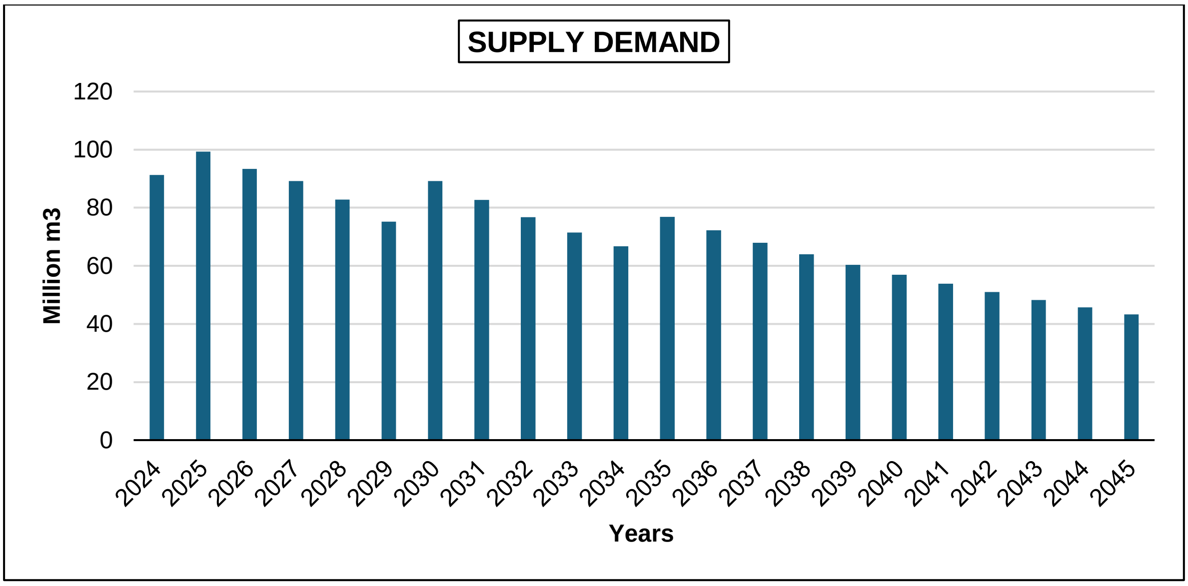


Figure 4. 31:The supply delivered under the combined integrated management scenario

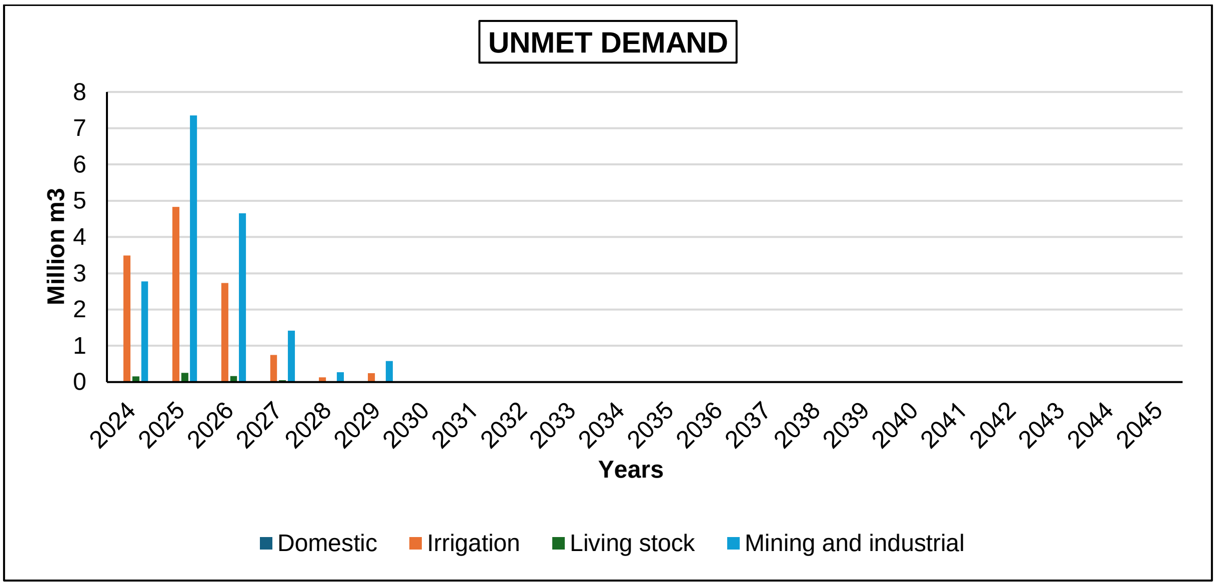


Figure 4. 32: The unmet demand under the combined integrated management scenario is plotted above

4.9. Conclusion

The findings of this study indicate that the Mokolo River Catchment successfully meets its water demand during the current assessment years of 2010 and 2023. However, projections under different climate scenarios, specifically SSP245 and SSP370, demonstrate that climate change significantly impacts water availability within the basin. These scenarios reveal a concerning trend of high unmet demands, particularly in the irrigation and industrial sectors during dry years. The analysis highlights that under both SSP245 and SSP370, the Mokolo River is unable to supply sufficient water during periods of low inflow, exacerbating shortages in critical demand areas. In light of these findings, demand-supply management scenarios were developed to evaluate how various management options could influence water demand and supply within the catchment. The results suggest that implementing an inter-basin transfer strategy emerges as the most effective option for mitigating unmet demand within the Mokolo River Catchment. This approach not only addresses immediate supply deficiencies but also enhances overall water resource management in response to the challenges posed by climate variability.

Chapter 5: Conclusion and recommendations

5.1. Introduction

In the chapter, it is vital to reflect on the key findings and insights gained throughout the study. This chapter consolidates the results of the modelling of water demand and supply within the Mokolo River Catchment, emphasising their implications for future water resource management. The analysis highlights the critical challenges posed by increasing water demand driven by population growth and industrial expansion, set against the backdrop of climate variability and its impact on water availability. The results reveal a significant upward trend in water demand across various sectors, particularly in domestic and industrial use, while also exposing a troubling gap between demand and supply under projected climate scenarios. This conclusion not only summarises the main outcomes of the study but also explores potential management strategies to mitigate water scarcity challenges in the region. The findings make it clear that adaptive management practices are essential for ensuring sustainable utilisation of water resources in the face of ongoing environmental changes.

This chapter outlines the study's results that were obtained in accordance with the study's objectives:

- Determine current what supply and water demand for various water users, such mining, irrigation, power generation and domestic in the Mokolo River catchment of Limpopo Province.
- Predict the future water demand and supply in the Mokolo River catchment.
- Develop future water demand and supply management scenarios for the Mokolo River catchment.

5.2. Current water demand and supply

The findings of this study under this objective demonstrate that the current water demand within the Mokolo River Basin is adequately met under average hydrological conditions. However, during dry years, unmet demand increases, predominantly affecting the mining and industrial sectors, followed by irrigation. While livestock also experiences unmet demand, the volume is relatively minor compared to the two dominant sectors. Notably, the domestic sector encounters no unmet demand, as it is prioritised above all other sectors.

The analysis further revealed that water sources within the catchment comprise reservoirs, groundwater, precipitation, and local dams, collectively contributing to the total inflow to the area. During dry years, the results indicate that the available water supply becomes insufficient to meet the demands of all sectors within the catchment. These findings underscore the critical importance of developing adaptive water management strategies to address supply limitations during periods of reduced inflow.

5.3. Projections of future water demand and supply

The projection of future water demand and supply within the Mokolo River Basin was conducted using a linear forecasting model and climate change scenarios derived from global climate models. The future water demand projections assumed that demand would follow historical trends across all climate models. The findings indicate a substantial increase in water demand, particularly in the mining and industrial sectors, driven by industrial expansion. The trend analysis revealed that water demand in these sectors nearly tripled over the 30-year projection period, highlighting the urgent need to assess water availability within the catchment.

The analysis demonstrated variability in climate change impacts under SSP245 and SSP370 scenarios. Historical meteorological data, including precipitation, average temperature, humidity, and wind speed, were identified as critical factors influencing the modelling of future water supply in the Mokolo River Basin. Among the evaluated models, the IPSL-CM6A-LR performed most effectively under both SSP245 and SSP370, showing minimal unmet demand and higher inflows compared to other models. These findings underscore the necessity for proactive water resource management to mitigate the anticipated challenges associated with increasing demand and climate variability.

5.4. Plausible future management scenarios.

Future water demand in the Mokolo River Basin is projected to increase due to population growth and industrial expansion. Consequently, it is anticipated that the available water supply will be insufficient to meet future demands, necessitating the development of plausible water management scenarios.

The reference scenario indicated that water demand would rise while water supply would continue to follow historical climate change trends. The findings revealed that the available supply is inadequate to meet the increasing demand. The Irrigation Efficiency Scenario demonstrated that reducing irrigation water use through advanced technology could lower irrigation demand effectively.

The Domestic Conservation Measures Scenario showed that reducing domestic water use had minimal impact on unmet demand within the Mokolo catchment. Similarly, the Mining and Industrial Efficiency Scenario revealed that decreasing industrial water use had little to no effect on reducing unmet industrial demand.

In contrast, the Inter-Basin Transfer Scenario and the Integrated Management Strategy Scenario, which combined additional water supply from inter-basin transfers with other measures, proved more effective. These strategies demonstrated the potential to significantly reduce unmet demand within the catchment, highlighting the importance of augmenting the current water supply alongside implementing comprehensive water management approaches.

5.5. Recommendations and future work.

- The study revealed the current water balance in the Mokolo river basin using data from the reconciliation strategy. Although there was no unmet demand in the baseline year, future water use is expected to increase in the area due to population growth and industrial expansion. Therefore, the study recommends, that more current data on the water requirement within the catchment should be made available by the Department of water and sanitation to accurately predict the current water demand and to check if indeed the model is able to capture the current water needs within the catchment.
- The study highlighted that when domestic is given more preference, there will be no unmet demand in that sector, therefore the study recommends that the Lephalale local municipality and policy makers should give priority

to the domestic sector over other sectors to reduce the high exploitation of groundwater within that region that tends to run dry. Future research can be done to check the current status of ground water within the Mokolo region and its availability for domestic and irrigation use.

- The outcomes of the study showed that livestock water demand within the mokolo catchment is not met. The study recommends that more research and data collection on livestock water requirement should be conducted. The research will help water authorities to see the need to increase the water consumption of the livestock.
- The study findings reveal that the water availability within the catchment is susceptible to climate change. the flow of the river basin, reduces in dry and very dry years. This reduction in inflow causes a rise in unmet demand in various sectors such as mining and industrial and irrigation. The study recommends that, further studies can be explore, how climate change influence the production of irrigation coal mining and power plant within the Mokolo catchment.
- The study recommends that the coal mining and power plant within the catchment should use the adoption of water Efficiency Technologies. The prioritisation of the integration of advanced technologies can reduce water consumption, as demonstrated in the scenario findings.
- The results also show that promotion of water-saving irrigation practices can be implemented. Encouraging the adoption of efficient irrigation systems, such as drip irrigation and precision agriculture, can substantially reduce water use in agriculture while maintaining productivity.
- The findings of the study recommend that there must be an Inter-Basin Water Transfers within the catchment: The transfer of water from other basins can significantly alleviate unmet demand, especially during critical periods of high industrial and irrigation needs.

5.6. Conclusion

The findings from this dissertation demonstrate that water demand and supply dynamics within the Mokolo River Basin are significantly influenced by climatic changes, population growth, and sectoral water use. The current baseline data reveal an increasing trend in water demand, particularly driven by the mining and industrial sectors. Climate projections under SSP245 and SSP370 scenarios suggest continued challenges with water availability, including reduced inflow during dry years and escalating unmet demands across various sectors. The management scenarios explored in this study such as irrigation efficiency, domestic water conservation, industrial technological advancements, and inter-basin water transfers—offer insights into potential strategies for addressing these challenges. The combined scenario, integrating all these strategies, was the most effective in reducing unmet demand and promoting sustainable water management, highlighting the necessity of a holistic approach to water resource planning.

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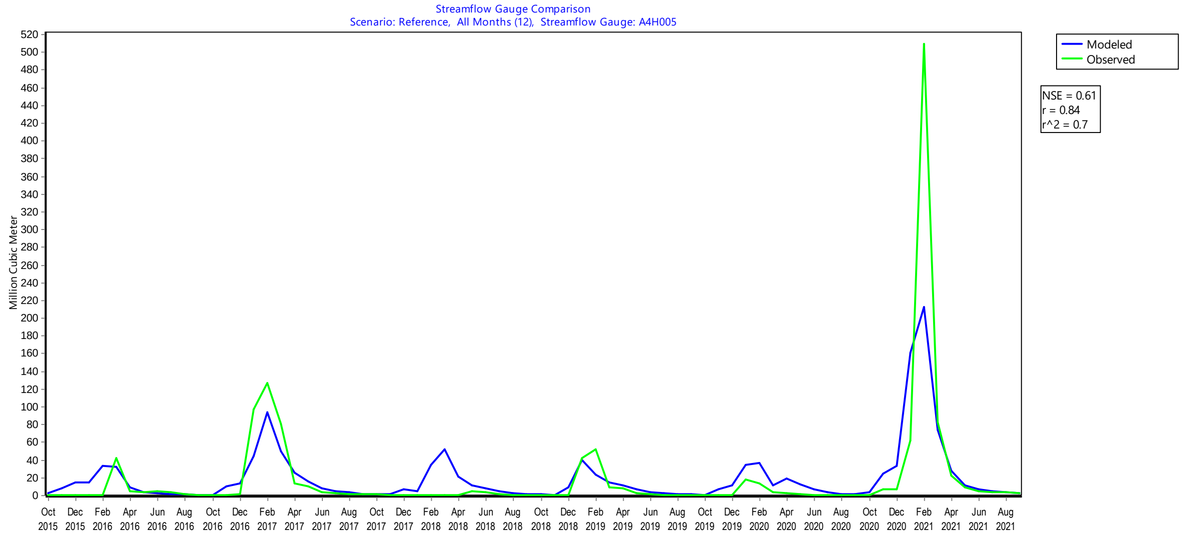
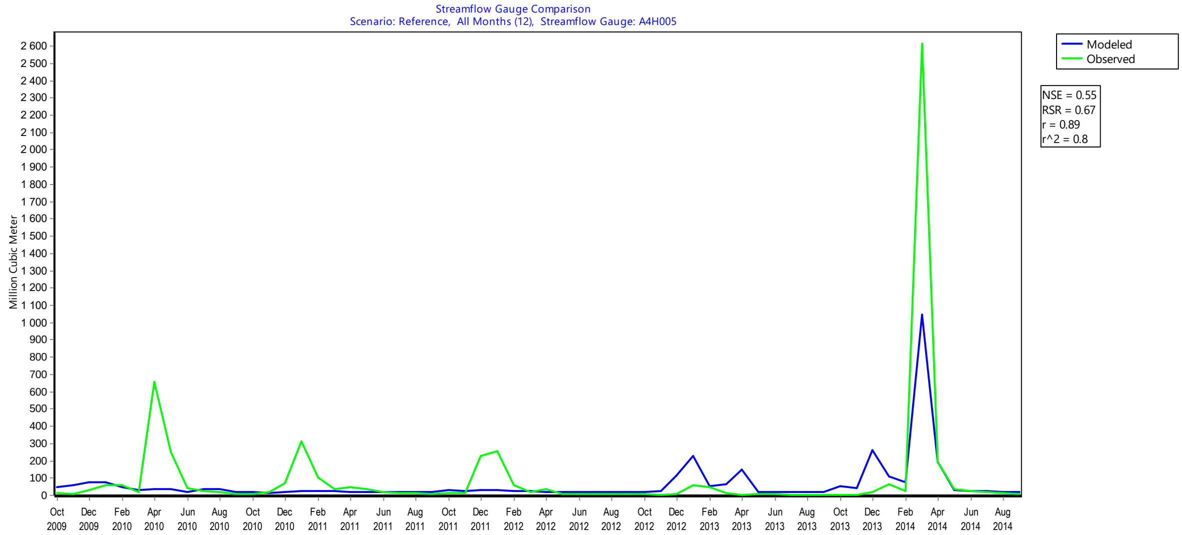
APPENDICS

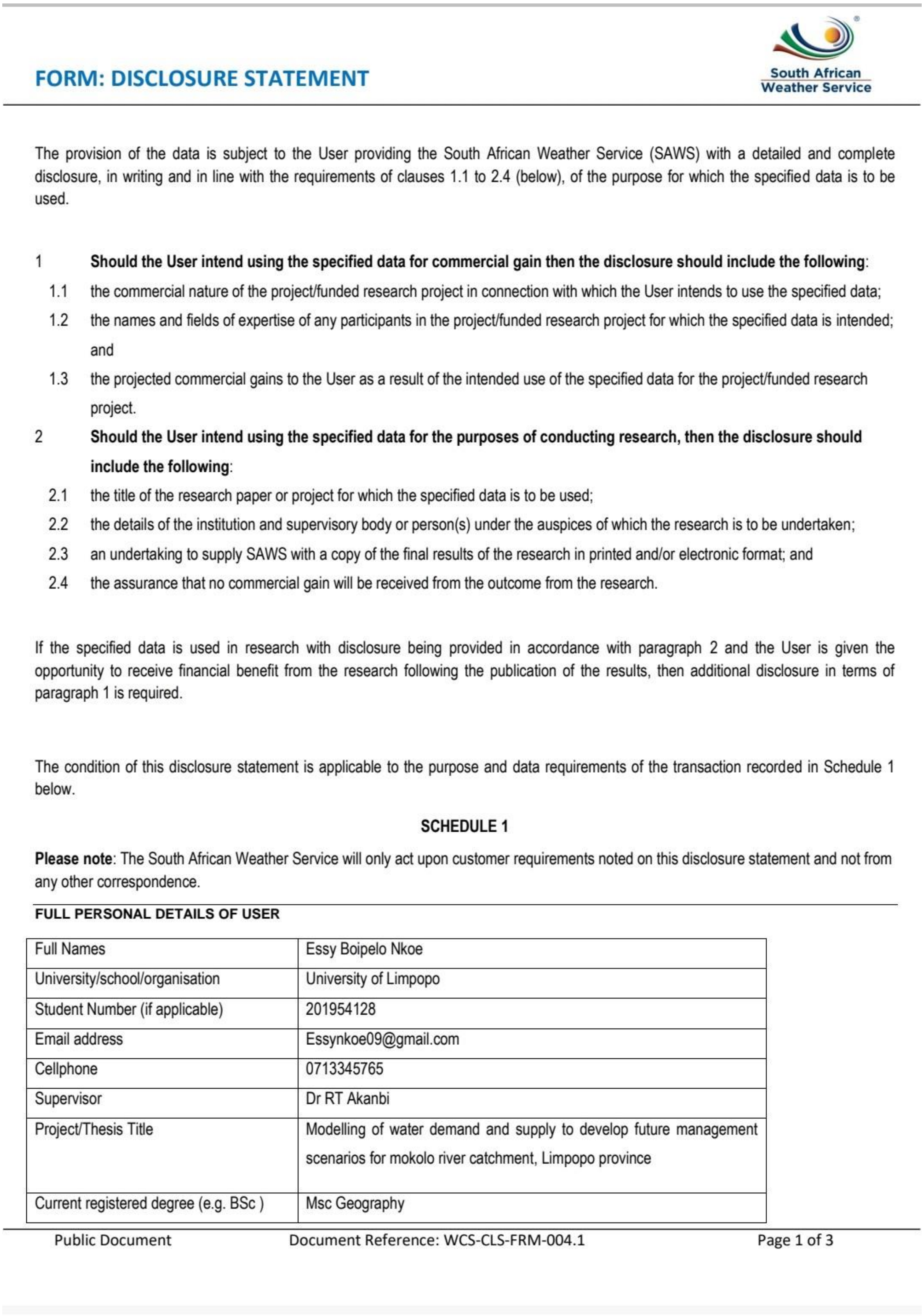
APPENDIX A: CALIBRATION AND VALIDATION PLOT FROM THE WEAP MODLE





APENDIX A: CALIBRATION AND VALIDATION PLOTS FROM THE WEAAP MODEL

APENDIX B: DISCLOSURE STATEMENT FROM THE SOUTH AFRICAN WEATHER SERVICE



FORM: DISCLOSURE STATEMENT

South African
Weather Service

The provision of the data is subject to the User providing the South African Weather Service (SAWS) with a detailed and complete disclosure, in writing and in line with the requirements of clauses 1.1 to 2.4 (below), of the purpose for which the specified data is to be used.

1 **Should the User intend using the specified data for commercial gain then the disclosure should include the following**:

1.1 the commercial nature of the project/funded research project in connection with which the User intends to use the specified data;

1.2 the names and fields of expertise of any participants in the project/funded research project for which the specified data is intended; and

1.3 the projected commercial gains to the User as a result of the intended use of the specified data for the project/funded research project.

2 **Should the User intend using the specified data for the purposes of conducting research, then the disclosure should include the following**:

2.1 the title of the research paper or project for which the specified data is to be used;

2.2 the details of the institution and supervisory body or person(s) under the auspices of which the research is to be undertaken;

2.3 an undertaking to supply SAWS with a copy of the final results of the research in printed and/or electronic format; and

2.4 the assurance that no commercial gain will be received from the outcome from the research.

If the specified data is used in research with disclosure being provided in accordance with paragraph 2 and the User is given the opportunity to receive financial benefit from the research following the publication of the results, then additional disclosure in terms of paragraph 1 is required.

The condition of this disclosure statement is applicable to the purpose and data requirements of the transaction recorded in Schedule 1 below.

SCHEDULE 1

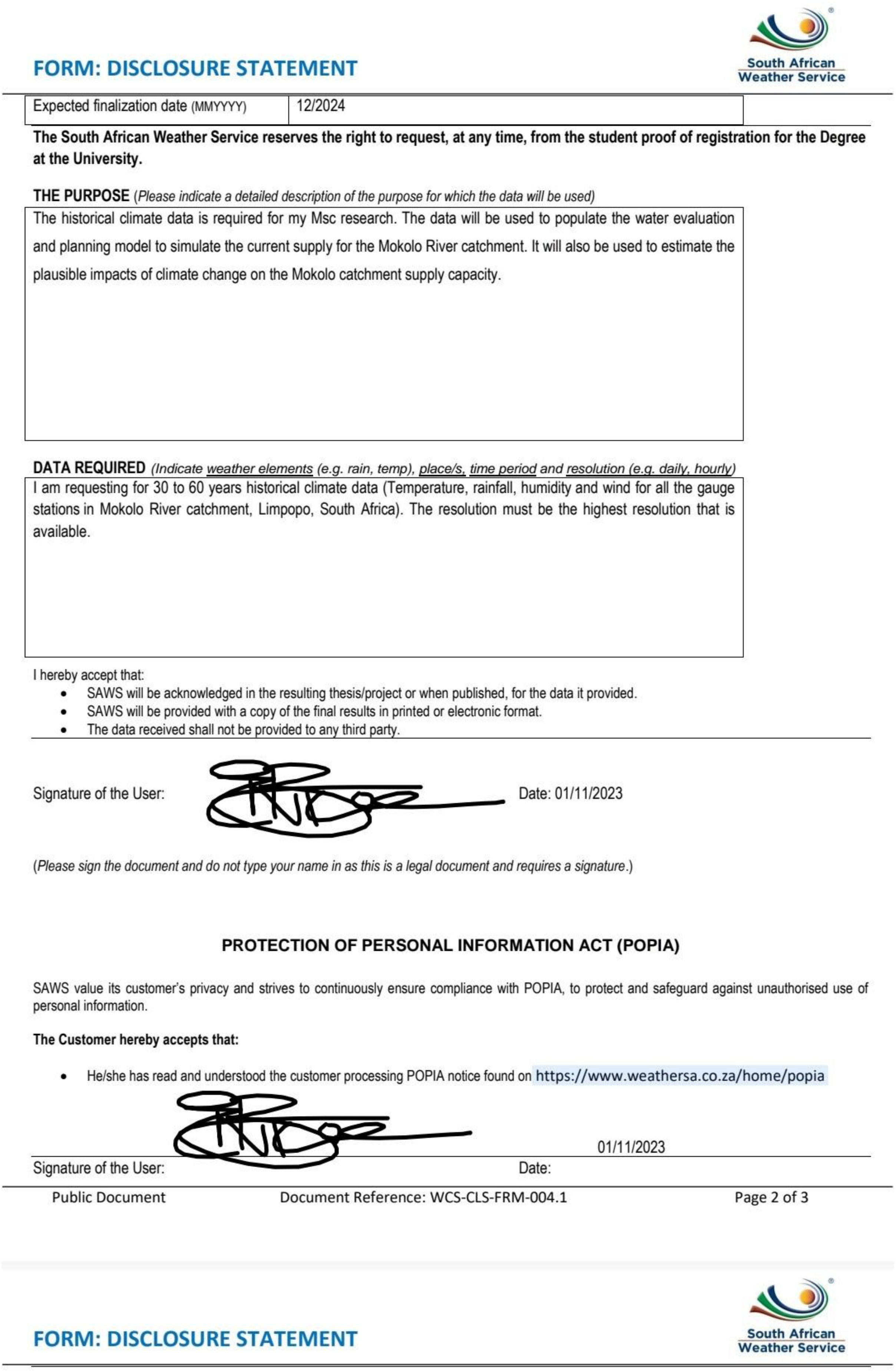
Please note: The South African Weather Service will only act upon customer requirements noted on this disclosure statement and not from any other correspondence.

FULL PERSONAL DETAILS OF USER

Full Names	Essy Boipelo Nkoe
University/school/organisation	University of Limpopo
Student Number (if applicable)	201954128
Email address	Essynkoe09@gmail.com
Cellphone	0713345765
Supervisor	Dr RT Akanbi
Project/Thesis Title	Modelling of water demand and supply to develop future management scenarios for mokolo river catchment, Limpopo province
Current registered degree (e.g. BSc)	Msc Geography

Public Document Document Reference: WCS-CLS-FRM-004.1 Page 1 of 3

APENDIX B: THE DISCLOURSE STATMENENT BY THE SAWS



Expected finalization date (MMYYYY)	12/2024

The South African Weather Service reserves the right to request, at any time, from the student proof of registration for the Degree at the University.

THE PURPOSE (*Please indicate a detailed description of the purpose for which the data will be used*)

The historical climate data is required for my Msc research. The data will be used to populate the water evaluation and planning model to simulate the current supply for the Mokolo River catchment. It will also be used to estimate the plausible impacts of climate change on the Mokolo catchment supply capacity.

DATA REQUIRED *(Indicate weather elements (e.g. rain, temp), place/s, time period and resolution (e.g. daily, hourly)*

I am requesting for 30 to 60 years historical climate data (Temperature, rainfall, humidity and wind for all the gauge stations in Mokolo River catchment, Limpopo, South Africa). The resolution must be the highest resolution that is available.

I hereby accept that:

- SAWS will be acknowledged in the resulting thesis/project or when published, for the data it provided.
- SAWS will be provided with a copy of the final results in printed or electronic format.
- The data received shall not be provided to any third party.

Signature of the User: Date: 01/11/2023

(*Please sign the document and do not type your name in as this is a legal document and requires a signature*.)

PROTECTION OF PERSONAL INFORMATION ACT (POPIA)

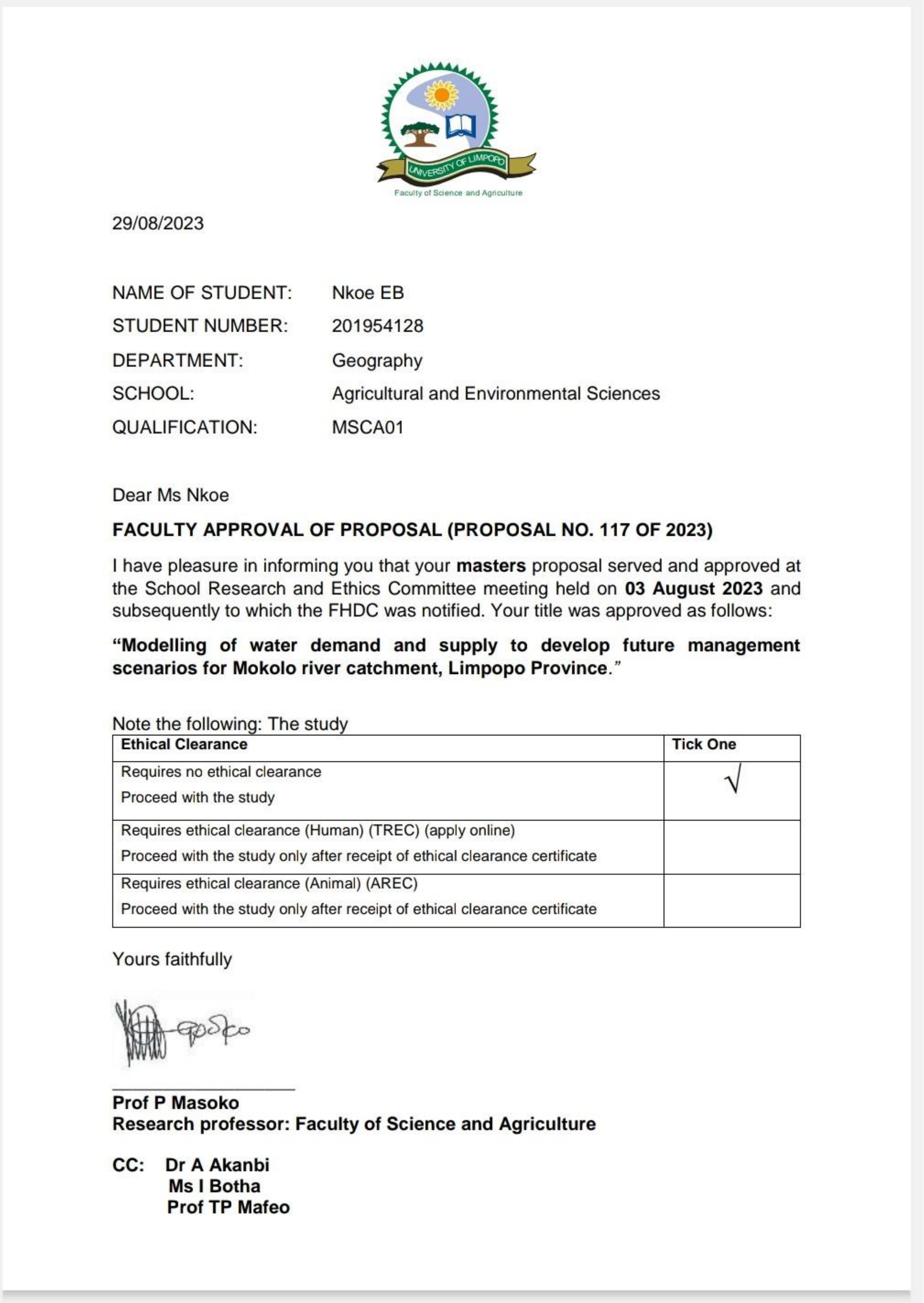
SAWS value its customer's privacy and strives to continuously ensure compliance with POPIA, to protect and safeguard against unauthorised use of personal information.

The Customer hereby accepts that:

- He/she has read and understood the customer processing POPIA notice found on https://www.weathersa.co.za/home/popia

Signature of the User: Date: 01/11/2023

APENDIX C: FACULTY APPROVAL LETTER



UNIVERSITY OF LIMPOPO
Faculty of Science and Agriculture

29/08/2023

NAME OF STUDENT:	Nkoe EB
STUDENT NUMBER:	201954128
DEPARTMENT:	Geography
SCHOOL:	Agricultural and Environmental Sciences
QUALIFICATION:	MSCA01

Dear Ms Nkoe

FACULTY APPROVAL OF PROPOSAL (PROPOSAL NO. 117 OF 2023)

I have pleasure in informing you that your **masters** proposal served and approved at the School Research and Ethics Committee meeting held on **03 August 2023** and subsequently to which the FHDC was notified. Your title was approved as follows:

"Modelling of water demand and supply to develop future management scenarios for Mokolo river catchment, Limpopo Province."

Note the following: The study

Ethical Clearance	Tick One
Requires no ethical clearance Proceed with the study	√
Requires ethical clearance (Human) (TREC) (apply online) Proceed with the study only after receipt of ethical clearance certificate	
Requires ethical clearance (Animal) (AREC) Proceed with the study only after receipt of ethical clearance certificate	

Yours faithfully

Prof P Masoko
Research professor: Faculty of Science and Agriculture

CC: Dr A Akanbi
Ms I Botha
Prof TP Mafeo

APENDIX C: FACULTY APPROVAL LETTER