ADDIS ABABA UNIVERSITY

COLLEGE OF TECHNOLOGY AND BUILT ENVIRONMENT

SCHOOL OF CIVIL AND ENVIRONMENTAL ENGINEERING

WATER RESOURCES EVALUATION AND ALLOCATION FOR MULTIPLE-USE IN DABENA WATERSHED, BLUE NILE BASIN, ETHIOPIA

By

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A Thesis Submitted to the School of Graduate Studies of Addis Ababa University, School of Civil and Environmental Engineering in Partial Fulfillment of the Requirements for the Degree of Master of Science in Water Resource Engineering and Management Specialization in Groundwater Engineering and Management.

June, 2026

Addis Ababa, Ethiopia

CERTIFICATION

This is to certify that I have reviewed and hereby recommend for acceptance by the Addis Ababa University, School of Civil and Environmental Engineering, the thesis entitled "**Water Resources Evaluation and Allocation for Multiple-Use in Dabena Watershed, Blue Nile Basin, Ethiopia** ", submitted by **Obse Gudeta** in partial fulfillment for the Degree of Master of Science in Water Resource Engineering and Management Specialization in Groundwater Engineering and Management.

I further certify that the student conducted original research for this thesis under my guidance and supervision. To the best of my knowledge, the work presented in this thesis is original to the student and has not been submitted to this or any other university for consideration for any other degree or professional certification.

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ACKNOWLEDGEMENT

First and foremost, I would like to thank the Almighty God for His boundless grace, strength, and wisdom bestowed upon me throughout my life and especially during this academic journey. I wish to express my deepest gratitude to my advisors, Taye Alemayehu (PhD), Felix Mtalo (Prof.) and my co-advisor, Tena Alamirew (PhD), for their invaluable guidance, professional expertise, and consistent encouragement. Their insights into water resources management were vital to the successful completion of this work.

I am profoundly grateful to Addis Ababa University for awarding me the A-Female Scholarship, which granted me the opportunity for tuition-free study and allowed me to pursue my Master's degree.

My sincere thanks go to the Eastern Nile Technical Regional Office (ENTRO) for providing me with a valuable internship opportunity. The knowledge I gained there, particularly regarding the application of hydrological models, significantly enhanced the technical quality of this study.

I would also like to extend my heartfelt appreciation to the Nile Basin Capacity Building Network (NBCBN) Foundation for granting me the MSc research fund under the Nile Academic Exchange Program (NAEP) project. This support was essential in providing the resources necessary to carry out this study.

During my stay in Tanzania as part of the exchange program, I was fortunate to receive immense support from the University of Dar es Salaam. I would like to thank the staff and my friends at the university for their hospitality, academic support, and for making my time there both productive and memorable.

Finally, I wish to thank my family and friends for their unwavering moral support, love and prayers during my academic journey. To everyone who contributed directly or indirectly to this milestone, I offer my sincerest thanks.

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ABSTRACT

This study was carried out in the Dabena watershed, a sub-watershed of the Didessa River in the Blue Nile Basin, located in Western Ethiopia. The area faces numerous challenges related to water security and allocation of the available water resources. As a result, there was an emerging conflict between different water uses. The general objective of this study was to evaluate and allocate the available water resources for multiple uses in the Dabena watershed. The study employed an integrated modelling framework, combining the SWAT hydrological model to assess surface water availability, the WetSpass-M model to estimate groundwater recharge and WEAP for water allocation for different uses like domestic, irrigation, industrial and environmental flow requirements. The SWAT model was successfully calibrated and validated against observed streamflow, confirming its high performance in modelling surface hydrology of the watershed. The result from SWAT model reveals that the mean annual surface runoff of Dabena watershed is 465.81mm. The spatial and temporal average monthly, seasonal and yearly groundwater recharge was estimated using WetSpass-M model. The result shows the long-term water balance components of the Dabena watershed consist of a mean annual groundwater recharge of 478.12mm (1,542,418,352m3/year) representing 24%, surface runoff of 532.8mm which accounts 27% and actual Evapotranspiration of 961.6 mm represents 49% of total rainfall. The output from the SWAT model was used as input data for the WEAP model. Six alternative scenarios were created to assess the impact of population increase, irrigation expansion, groundwater use, irrigation priority, environmental flow requirement priority and the combined impact on supply delivered and unmet demands for different water demand sites. The finding reveals irrigation water unmet demand in the irrigation expansion, and irrigation priority is the highest compared to other scenarios. To mitigate emerging conflicts between different water uses, the study recommended the conjunctive use of groundwater and surface water and rainwater harvesting as additional water sources to meet the unmet demands, particularly that of irrigation.

Keywords: *Dabena watershed, SWAT model, WetSpass-M, Conjunctive use, Water allocation, WEAP model*

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ABBREVIATIONS

AET	Actual Evapotranspiration
ASCII	American Standard Code for Information Interchange
BCM	Billion Cubic Meter
DEM	Digital Elevation Model
DSS	Decision Support System
EFR	Environmental flow Requirement
FAO	Food and Agricultural Organization
GIS	Geographical Information System
GPS	Global Positioning System
GWD	Groundwater Depth
GWP	Groundwater potential
GTP	Growth and Transformation Plan
HEC-HMS	Hydrologic Engineering Center's Hydrologic Modeling System
HRU	Hydrologic Response Unit
IDW	Inverse Distance Weighting
IWRM	Integrated Water Resources Management
ITCZ	Inter-Tropical Convergence Zone
LAI	Leaf Area Index
LULC	Land Use Land Cover
MCM	Million Cubic Meter
MIKE-SHE	Mike Surface Water- Groundwater Hydrodynamic Model
MoWE	Ministry of Water and Energy
NMA	National Meteorological Agency
NSE	Nash–Sutcliffe Efficiency
PET	Potential Evapotranspiration
SEI	Stockholm Environmental Institute
SRTM	Shuttle Radar Topography Mission
SUFI	Sequential Uncertainty Fitting
SWAT	Soil and Water Assessment Tool

SWAT-CUP	Soil and Water Assessment Tool-Calibration and Uncertainty Program
USDA	United States Department of Agriculture
USGS	United States Geological Survey
WEAP	Water Evaluation and Planning System

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CHAPTER ONE: INTRODUCTION

1.1 Background of the Study

Water resources are extremely vital for ecosystem health, the support of agriculture, and diverse human needs. While water is the most important natural resource for all life on Earth, it is a limited asset that is often difficult to access and unevenly distributed in a way that population needs are met (Nannawo, Lohani, Eshete, et al., 2021; Ruidas et al., 2021). As the demand for water rises globally, effective management and allocation become essential, especially in water-scarce regions where economic, social and environmental factors overlap. Water resources are allocated to cover a number of needs such as environment, industry, agriculture, and urban use. The differences between the amount of water consumed and the amount available caused by population growth, increasing agricultural demands, and concerns for the environment lead to conflicts and tensions among stakeholders (Kazemi et al., 2021). Consequently, the only way to solve these problems is to resort to the effective and scientific management of water resources.

Sustainable development and meeting the growing demand for water can be accomplished through the integrated use of surface and groundwater resources (Harmancioglu et al., 2013). The most effective possible planning for the conjunctive use of surface and groundwater is necessary to provide a sustainable supply of water for all industries, thereby reducing losses to the economy, society, and environment in arid and semi-arid regions(Yates et al., 2005a). Moreover, the conjunctive use of surface and groundwater resources is recognized as the most important measure to water management in a sustainable way, particularly in areas suffering from water scarcity and having difficult water quality problems(Irvine et al., 2024; sekar et al., 2024). According to (Jain et al., 2023) conjunctive surface and groundwater management has two advantages: (1) It reduces salinity, waterlogging, and groundwater depletion; and (2) It boosts crop output and offers a dependable water supply to fulfill the sustainable water demand.

Water resources assessment and distribution are among the main aspects of the economy in Ethiopia, which is a country that depends greatly on agriculture, hydropower production and water supply for different industries. The different climate areas and the large agricultural sector make water resources understanding and management to be very critical for the sustainable development of the country and the well-being of the people. The Ethiopian water sources consist mainly of river and lake surface water and groundwater. It is critical to assess these water sources availability, quality, and flow rates to ensure proper planning and allocation of water resources.

Water resources management has recently been made more significant, mainly due to the natural system's burden of rising demand for water, particularly of better quality, and the increased use of water for various purposes. The concept of sustainability, conflicting water usages, and the highly developed methods of water application have all added to its complexity (Loukas et al., 2006). Hydrologists are exploring the dynamics between surface water and groundwater, because it would be possible to increase the combined consumption of water from these two different sources if properly done. In the case of irrigated agriculture, the development of proper conjunctive usage can minimize water shortages, increase water use efficiency, and improve the environmental conditions of the region (El-Rawy et al., 2016). To really know the water resources of the Dabena watershed, it is necessary to assess their availability and characteristics. The assessment involves surface water and groundwater sources analysis, hydrological processes, and the whole water balance exercise. By water resource evaluation, the stakeholders can get a clear picture of the water supply in terms of quantity, quality, and reliability, which is the principal factor of good water management.

Hydrological and hydrogeological characterization are essential for understanding the behavior of the water within the hydrological cycle and subsurface systems. These processes consist of data gathering, analysis, and interpretation of results concerning water resources, hydrological aspects, and geological formations that affect water movement and storage. Hydrological characterization involves systematic gathering and analysis of parameters like precipitation, evapotranspiration, surface runoff and streamflow. Analyzing these variables allows researchers to quantify total water availability, predict Watershed losses and recognize seasonal patterns. Surface runoff is used to describe the water that, after rain or snowmelt, flows over the land surface. Streamflow data indicate the volume of water discharged from rivers or streams within the watershed.

Groundwater potential assessment is an important step towards the sustainable use and management of groundwater resources(Kedir, 2023). It represents the evaluation of a particular area's potential to produce water from underground sources(Shabani et al., 2022). In addition to this, it reveals to water authorities' places where hydrogeological conditions are best for underground storage and replenishment of water. Groundwater potential assessment includes different factors such as geological formations, aquifer characteristics, recharge rates, groundwater levels, and climate(Ahmed & Sajjad, 2018). The latter implies to have a good understanding of the existing aquifers, their location, the direction of groundwater flow, the amount of water that can be recharged, and the prediction of water availability in the future(Asrade, 2024).

The Dabena watershed encounters numerous difficulties in the distribution of water owing to competition for water and its scarcity at the same time. The watershed has agriculture as its proponent that needs water supply among other sectors, and fulfilling the irrigation demands, which are increasing, will certainly raise agricultural production. Moreover, the allocation process is to be planned so as to satisfy the needs of the domestic water supply, industrial use, and environmental protection. Balancing these diverse requirements requires a systematic approach that optimizes water allocation decisions while ensuring sustainability and equity. The primary objective of decision-makers in the river basin should be to allocate water in a way that takes justice, efficiency, and sustainability into account in every water sector (Wang et al., 2015). Based on the rational demand of local water users, the best distribution of water resources should assign users to different water sources in a way that is supported by science(Wang et al., 2016). In order to balance the supply and demand of water resources based on economic development, effective and optimal resource allocation is critical. When the water demand exceeds the supply, the allocation cannot meet the required demand. As the economy grows and water demand rises, the challenges become worse.(Gedefaw et al., 2019)

According to (F. Zhang et al., 2023a), due to the limited availability of water coupled with the high demand, the confrontation among water users has become sharper. The researchers have found that these problems can be resolved with the proper allocation of water resources. Therefore, the specific allocation model implementation for Dabena watershed intends to attain and achieve several significant objectives. The objectives are to optimize the distribution of water resources among competing uses, the requirements of ecological flow to maintain the health of an ecosystem, increase water-use efficiency, and the resolution of conflicts and trade-offs among various sectors. The allocation model will lay down the foundations for a decision that is well-informed based on factors like the availability of water, the demands of different sectors and the sustainability goals.

1.2. Statement of the Problem

The evaluation and allocation of water resources in Ethiopia are subjected to very serious challenges, which prevent the management and distribution of water in a sustainable and equitable manner. The country possesses a lot of water resources, but the majority of them are still unusable because structured water allocation is not yet an established practice. Due to a lack of strategic management and infrastructure, available water is not properly directed to where it is most required. As a result, it is very difficult to satisfy the demand for water in agriculture, domestic use, and industry, which will eventually affect food security, people's livelihoods, and economic growth (Mesene, 2020).

Similarly, the Dabena watershed is experiencing difficulties with water use and management due to lack of effective water management and allocation. There is a conflict over the available limited water resource in the watershed among different water uses such as irrigation downstream, Bedele Brewery, and water supply for Bedele town. The major causes of the water conflict in the Dabena watershed are basically how water is taken upstream. Bedele Brewery, which is located in the upstream part of the watershed pumps water straight out of the river. Because that industrial pumping is happening upstream, it reduces the volume of water that keeps moving downstream. This leads to a rather severe water shortage during the dry season. So, as a consequence, downstream towns and irrigation sites don’t get enough water to cover their daily requirement. The conflict is over the equitable and fair distribution of the scarce water resources among these sectors. (Adgolign et al., 2015) in his study states that at the end of the long-term future development scenario, all of the demands in the Dabena Watershed, including the Bedele town demand site, remain unfulfilled. Unless an alternate source of water is available, there will be a severe shortage of water to meet Bedele Town's water demand. To address these problems, it is vital to implement appropriate strategies for water resource management in the Dabena watershed. This requires determining the allocation of water between various sectors that is economically, socially, and ecologically acceptable and sustainable. The implementation of a water allocation model would facilitate the allocation of water in a way that would optimize the resources and reduce the conflicts among the different users.

1.3. Objective of the study

1.3.1. General Objective

The general objective of this study was to assess and evaluate the water resources of the Dabena watershed of the Blue Nile Basin and determine water allocation for the multiple uses.

1.3.2. Specific Objectives

The specific objectives include:

1. To characterize the hydrological and hydrogeological nature of the Dabena Watershed.
2. To evaluate the water resources potential of the watershed, and
3. To allocate the available water resources for multiple uses in the watershed

1.4. Research Questions

1. What are the key hydrological and hydrogeological characteristics of the Dabena watershed?
2. How much water is available in the watershed?
3. What are the key factors and criteria that should be considered in the water allocation model that ensure equity, efficiency, and sustainability in the Dabena watershed?

1.6. Significance of the Study

This research was aimed at enhancing the water resource development and management within the Dabena watershed through an in-depth evaluation of the existing water and a working model for distribution. This ultimately equips decision-makers with the required water distribution data, allowing for the more efficient use of water and, at the same time, avoiding possible disagreements among different water user groups.

1.7. Scope of the Research

The investigation was concerned with the Dabena Watershed, which is situated in the western part of Ethiopia within the Blue Nile basin. The area of the study embraced the major hydrological characteristics of surface water, rivers, and lakes, together with groundwater everywhere in the watershed. The research considered water resources, their availability, and their nature in the area, looking at surface and groundwater resources in the same way. In order to determine the total amount and the changes of these resources during the period under study, fieldwork, analyses, and hydrological modeling were used as steps in the process.

The research conducted an examination of current and future water requirements for various sectors, like agriculture, domestic use, and industries within the watershed. It considered the exact water users' demands and indicated the areas and periods of the highest water demand. Eventually, the project was directed towards creating a water allocation model that would allocate the water supply of Dabena Watershed according to the water demand of the different competing users. The model applied criteria such as fairness, efficiency, environmental health, and economic worth in the process of determining the most suitable distribution of water resources between the sectors and groups involved. Due to limitations in used model inputs and availability of data, the recharge estimate considers only the shallow groundwater resources, regardless of the deep regional flow.

1.8. Limitations of the Research

The key limitation of the study was data scarcity regarding to borehole and station climate data. There were insufficient borehole data and their distribution was uneven, making it difficult to demonstrate how groundwater changes across the whole area. Additionally, the meteorological data was either incomplete or of poor quality. So only data up to 2020 was used in this study. While the use of this cutoff kept the findings accurate, it also implied that the most recent changes in the area may not have been completely captured.

CHAPTER TWO: LITERATURE REVIEW

2.1. Introduction

Effective management of water resources is essential for encouraging fair and supportable distribution across multiple uses, such as household consumption, farming, industrial operations, and environmental conservation. The increasing population, urbanization, and climate change impacts demand efficient water allocation to ensure that multiple sectors, and at the same time, the ecosystems do not suffer (Li & Wu, 2023). This rise in water demand leads water resource management and planning to face additional challenges. One of the best options for water management is to combine the use of surface and groundwater to address the problem of growing irrigation demand and insufficient surface resources(Tefera et al., 2023). Countries formulate water regulations based on the idea of equitable, reasonable, and fair use. The main goal of water policy is to develop and manage the available water resources in a sustainable manner. According to(Qian, 2016) it is important to plan, develop, and manage water resources properly in order to meet current and future water demands and avoid future water scarcity, crises, and conflicts.

Allocation models provide decision-makers with tools to optimize the allocation of water among different sectors and users. These models integrate multiple objectives, such as economic efficiency, social equity, and environmental sustainability, to facilitate the fair and effective distribution of water resources. Researchers have created a variety of models to analyze the water balance of river basins and to distribute scarce water resources among competing water users(Ndayizeye, 2022). One of the approaches for allocating water, called WEAP, basically uses an allocation priority mechanism (Adgolign et al., 2016).

2.2. Water Resources Evaluation

The water resources evaluation is a vital technique that ensures the proper management and development of the water sources that are indispensable for human activities, the functioning of ecosystems, and agricultural production (Wang et al., 2024). The process of evaluating water resources entails a thorough analysis of the water condition in a specific region taking into account its sources, uses, and management. Due to the factors of climate change, environmental degradation, and the growing demand for water, resource evaluation for water has become increasingly necessary for the present and future generations (Alamanos & Koundouri, 2024; Ndubuisi & FNisafetyE, 2025). It entails the measurement, gathering, and examination of parameters related to water quantity and quality that are significant for the enhancement of water resource development and management. The assessment of water resources is crucial for the sustainable and responsible utilization of water, and therefore the availability of water in the long run, as it concerns every sector of development and connects to almost every Sustainable Development Goal. It is a major factor of economic development, helps to preserve ecosystems and is very important and basic for life (Bezerra et al., 2022; Grigg, 2025).

Before analyzing the stress on the water resources and implementing suitable management techniques to prevent negative environmental effects and resolve user conflicts, an evaluation of the available water resources is required. Growing demand for water as a result of the world's largest population expansion the highest ever level of living and rapid economic growth. Because of the growing contamination of water resources, the situation has become significantly more serious(Armas Vargas et al., 2023). The range of socioeconomic development that may be reasonably sustained by the available water resources is what is required. Determining the level of socioeconomic growth that can be sustained by the existing water resources is therefore crucial(Balata et al., 2022).

Global water supplies are under stress as a result of growing demands carried on by the world's exponential population increase. The need for water for drinking, fisheries, food safety, and environmental preservation has increased as a result of global population and economic expansion(Rahi et al., 2019). Particularly, water scarcity issues are more difficult to overcome in arid and semi-arid areas. Throughout a particular hydrological year, an increasing demand for the finite water resource denotes scarcity and rising value. Effective quantity estimation and management of the requested quantity may guarantee minimal resource waste, provided that the overall demand is smaller than the available water resource. Quantitative knowledge of the supply-demand relationship may help users distribute the scarce resource fairly as demand begins to outpace the availability of water(Dessu et al., 2014).

The effects of climate variability and change on water resources are expected to have an impact on installed power capacity, irrigated agriculture, environmental flows during the dry season, and increased flows during the rainy season, ultimately leading to severe droughts and floods in both urban and rural areas(Tofu, 2025). The effects of climate change on water resources are discussed and examined, including effects on the availability of water on an annual and inter-annual basis as well as on exceptional drought and flood occurrences. According to (Benini et al., 2016) future trends in climate change will pose a threat to the availability of freshwater resources in coastal zones. These trends include expected increases in temperature and rainfall in many Mediterranean basins, as well as a general rise in sea level and potential consumption due to population growth.

Water Resources evaluation is handled by employing various methods and techniques like hydrological modeling, integrated water resources management (IWRM), GIS and remote sensing, and statistical analyses(Akanksha D Salvi, 2024; Baker, 2024). Hydrological models replicate water cycle processes and are utilized for a variety of purposes, such as flood forecasting, water resource management, and assessing the impact of climate change (Yang et al., 2021). IWRM presents a comprehensive methodology that considers the trade-offs among economic efficiency, social equity, and environmental sustainability (Mukhtyar Singh, 2024). GIS and remote sensing combine spatial data and give crucial information for tracking water bodies, changes in land cover, and hydrological processes(Baker, 2024).

Even though the evaluation methods have improved a lot, there are still numerous difficulties, such as a lack of data and good quality data, complex models, uncertainties, climate change effects, increasing urban demand, and water quality deterioration(Ferdowsi et al., 2024). The scarcity of hydro-climatological data and the requirement for long-term datasets are major hindrances (Dinar, 2024). Predicting extreme events and the uncertainties of model structure and parameter selection are still very difficult (Pengxiao et al., 2025). The changes in climate affecting precipitation patterns and river flow regimes add another layer of complexity to water resource evaluation (Dinar, 2024). Urbanization and aging infrastructure are among the factors pressuring the water supply and this, in turn, leads to water loss(Dinar, 2024). Pollution, salinization, and overexploitation are the main causes of water quality degradation, thus, affecting its availability and usability.

2.2.1. Surface water availability assessment

The availability of water resources is crucial in countries like Ethiopia, where agriculture both supports and sustains the living standards of the populace. The main source of water is surface water. Understanding surface water's potential, availability, and use will help improve conventional water management techniques, boost the supply of drinking water, and generate more hydroelectric power in the future. It will also help to raise agricultural productivity(Hussen et al., 2018).

Assessment of surface water availability is the most important part of the management of water resources that will be sustainable, especially with the increasing global water consumption and climate change consequences (Akanksha D Salvi, 2024; Touseef et al., 2021). It is done through the evaluation of surface water quantity and quality, taking into account the factors of precipitation, evaporation, runoff, and human activities(Merga et al., 2022). This evaluation is important for water resource management, allocation, drought mitigation, and ecosystem protection. The use of different methods, such as direct measurement, velocity-area techniques, rainfall-runoff models, and hydrological models like SWAT and HEC-HMS are the main ones that are utilized (Akanksha D Salvi, 2024). Hydrological models are used to predict water movement in watersheds and thus are suitable for long-term assessments (Touseef et al., 2021).

The evaluation of surface water resources includes rivers, lakes, and reservoirs assessment with respect to the water quantity, quality, and availability. It requires huge data collection relating to river flow, rainfall, and water levels, along with the analysis of hydrological processes and the calculation of water balance(Genjebo et al., 2023). Besides, the assessments take into account the impacts of climate change, water infrastructure, and conflicts among stakeholders, thus providing a comprehensive view of surface water availability. Limitations of data, spatial and temporal variability, uncertainties, and competing water demands are some of the challenges facing the assessment. To overcome these challenges and, consequently, numerous decision-making and sustainable management of surface water resources, better data collection, advanced modeling techniques, and the involvement of stakeholders are essential(Das, 2025).

Hydrological processes must be thoroughly understood in order to determine the availability of water supplies. But comprehending the features of rainfall and watershed attributes is fundamental to researching the complicated nature of hydrological processes, which is required for sustainable Watershed management (Munyaneza et al., 2014). Rainfall and atmospheric demand (evapotranspiration) must be analyzed in order to determine future water availability. Runoff, which measures the amount of moisture available, is typically equal to the difference between precipitation and evapotranspiration when averaged over a number of years (Tramblay et al., 2018).

2.2.2. Groundwater potential assessment

Groundwater is one of the most valuable natural resources for human health and economic development. Groundwater is getting more and more important as a water supply in the cities and rural areas of the world, mainly because of its uninterrupted existence and wonderful natural quality (Berhanu & Hatiye, 2020).To manage groundwater sustainably, an accurate assessment of groundwater potential and an estimate of recharge are required (Gebreslassie et al., 2025; Sajil Kumar et al., 2021). The major factors that determine the groundwater availability and movement in a particular region are soil, rock, geological structures, slope, drainage patterns, geomorphology, land use/cover, and the interactions between these factors (Andualem & Demeke, 2019; Boitt et al., 2023; Sajil Kumar et al., 2021). Local factors such as climate, tectonics, geomorphology, and geology all determine the amount of groundwater that can be accessed. The variations of these factors greatly influence the groundwater quantity and quality in different parts of Ethiopia. The geological conditions of the country provide not only good quality groundwater but also support recharge of aquifers through rainwater infiltration from surface and subsurface sources, which later on result in springs and rivers that never dry up(Gebreslassie et al., 2025).

The groundwater potential and recharge assessments impose challenges due to the unavailability of data, scale issues, and uncertainty surrounding the input data and model parameters (Cooper & Hiscock, 2025; Ojha et al., 2015). It is suggested that the future research should be increasingly dedicated to merging various techniques, creating sophisticated models that consider the interaction of climate change and land use alterations as well as enhancing the networks for data collection (Ojha et al., 2015). The groundwater resources are under the threat of overexploitation, the rising population, and economic activities (Ojha et al., 2015). The sustainability and security of groundwater resources depend on the identification of specific challenges in the region and the accompanying solutions to allow water use in different sectors, including ecosystems (Mukherjee et al., 2024).

Groundwater resources are consistently under stress due to the ever-increasing demand for water. Both the quantity and quality of groundwater were directly or indirectly impacted by uncontrolled population growth and poor resource management in emerging countries like Ethiopia. Thus, inappropriate application of water policy and unscientific extraction are also potential causes. For sustainable management, therefore, evaluating groundwater resources is essential(Tolche, 2021). Ethiopia's potential groundwater resources are estimated to be over 40 billion cubic meters. Over 90% of Ethiopia's water supply for home and industrial uses comes from groundwater, according to reports; however, only a relatively small portion of water is used for irrigation, which mostly uses surface water(Melese & Belay, 2022).

Geographical features of a drainage basin can be taken into consideration for assessing groundwater potential, watershed management, and environmental evaluation(Malik et al., 2016). Hydrogeological research and applications are being aided in many ways by the past, present, and future advancements in remote sensing technology. The conventional methods of groundwater exploration, which rely on geophysical and geoelectrical approaches, are costly and time-consuming(Fenta et al., 2015). A growing number of hydrogeological researchers can benefit from better land surface characterization made possible by remote sensing evaluations. Therefore, new kinds of research and services are beneficial to applied studies on a regional to worldwide scale. Furthermore, the development of remote sensing techniques makes it possible to create considerably more sophisticated hydrogeological models than are now able to constrain using observational data.

Groundwater recharge can be estimated using a variety of techniques, such as the water-balance approach hydrological budget, imperical methods, the isotope methodology, scaling the size of well water-level fluctuations by the specific yield of the aquifer material, or employing conservative geochemical tracers like chloride and numerical modelling (Gebreslassie et al., 2025; Sajil Kumar et al., 2021). However, the majority of the time, the difference between precipitation and evaporative demand at the land's surface determines the amount of groundwater recharge (Kahsay, 2008). Precisely predicting the distributed quantities of groundwater recharge in a hydrologically and geographically varied Watershed is one of the primary issues in this field. Some of the issues could be resolved with the development of Geographic Information Systems (GIS), which uses physically-based hydrologic modeling. Surface runoff, real evapotranspiration, and groundwater recharge are the three long-term average, geographically variable components of the water balance that may be estimated using the GIS-based model WetSpass-M model (Batelaan & De Smedt, 2001b, 2007).

2.2.3 Hydrological Models for Water Resources Evaluation

Hydrological models are important tools for revealing, predicting, and controlling water resources and thus are a simplification of actual systems. The models play an important role not only in estimating the flow and quality of water but also in monitoring the effectiveness of water resource management. Detailed evaluations of hydrological components, like the interactions of surface, subsurface, and groundwater, are absolutely necessary for making water supply simulations better. Hydrological modeling is a highly effective method for the assessment of water resources that employs a variety of hydrological models for simulating and analyzing the intricate water systems.

Among the widely used models are SWAT (Soil and Water Assessment Tool), HEC-HMS (Hydrologic Engineering Center's Hydrologic Modeling System), MIKE SHE (Mike Surface Water - Groundwater Hydrodynamic Model) MODFLOW and WetSpass-M model. All these models essentially take into account different factors such as the meteorological data, land surface characteristics, soil properties, and the involved hydrological processes for simulating the water movement, which includes the processes of rainfall-runoff, evapotranspiration, and groundwater recharge. The hydrological models, by means of these simulations, provide the very crucial information regarding the availability of water, hydrological processes, and the impacts on water resources, which can be, thus support the decision-makers in the effective water management and sustainable planning.

2.2.3.1 SWAT Model

SWAT is a continuous, conceptual model with a physical base. It is intended to forecast the effects of watershed management techniques on hydrology, sediment, and water quality in a gauged or ungauged watershed. It runs on a daily time step (Golmohammadi et al., 2014). SWAT, which was developed by the USDA Agricultural Research Service, is a model that can simulate the long-term effects in huge and complex watersheds with different soil types, land uses, and management practices (Janjić & Tadić, 2023; Shiva Dwivedi, 2024). Weather generation, hydrology, sediment, crop growth, and nutrient and pesticide subroutines are among the main model components(Arnold et al., 1998). In order to accurately simulate water quality and quantity, SWAT needs precise data regarding topography, meteorology (temperature, precipitation), hydrography (groundwater reserves, channel routing, ponds or reservoirs, sedimentation patterns), soil properties (composition, moisture and nutrient content, temperature, erosion potential), crops, vegetation, and agronomic practices.

The model principle is to divide the watershed into small basins, then further to hydrological response units (HRUs) according to the specific combinations of land use, soil, and slope characteristics, and to simulate some of the most important hydrological processes such as surface runoff, return flow, percolation, evapotranspiration, and water routing using a water balance equation (Shiva Dwivedi, 2024). SWAT simulates the following for each HRU in each sub basin: soil water balance; groundwater flow; lateral flow; channel routing (main and tributary); evapotranspiration; crop growth and nutrient uptake; pond and wetland balances; degradation of soil pesticides; and in-stream transformation of minerals and pesticides(Vazquez-Amábile & Engel, 2005). The hydrologic components of SWAT comprise the following: shallow aquifer involvement in the stream flow for a nearby stream (base flow); infiltration; evapotranspiration; lateral flow; tile drainage; percolation/deep seepage; consumptive use through pumping; and recharge by seepage from surface water bodies. SWAT is extensively used in the fields of water resource management, climate change impact prediction, non-point source pollution modeling, soil erosion assessment, and drought monitoring and prediction (Shiva Dwivedi, 2024). Calibration and validation are very important for the model's accuracy, usually applying software like SWAT-CUP for sensitivity and uncertainty analysis (Awasthi & Kumar, 2021).

The SWAT model has been utilized in a variety of regions across Ethiopia for a range of purposes. The research in the Lake Tana Basin mainly revolves around hydrological water balance modeling and streamflow forecasting (Setegn et al., 2008). The Fincha watershed is another site where the SWAT model has been used for predicting the impact of land use and land cover changes on soil erosion and sediment yield entering the Fincha Dam (Regasa & Nones, 2023). Besides, in the Keleta watershed, SWAT has been used for hydrologic and soil erosion predictions and to assess water harvesting areas for irrigation practices (Debebe et al., 2023). (Mekonnen et al., 2018), analyzed the combined and isolated effects of land use and land cover change and climate change on the stream of Upper Blue Nile basin. (Mekuria, 2022) assessed the water balance of Deme Watershed, Omo-Gibe Basin using SWAT. In Fincha Catchment (Dibaba et al., 2020) employed SWAT model to investigate the hydrological Response of watershed to combined land use/land cover. (Daniel & Abate, 2022) examined the effect of climate change on streamflow in the Gelana watershed. In the ungauged Gelana watershed, (Daniel, 2024) modelled surface water potential by combining SWAT model with principal component analysis

2.2.3.2. WetSpass-M Model

WetSpass model (Batelaan & De Smedt, 2001a) is used to determine long-term spatial variations of groundwater recharge, allowing us to solve some of the fundamental problems in spatially distributed accurate groundwater recharge calculation.(Dereje & Nedaw, 2019; Meresa & Taye, 2019). The WetSpass-M model is the modification of the original WetSpass model. A new version of WetSpass-M has been created to predict the distribute water balance component (actual evapotranspiration, surface runoff and groundwater recharge) at monthly time increments, taking advantage of the popularity of Python programming, enhanced input datasets, and advancements in remote sensing and Geographic Information System (GIS)(Abdollahi et al., 2017). The WetSpass model is limited to forecasting seasonal or annual recharge (Dawana, 2025; Gebreyohannes et al., 2013; Kahsay et al., 2019). The WetSpass-M model quantifies monthly water balance components, including surface runoff, evapotranspiration, and groundwater recharge (E. D. Ashaolu et al., 2020; Nannawo, Lohani, & Eshete, 2021). To work properly the model requires an optimal spatial resolution and datasets that are perfectly aligned and using the same coordinate system. Static data (elevation, slope, soil, and land use) and monthly climatic data (rainfall, temperature, wind, and PET) are the input parameters. For soil and land cover classifications, lookup tables are employed to maintain uniformity and to make the processing smoother(Woldu et al., 2024).

Previously, WetSpass-M model was applied in some studies to characterize and analyse groundwater recharge in different parts of the world, for example it successfully applied in Belgium (Batelaan & De Smedt, 2001a), in Jordan on the Hasan and Jafr basin (Abu-Saleem et al., 2010; Al Kuisi & El-Naqa, 2013), In Black Volta basin, West Africa (Abdollahi et al., 2017), In Iran (Zarei et al., 2016), in West Africa, Nigeria (E. Ashaolu et al., 2020), in North Africa, Morocco Moulouya Basin(Amiri et al., 2022), in Tanzania, Makutupura basin (Kisiki et al., 2023) and Crotia (Karlović et al., 2021). In Ethiopa, Upper Awash Basin(Woldu et al., 2024), Chemoga watershed (Mulie Asrade, 2024), Jedeb watershed, Upper Blue Nile Basin (Asrade et al., 2024)

2.3. Integrated Water Resources Management

The amount of available water is indeed just one factor among many that determine the way water challenges are resolved. Such factors include water management techniques, the training and expertise of the institutions responsible for water management, the sociopolitical context that governs water planning, development, and management practices, the suitability and status of the legal frameworks currently in place, the financial resources available, the social and environmental conditions of the countries involved, the degree of accessible and useable technology, national, regional, and international perceptions, modes of governance that address issues like political interference, transparency, corruption, etc., conditions related to education and development, and the status, quality, and relevance of research that are being conducted on the national, subnational and local water problems (Biswas, 2004).

Integrated Water Resources Management (IWRM) is a comprehensive and participatory method that aims to reconcile the different water demands and at the same time, to guarantee the sustainable and fair handling of water resources. By bringing together various sectors, stakeholders, and factors, IWRM advocates for effective governance, active participation of stakeholders, and the sustainable development of water resources. The Indonesian study on the use of IWRM for climate-adaptive urban resilience building pointed out multi-layered policy and stakeholder engagement as crucial factors for successful slum upgrading and urban resilience processes(Wicaksono et al., 2024). It underlines the necessity of integrated planning, adaptive management, and transboundary cooperation in order to solve the complicated problems related to water resources. At last, IWRM aspires to provide water security, environmental sustainability, and socio-economic development not only for the current but also for future generations. To manage the different conflicting water resources applications, IWRM was proposed to be the solution (Rahaman & Varis, 2005).

IWRM was anticipated to "enhance the production of water and the quality of water" in the developing world by dealing with the problems related to their institutions, coordination, and system limitations. It is also believed to further the discussions among policymakers, help develop better ways of managing water resources, and contribute to capacity building and the education of people (Hailu et al., 2018). (Agarwal et al., 2000) characterized IWRM as a procedure, which facilitates the simultaneous development and management of water, land and their resources, thereby maximizing the economic and social welfare resulting from such activities, distributed fairly and without endangering the sustainability of essential ecosystems.

2.4. Water Demand

Water demand is the total amount of water needed for consumption by people, society, industries, and agriculture(Cai & Rosegrant, 2002). It is impacted by diverse factors such as population increase, migration to cities, industrial development, and weather conditions(Gupta et al., 2020). Projections suggest an ongoing increase in global demand for water, stimulated by these factors (Amarasinghe & Smakhtin, 2014; Rosegrant & Cai, 2002). The total water demand is mainly composed of four sectors: the household/municipal, industrial, agricultural, and environmental sectors. Water demand management encompasses approaches like water conservation, application of efficient use practices, and infrastructure development that together form a reliable water supply for all sectors(Liu et al., 2024). Being aware of the local water demand trends and barriers is crucial for effective water management(Bessedik et al., 2023). Allocating available water to customers who have high demands is the essence of water allocation(Speed et al., 2013). A basic scientific understanding of the efficient sharing of the limited available water resources is necessary to make informed operational decisions on water sharing solutions in a river basin or watershed(Arjoon et al., 2016). The demand for water use is influenced by several factors, such as the quantity of water needed for a specific activity, the number of households, hectares of irrigated land, types of crops planted, minimum stream flows, and other environmental, social, and economic factors. Whenever the available resources are less than the demands, conflicts between different users will occur, as it happens in a few places with irrigation.

As stated by (Farriansyah et al., 2018) because of population growth and the acceleration of global urbanization, industrialization, and commercial development, there will be a growing demand for water resources of adequate quantity and quality for human consumption, sanitation, agricultural, and industrial applications. Water demand prediction is a multifaceted process that involves various methodologies and is commonly employed to forecast future water requirements for various applications such as hydropower, household, and agricultural applications. The number of households and population size are typically used to estimate municipal demand, while the number of employees is frequently used to estimate industrial demand and crop type and irrigated land is widely used to estimate agricultural demand (Nauges & Whittington, 2010).

2.5. Water Resources Allocation

Water allocation is the term used to describe how water resources are shared and managed among different users and sectors(S. Zhang et al., 2023). It includes the determination and control of the amounts of water that are allowed to be used by the stakeholders, which can be households, agriculture, industry, and the environment(Yang et al., 2024). On the other hand, the allocation of water and water rights is a problem-solving issue in that it is a matter of how much water can be used by the different sectors and how to distribute it in an effective way and it is essential for mitigating water scarcity and resolving conflicts among users (Zhang et al., 2022). Different regions and countries have different approaches, like riparian rights, prior appropriation, permit systems, water markets, and integrated water management, for example, to support and even to regulate the distribution and use of water fairly and sustainably. In the process of water allocation and management, it is very important to take into consideration the diverse needs and demands of water users as well as to protect the environment (Nancarrow & Syme, 2004). The basic principles of water resource allocation are sustainability, equity, and good practice. The aim is to create the highest possible benefits for the economy, society, and nature giving at the same time equal shares to different areas and groups of people(Wang et al., 2008).

Sustainable water resource management is crucial for the development of sustainable economies in arid and semi-arid regions, as determined by (Farrokhzadeh et al., 2020) systems of water resources that are managed and intended to properly support societal goals both now and in the future while preserving their ecological, environmental, and hydrological integrity. In order to distribute water resources rationally, a complicated balance between supply and demand must be maintained across time (annual, inter-annual, or even generational) in a variety of economic sectors

(F. Zhang et al., 2023b). Establishing a priority allocation system for water shortage periods is crucial when it comes to the need for higher priority sites, such as meeting urban and rural areas' drinking demands before meeting those of other consumers. This is because determining the proper right of water over a region depends on making this decision (Mirdashtvan et al., 2021**).** When prioritizing water supply sites, the supply preference option can be used if the demand site is connected to multiple water supply sources. This means that, out of all the available supply sources for a point of demand, such as surface water, groundwater, river flow, etc., priority is assigned to a particular demand area for a particular consumption type.

Over time, allocation objectives have changed, and new methods for identifying, assessing, and managing water resources emerged. Allocating water resources has ultimately come down to determining who has the right to the water that is available. At its fundamental level, this comprises:

1. Figuring out how much water is available for distribution. Examining various sites, sources (such surface water and groundwater), periods of the year, and weather circumstances can all be included in this.

2. Deciding who should have the right to what when it comes to sharing that water among competing customers and various locations. Different sectors, various administrative or geographic regions, and (in the end) individual water abstractors and users may all be distinguished during the water allocation process.

2.6. Models for Water Allocation

Water resources management includes the development, management, preservation, control, and wise use of surface and groundwater resources. Computer models are crucial to practically every part of water resource management, including the process of making decisions about water resources generally (Wurbs, 2005). A water management model is used to create a plan for allocating water that considers the requirements of various stakeholders and water users in a basin. A water management model is also helpful when analyzing the effects of various future scenarios on the system as a whole, including changes in hydrology, management choices, socioeconomic shifts, etc.

When addressing water allocation issues involving competition for limited water supplies, simulation and optimization models can be useful complimentary tools. Through the usage of detailed simulation models, it is possible to assess the water allocation policies set by optimization models with respect to the infrastructure operations and the reactions of water resources system under extreme conditions, although they cannot be integrated into the optimization process.(Faisal et al., 1997). Since its establishment, the Water Evaluation and Planning Model, WEAP model, has been extensively used in several IWRM projects with a variety of goals all over the world. WEAP is a multi-scale modeling tool for water allocation and planning that can be used at the community, Watershed, and basin levels(Sieber & Purkey, 2009; Yates et al., 2005b).

2.6.1 Water Evaluation and Planning (WEAP) Model

The Water Evaluation and Planning (WEAP) model was created in 1988 by the Stockholm Environmental Institute (SEI) https://www.weap21.org . It offers transparent, flexible, and easy-to-use planning for assessing the patterns of current water supply and demand as well as for creating and analyzing alternative scenarios(Leong & Lai, 2017). It is an integrated Decision Support System (DSS) designed to support water planning that balances water supplies and multiple water demands. According to the equation of equipment efficiencies, water use rate, re-use, and allocation, the following are the demand sides: domestic water need for urban and rural sites; livestock water need; irrigation water requirement; and environmental flow water requirement. The supply side encompasses groundwater, streams, Watershed, and reservoirs.

One of the advantages of the WEAP is its capability to adapt to every kind of data is provided to represent a water resources system. That is, it can describe the water supplies and demands of the system using daily, weekly, monthly, or annual time-steps(Hadri et al., 2022). It is applicable on a variety of temporal and spatial scales due to its adaptability(Yao et al., 2021). In fact, WEAP has been utilized globally to evaluate a diverse water management problems from the smallest cities to the large-scale managed watersheds (Agarwal et al., 2018). WEAP always allocates water in an optimal manner, taking into account the priorities established for each demand site. When compared to other water allocation tools, WEAP is distinct because of this(Sieber & Purkey, 2015).

CHAPTER THREE: MATERIALS AND METHODS

3.1 Description of the study area

3.1.1 Location of the Study Area

The study area is located in Bedele, which is situated in the Buno Bedele zone of the Oromia Regional State of Ethiopia. The Dabena watershed is one of the three sub-watersheds of the Didessa River, which is the major sub-basin of the Blue Nile River basin in the western part of Ethiopia. Geographical coordinates of the watershed area are between Latitude 8° 12' 14" to 9° 11' 57" N and Longitude 35° 57' 50" to 36° 31' 60" E. The area of the watershed drained by the river is about 3225.98 square kilometers. The river draining the watershed starts at Buno Bedele Zone and merges into the Didessa sub-basin at East Wollega, Oromia national regional state. (Figure 3.1).

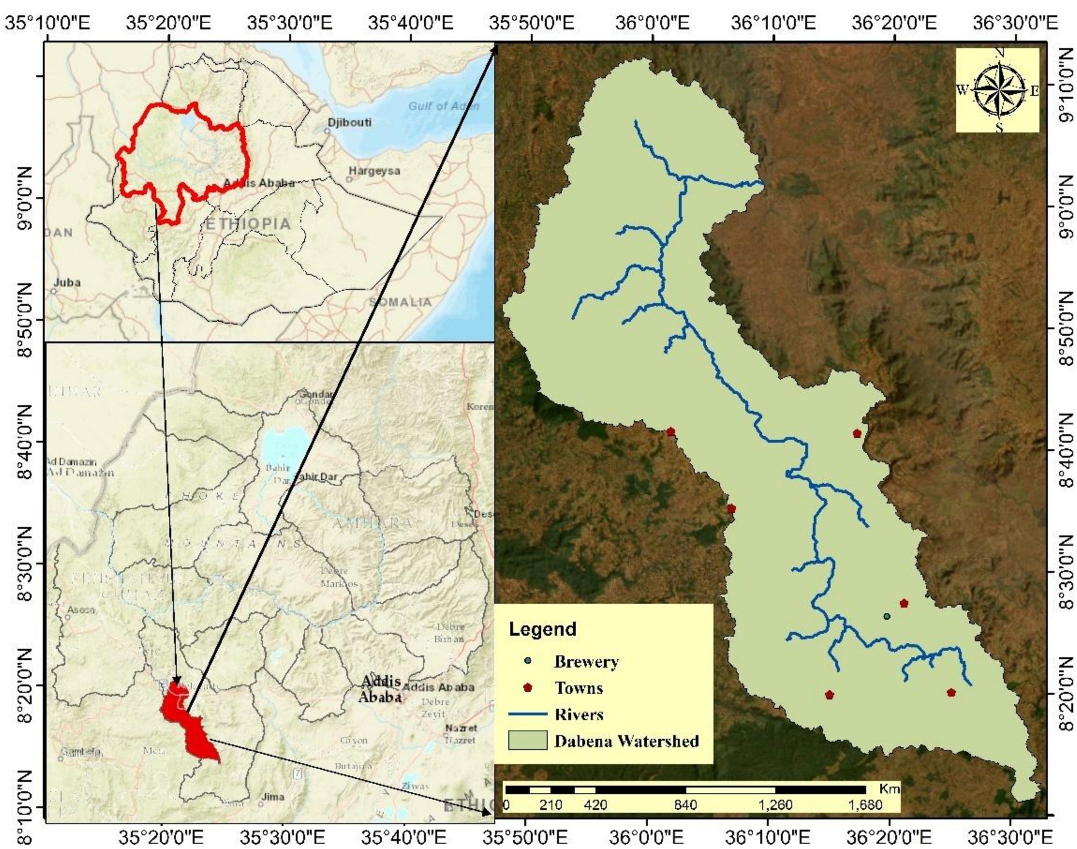

Figure 3.1 Location Map of the Study Area.

3.1.2 Topography

The topography of the watershed is somewhat heterogeneous, and the areas occupy landscapes with varying elevations and topographic features ranging from flat to mountainous. The watershed stretches across different topographical zones. The altitude of the study ranges from 1136 to 2525m.a.s.l, see Figure 3.2. The slope classification of the study area, based on FAO criteria, indicates a variety of topography. The flat to gently sloping sections, with slopes ranging from 0-5%, account for 6% of the topography and provide essentially level ground. Gently sloping to moderately sloping lands, with slopes ranging from 5-15%, cover 36% of the land and have notable inclines. The most dominating category, moderately steep terrain with slopes ranging from 15-30%, covering about 44% of the research area, showing significant elevation changes. Finally, the steepest slopes, above 30%, account for 14% of the area.

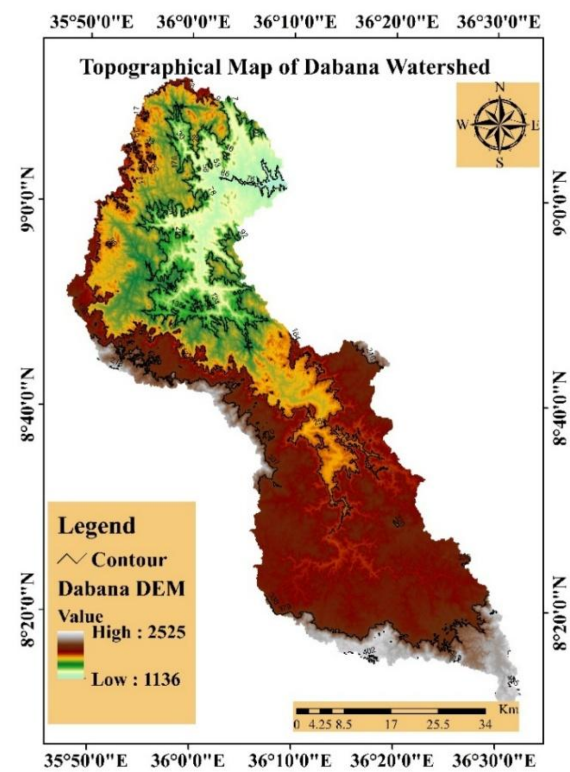

Figure 3.2 Topographical Map of the Study Area

3.1.3 Climate

In this research, the watershed covering area comprises three agro-climatic regions: lowland (kola), midland (weynadega) and highland (dega), with different elevation range of 500-1500, 1500-2300, and above 2300, respectively. The major part of the watershed area, over 80% is assigned to the Weynadega zone with its altitude of 1500-2300 m.a.s.l. The climate in the area of research is characterized by the Inter-Tropical Convergence Zone (ITCZ). The rainy season and the amount of rainfall during this season in the area are the results of the yearly movement of the ITCZ(Wikipedia, 2022).

The study area experiences a monomodal type of rainfall (one wet season) with mean annual rainfall of 1957.1mm. The rainfall pattern in the study area shows that a strong peak occurs in the months May to September, and short rainfalls in the rest of the months. Figure 3.3 shows the average monthly rainfall of the watershed. The average monthly temperature of the Dabena watershed varies from a minimum average of 16.49 °C in the Arjo station to a maximum average of 24.24 °C in the Didessa station. The highest temperature is recorded in March, and the lowest value is in November, see Figure 3.4.

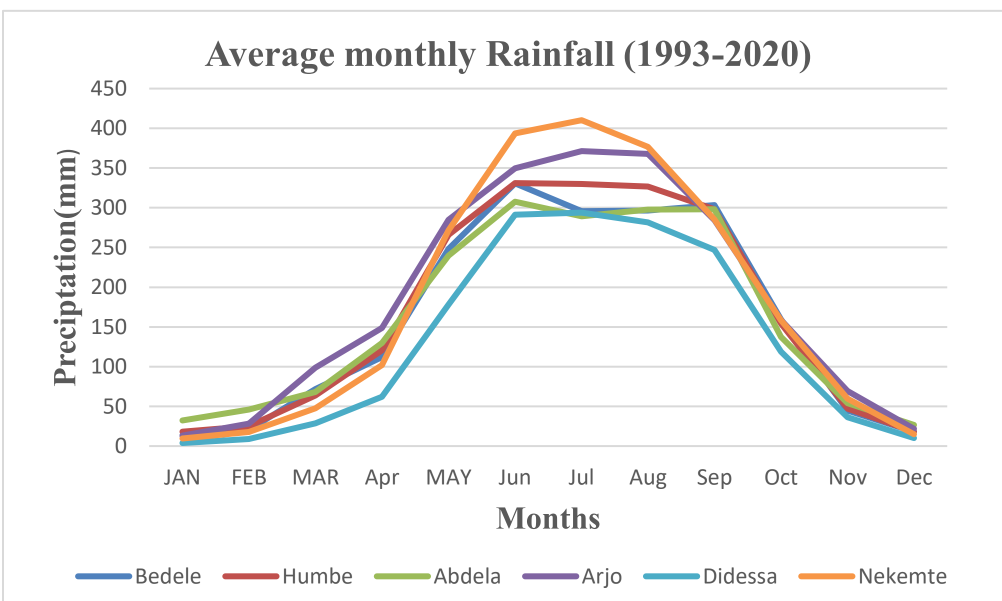

Figure 3.3. Average Monthly Rainfall of Dabana Watershed

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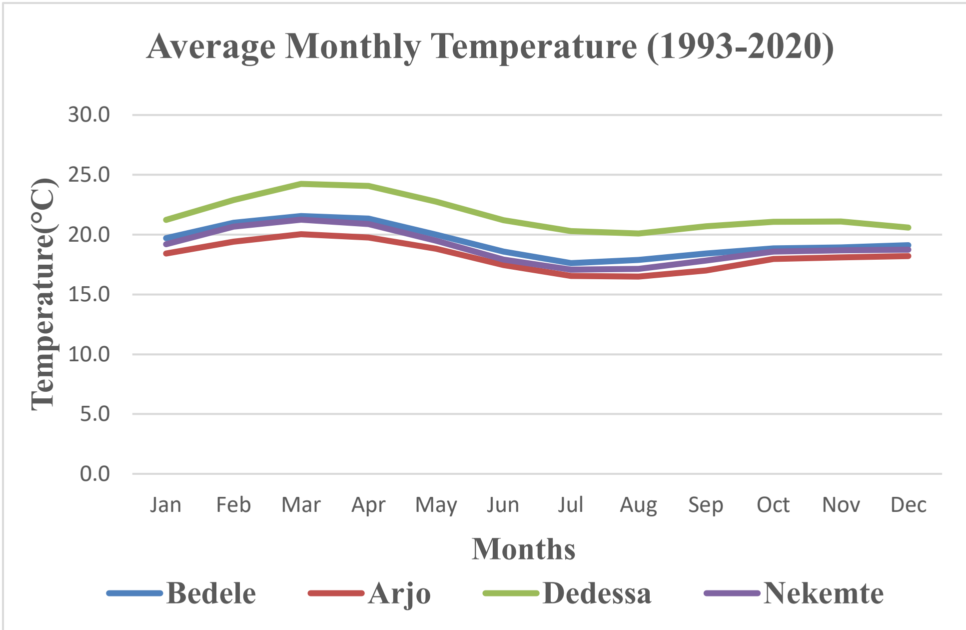


Figure 3.4 Average Monthly Temperature of Dabena Watershed

3.1.4. Drainage

The Dabena River and its tributaries typically display a dendritic drainage pattern where water flows through a hierarchy of six stream orders, and it flows in a direction from southwest to northeast. The entire system starts with a large number of small, first-order streams that gather headwater runoff and then continue to combine into larger channels, stepwise. Finally, this network culminates in a single thick trunk of the sixth order, which is the Dabena River itself. The Dabena River is one of a major tributary of the Didessa River located in the Blue Nile (Abay) Basin, conducts the total discharge of the basin towards the northeast, and eventually, the Abay River benefits from this flow. Figure 3.5 shows the drainage pattern of Dabena watershed.

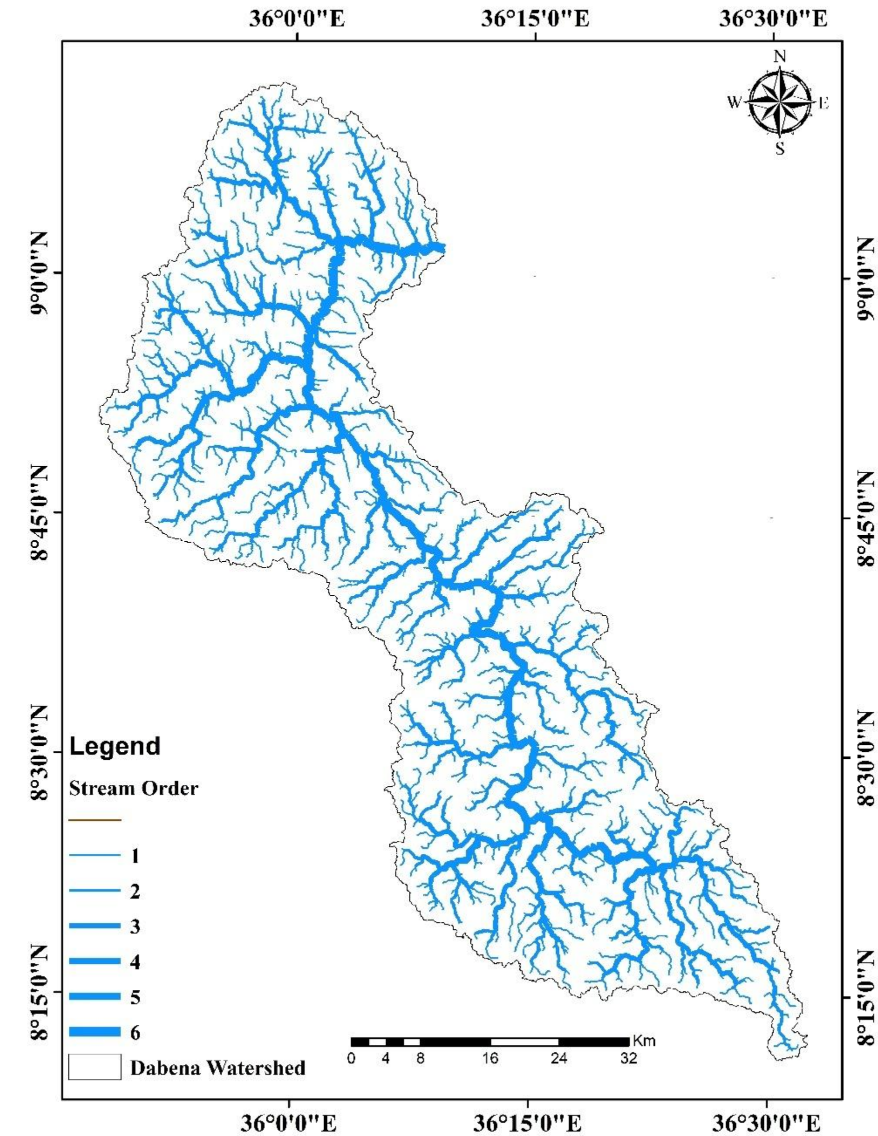


Figure 3.5 Drainage Map of Dabana Watershed

3.1.5 Geology of the Study Area

3.1.5.1. Local Geology

Ethiopia can be categorized into four main physiographic regions that are commonly referred to as the western plateau, the southeastern plateau, the main rift, and the Afar depression. The study area is situated in the western Ethiopian plateau, particularly in the southwest. The geology of western Ethiopia is characterized by a variety of rock types ranging in age from Precambrian to Quaternary((GSE), 2006).

The study area is underlain by Precambrian basement rocks, Tertiary volcanic units, and Quaternary sedimentary covers(Hagereselam, 2005). The Tertiary volcanics are subdivided into three distinct identifiable units: Lower Basalt, Middle Basalt, and Upper Basalt based on variations in topographic expression, morphology, and lateral extent. The Quaternary deposits comprise alluvium and undifferentiated soil, consisting of reddish-brown to black soils, sandy and silty soils, and reworked materials containing basalt and trachyte fragments. See Figure 3.6

3.1.5.1.1 Precambrian Rocks

Quartzo-Feldspathic Gneiss and Banded Gneiss (Pgne1)

This unit generally forms low-lying terrains, with good exposures commonly observed along streams, riverbeds, and creeks. In some places, it appears as isolated hills and peaks with blocky and slabby disturbed outcrops. The unit covers a large area and consists of moderately to highly weathered, fractured rocks that are gray, grayish white, or pale pink, fine- to medium-grained, and show weak to strong gneissic banding(GSE, 2000).

Deformed Granitoid (Pgt1)

The distorted granitoid makes up a body that is roughly circular to elliptical in shape and is situated approximately 5 kilometers to the south of the Chewaka settlement. It is characterized by a northwestern elongated mass that has a length of about 48 kilometers and is accompanied by moderate to high relief. The main rock type is granite, which ranges from grayish to reddish pink, has a medium to coarse grain size, and is equigranular (GSE, 2006).

Granitoid Orthogneiss (Pgne2)

This unit forms domical hills and ridges, including Mt. Chuta. It has a sub-circular to elliptical geometry, with maximum width near the center and narrowing margins (GSE, 2000). Its contact with unit Pgne1 is tectonically marked by NE trending shear zone. The lithology of this unit is characterized by different amount of migmatized granite gneiss.

Granite Gneiss

This is the most extensive Precambrian unit in the study area. It forms ridges, including Mt. Chuta, and is characterized by blocky, bouldery, and slabby outcrops. The rock displays gray, has a medium to coarse grain size, and predominantly exposed in the western part of the region, forming discontinuous hilltops, valleys cut by erosion, and ridges.

Hypersthene–Quartz–Feldspar (Charnockitic) Gneiss (Pgne3)

This unit is occurred in the northwestern part of the study area around the locality called Urgo and Bereda area, west of Chamman village. The manner of outcrop is blocky and boulder-forming hills and ridges. Its contact with the granitoid orthogneisses (unit Pgne2) is tectonic, marked by an NNE-trending dextral strike-slip shear zone. The rock is pink and greyish pink, fine to medium-grained, and looks banded on outcrop, but appears massive in hand specimen.

Late- to Post-Tectonic Granite (Pgt2)

They appear in the western section of the mapped region, to the west of Abdela village, and in the areas known as Boka Gudura, Terfa, and Tulu Senbeta as distinct roundish to oval bodies creating hills and ridges, and coming out as large rounded blocks. At places (Teba Chebeli, Gemeda and Yaya Sota localities), they form blocky small inselbergs and patchy outcrops on hillsides and stream beds. This unit consists of a mostly homogeneous mass made up of medium- to coarse-grained granite that is massive, pink to grayish-pink, and leucocratic in color. They vary in texture from medium-grained inequigranular to slightly megacrystic.

3.1.5.1.2. Tertiary Volcanic Rocks

Lower Basalt (Talb)

This unit represents the largest part of the Arjo group volcanics, which unconformably overlies the Precambrian rocks and the Tertiary sediments (Geba Sediments), and underlies the pyroclastic deposits of unit Tapx. Commonly, it forms gentle slopes and cliffs, but at places it forms low-lying rounded hills, which rise for about few tens of meters above the plain. It reaches an average thickness of 40 to 50 m, but it is thicker to the northeast at Wangere ridge around Gumbi locality, where it attains a maximum thickness of 280 m. The rock is greyish black to black and commonly aphanitic to locally porphyritic and amygdaloidal.

Pyroclastics (Tapx)

This unit is unconformably overlying the lower basalt (Talb), and its contact with the overlying middle basalt (Tamb) is gradational, but locally defined by a slight slope break. The base of this unit in most outcrops, especially in the Kumbabe, Dilbi, Toba, and Uta localities, is traceable using a sharp topographic break in which the underlying lower basalt forms a gentle slope, and that of a pyroclastic deposit forms a relatively steep slope. The pyroclastic deposits attained a maximum thickness of about 150 m near the Kumbabe town (Koda area) and drastically decreased towards the south, northeast, and north, and attained a thickness of a few tens of meters (about 20 m) in the Abdela and Tulu Mute areas.

Middle Basalt (Tamb)

This unit typically creates flat top ridges and plateaus and occupies a higher topography. The flow reaches an average thickness of 50 to 60 meters, although it gets thicker to the west, reaching a maximum thickness of 175 meters in the Meko region. It is mainly comprised of aphanitic basalt with minor layers of plagioclase and pyroxene phyric basalts. The lower part of this unit is relatively thick (about 200 m) and is made of columnar, jointed aphanitic basalt with lesser amygdaloidal varieties.

Upper Basalt (Taub)

The Upper Basalt is seen on the surface as a series of discontinuous, dome-shaped ridges and hills that trend in the northwest direction, at some places creating cones and isolated peaks. The rocks are of light gray to blackish gray color and their textures vary from aphanitic to phyric and locally porphyritic. Columnar and partially jointed structures are prevalent.

3.11.5.1.3. Quaternary Deposits

Alluvial Soils (Qal)

This alluvial deposit mainly occupies the vast plain alongside the river plains and marshy areas, but rarely covers the base of gentle-sloped hills. Mostly, they are silt size, less compacted, and dark brown to black soil. Usually they are thin-coated soil, but a considerable amount of thickness (about 9 m) was noted in the Nono plain and Tinishu Gibe River cut.

Undifferentiated Cover (Qus)

This unit occupies large areas in the northern part of the study area, particularly around the Chewaka settlement. It contains red to reddish-brown soils, brown to gray sand, silt, and gravel. Terrace deposits of unconsolidated sands and gravels occur along streams and creeks, with thicknesses of a few centimeters to about one meter (Hagereselam, 2005).

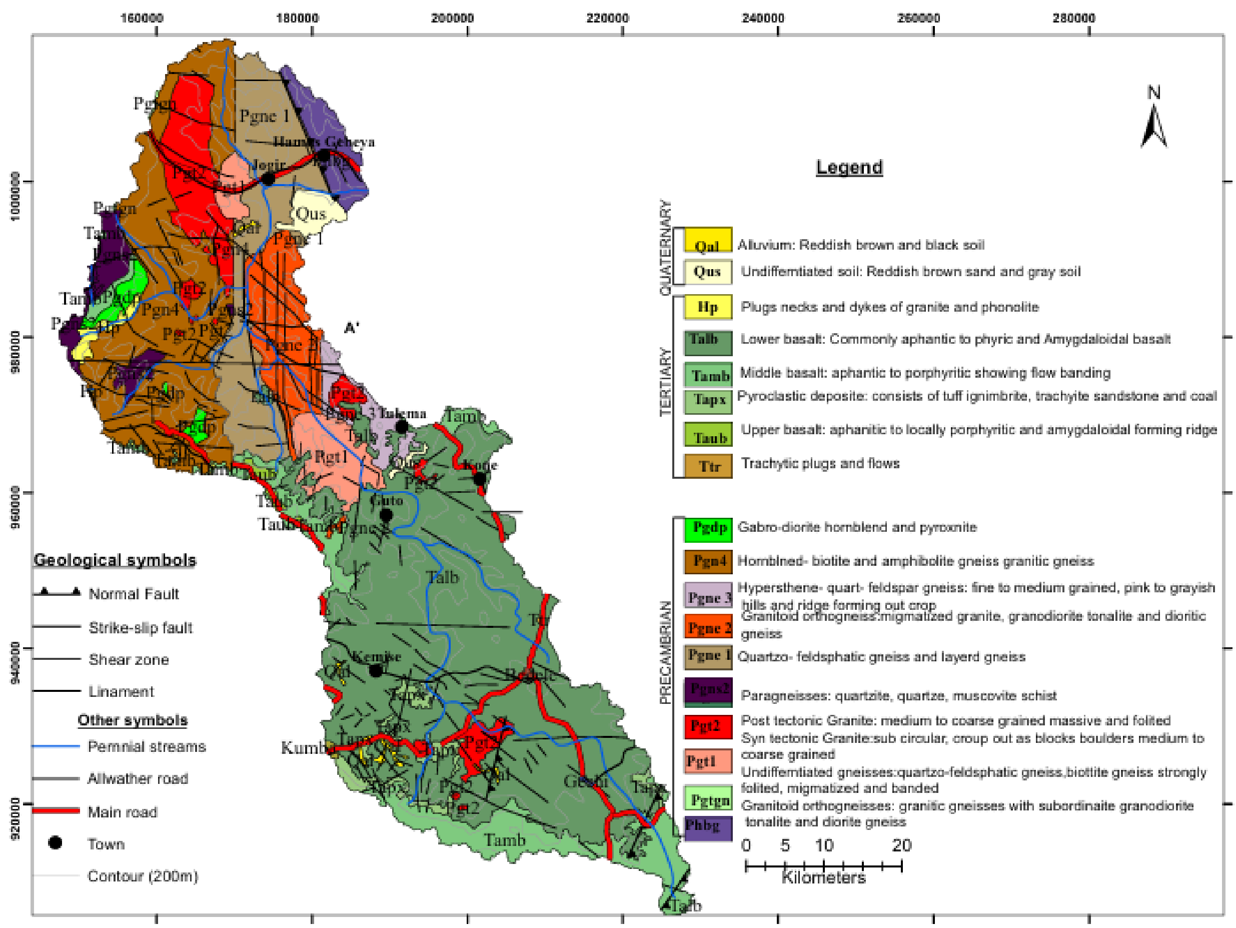


Figure 3.6 Geological Map of the Study Area, Modified after (Hagereselam, 2005)

The geological cross-section A–A′ depicts the topography and stratigraphy cutting across a vertical scale of 2.5 times greater than the horizontal. The elevation ranges between 500 m and 2000 m, with the maximum relief at the western side. The western part contains the Hp unit, a formation that is relatively resistant and a prominent highland. The eastern part of the landscape is a series of hills made by and composed of different Pgn units (Pgn4, Pgn1, Pgns2) that show alternate ridges and valleys formed through differential erosion. They differ in thickness and surface but generally dip very low, revealing the presence of a simple structural setting with little folding or faulting. The Pgne2 and Pgne3 units, which are younger, appear further east, creating the lowest terrain in the vicinity of point A′. A central geomorphic feature along the profile is the Dabena River, which erodes through various layers and forms a central erosional low. This valley of the river corresponds to the prevailing of water in the region, and overall, the cross-section depicts resistance to erosion of the highland in the west, while in the east, the opposite is the case, with overlying weak sedimentary or volcanic units that are heavily influenced by modern erosion and river incision. See Figure 3.7

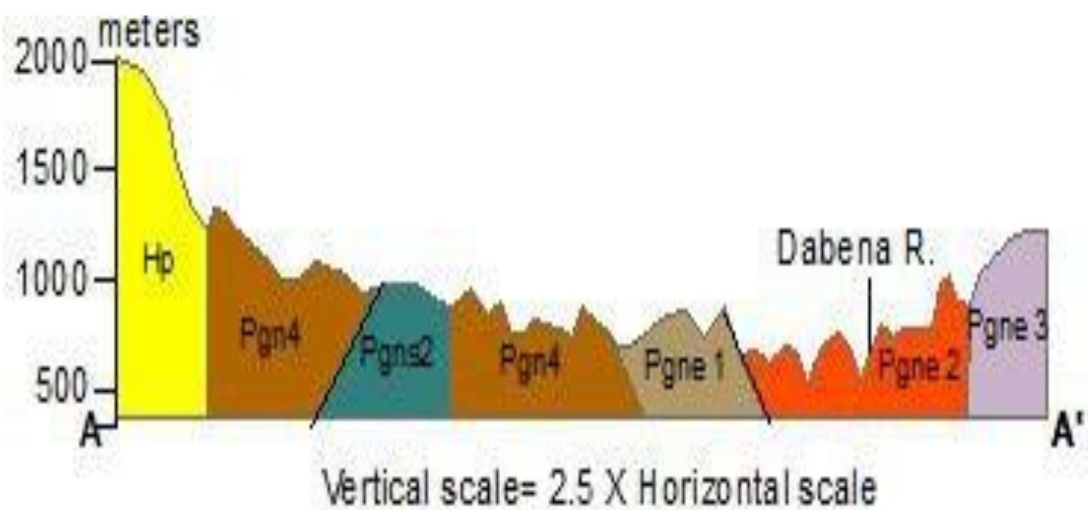


Figure 3.7 Geological Cross-Section of the Study Area, modified from (Hagereselam,2005)

3.1.6 General Hydrogeological Characteristics of The Study Area

Systematic hydrogeological and hydrochemical mapping has not yet been conducted in the study area for the assessment of groundwater resources. All groundwater exploration and exploitation activities carried out to date have been limited to drilling wells to supply water for local communities and resettlement sites. Furthermore, the absence of well-organized and properly recorded borehole data creates challenges during groundwater investigations. The available data do not include transmissivity values, which are essential for the quantitative classification of aquifers based on the hydrogeological standards of GSE (Sileshi, 2006). Consequently, aquifer yield, which is considered equivalent to transmissivity, has been used for aquifer classification.

The hydrogeological characteristics and potentiality of the study area are influenced strongly by the complexity of its geology, physiography, climate, and structural framework. According to hydrogeological principles, a good aquifer must possess sufficient permeability and transmissivity to store and transmit groundwater effectively. Groundwater-bearing potential is also associated with the presence of faults, as well as weathered and fractured zones within the rock mass. Additionally, the geology of the study area is a critical factor that influences both the occurrence and quality of groundwater. Tertiary volcanic formations constitute the largest portion of the area and represent good aquifers with variable yields and water quality. On the plateau, the Tertiary volcanics are weathered, fractured, and dissected by a system of SE- and NE-trending faults. Quaternary alluvial deposits occur along the major rivers Didesa, Dabena, and Gibe and are recharged seasonally during river floods. Physiographically, the lowlands are the discharge zones and the highlands are the recharge zones, with fresh groundwater that has low electrical conductivity and total dissolved solids(Jiri Sima, 2018).

3.1.6.1. Aquifer Classification

Quantitative classification of aquifers was carried out based on their areal extent, type of permeability, and basic hydraulic parameters, including transmissivity, specific yield of wells, and springs((GSE), 2006). Using geological descriptions, qualitative observations, and the limited quantitative data (spring and borehole yields) that was available within the study area, the aquifers were categorized as follows:

1. **Extensive and moderately productive porous aquifers.** These aquifers have transmissivity (T) of 1.1–10 m^2/d, specific yield (q) of 0.011–1 l/sm, and well/spring yield (Q) of 0.51–5 l/s. Flow is predominantly intergranular. Represented in light blue on the

hydrogeological map, they consist of Quaternary lacustrine sediments (unconsolidated sand and silt, Qal) and pyroclastic deposits (Tapx).

2. **Limited aquifers in unconsolidated material**. These aquifers are found in regolith with shallow groundwater, which provide different amounts of water according to their thickness and location relative to the recharge areas. They were represented with diagonal blue stripes for undifferentiated covers (Qus) on the map.
3. **Extensive and moderately productive fissured aquifers**. These aquifers have T = 1.1–10 m^2/d, q = 0.011–1 l/sm, and Q = 0.51–5 l/s. Flow occurs through a well-developed system of fissures and joints in volcanic and sedimentary rocks. Shown in light green on the map, they include large parts of Jimma volcanics (Talb, Tamb, Taub).
4. **Extensive and low productive fissured aquifers**. These aquifers have T = 0.11–1 m^2/d, q = 0.0011–0.01 l/sm, and Q = 0.051–0.5 l/s. Flow occurs in irregular fissures and the weathered mantle of crystalline rocks (granite gt1, gt2; gneiss Pgne1, Pgne2, Pgne3), representing limited groundwater resources. These aquifers are shown in brown-red on the hydrogeological map.
5. **Aquitards:** these minor aquifers have local and limited groundwater resources and are represented by trachyte flows and plugs (Ttr and Hp) in light brown on the map.

3.1.6.1.1. Porous Aquifers

Alluvial Deposits

The southern and southwestern regions of the study area contain the majority of this unit. It covers the moderately to severely fractured and fragmented lower and middle basalts, according to borehole data and field observations. The deposits are made up of silt and sand and range in color from reddish-brown to black. Thick alluvial deposits were observed around the village of Silk Amba. Topographically, this unit occurs on gentle flat slopes, with sparse vegetation, and is recharged by several perennial rivers.

Pyroclastic Deposits

Occurred in the southern, southwestern, and northeastern parts of the study area. Field inventory around Abdella indicates a thickness of 10–20 m, with spring yields of approximately 0.007 l/s.

The deposits include tuff, ignimbrite, trachyte, and tuffaceous sandstone. Around the Chewaka settlement, borehole logs show highly weathered pyroclastic deposits 14–32.2 m thick with yields up to 0.14 l/s.

3.1.6.1.2. Limited Aquifers in Unconsolidated Material – Regolith with Shallow Groundwater

Undifferentiated Covers (Qus)

This unit, which is exposed in the northern region of Chewaka, is made up of gravel, silt, brown to gray sand, and red to reddish-brown soil that ranges in thickness from a few centimeters to a meter. Borehole data indicate a thickness of 5 m, overlying 14 m of fractured basalt, 18.2 m of highly weathered pyroclastic deposits, and 87.8 m of moderate to highly weathered gneiss. The area has a flat, low-lying topography, low drainage density, and sparse vegetation. FAO soil classification identifies Nitisols as highly fertile, deep, and permeable, contributing significantly to aquifer recharge.

3.1.6.1.3. Fissured Aquifers

Lower Basalt (Talb)

The largest unit of Tertiary volcanics in the Dega and parts of Dinger and Arjo area, forming gentle slopes and steep cliffs. Average thickness is 40–50 m, reaching 280 m at Wangere Ridge around Gumbi. The basalt is grayish-black to black, aphanitic to porphyritic and amygdaloidal, moderate to highly weathered and fractured. Borehole data indicate average well yield of 6.63 l/s and a spring yield of 0.75 l/s.

Middle Basalt (Tamb)

Around Meko, they occupy higher elevations and form plateaus and flat ridges with a maximum thickness of 175 meters. The upper flow is fragmented, laterized, and severely fractured. Basalt is aphanitic to locally amygdaloidal and ranges in color from gray to grayish-black. Due to geographic and structural factors, low productivity was noted; the average spring production was 0.8 l/s

Upper Basalt (Taub)

Outcrops are discontinuous, dome-shaped hills and ridges that travel northwest; locally, they create isolated peaks and cones. The rock is extensively fractured, aphanitic to phyric, light gray to grayish-black, and moderately weathered. Field surveys revealed artesian conditions; the average yield of springs is 2 l/s.

3.1.6.1.4. Low Productive Aquifers in Basement

Quartzo-feldspathic and Banded Gneiss (Pgne1)

Forms low-lying topography, stream and river exposures, isolated hills and peaks. Boreholes show moderate to highly weathered and fractured rock; main aquifers reach thicknesses of 46–50 m with well yields of 8–10 l/s. Recharge sources include rainfall and perennial rivers (Didesa, Dabena, Madale).

Granite Gneiss

Forms ridges and Mt. Chuta, blocky to slabby outcrops, medium to coarse-grained. Average spring yield is 1 l/s.

Hypersthene-Quartz-Feldspar (Charnockitic) Gneiss (Pgne3)

Elongated NW-trending hills and ridges. Rocks are pink to grayish-pink, fine to medium-grained, appearing banded in outcrops.

Deformed Granitoid (Pgt1)

Sub-circular to elliptical, northwesterly elongated body. Composed of grayish to reddish-pink granite, medium to coarse-grained.

Late- to Post-Tectonic Granite (Pgt2)

Circular to sub-circular hills and ridges, medium to coarse-grained, pink to grayish-pink.

3.1.6.1.5. Aquitards

Volcanic Plugs and Diorite (Hp)

Volcanic plugs occur in the northwest, dark gray to grayish-black, medium-grained, massive to strongly foliated.

Trachyte Flows and Plugs (Ttr)

Distributed in the southern, southeastern, northeastern, and central parts, sub-circular to elongated dome-like shapes, highly weathered and slightly fractured. Borehole yield 1 l/s, spring yield 0.325 l/s. Hydrogeologically classified as a low-productive fracture aquifer, shown in light green on the map below (Figure 3.8).

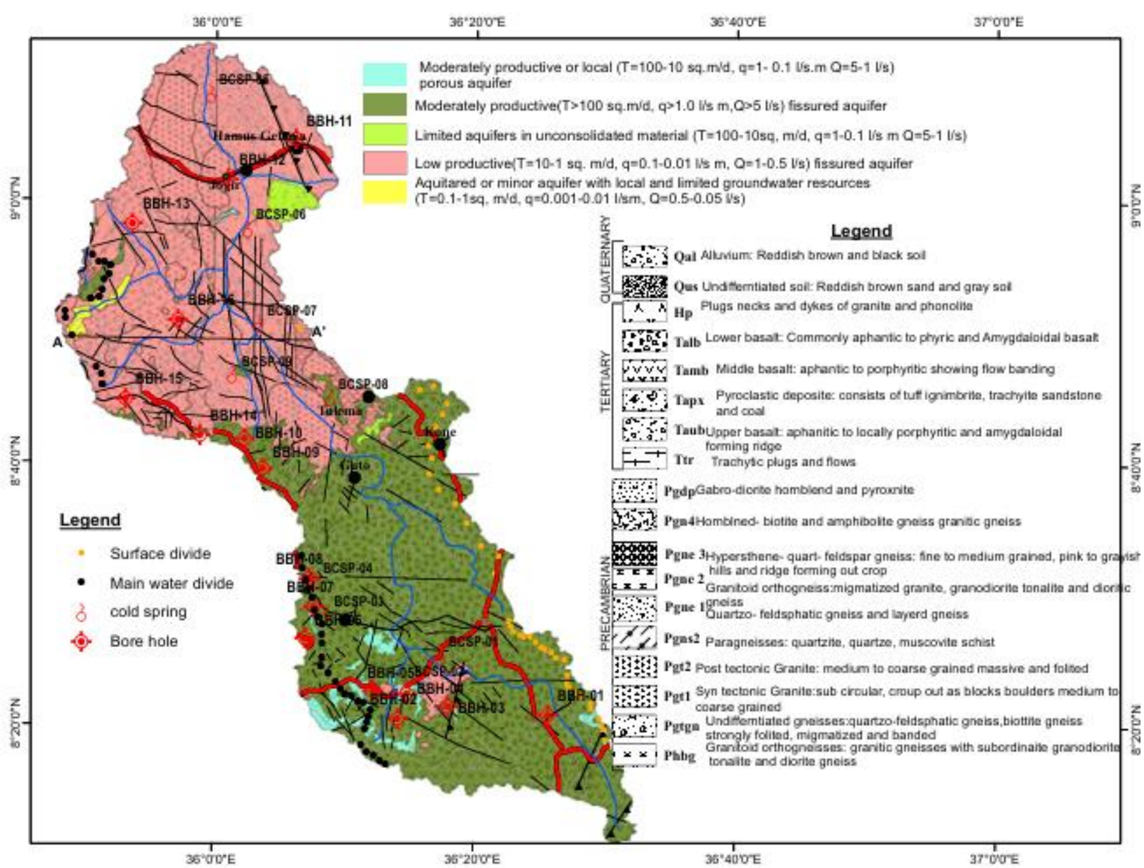


Figure 3.8 Hydrogeological Map of the Study Area, Modified After (Jiri Sima, 2018)

Geological cross-section of the Bedelle area reveals the control of groundwater circulation by the stacked volcanic units of the Jimma–Bedelle volcanic province. The upper section is made up of upper basalt, which constitutes the highest topographic ridges. This unit is very much fissured and porous, thus allowing quick infiltration of rainwater and acting as the main shallow aquifer. According to the diagram, water in lower basalt conforms to the local topography and shifts downward as local groundwater flow, finally discharging into the nearby valleys and springs at the transitions with less permeable layers. Under upper basalts lies the medium basalt, a moderately fractured sequence that is the intermediate aquifer system. Groundwater pours through from upper basalt to medium and then continues as local to intermediate flow, often appearing as springs where medium basalt meets slope surfaces. The lower basalt, deeper in the section, is the representation of an old and compact basaltic unit that serves as the deep regional aquifer. The diagram shows deep groundwater flow paths migrating through lower basalt, with longer residence times and greater flow distances toward major valley bottoms in the region. A prominent feature in the diagram is the trachyte plug, which intrudes vertically through the volcanic sequence. Trachyte, being considerably less permeable than the neighboring basalts, positively plays the role of a groundwater barrier, redirecting the flow either to the sides or to lower levels. The resultant barrier effect leads to groundwater local elevation on the intrusion's slope side, and thus, springs may appear along the barrier where water is pushed up. The overall picture the diagram (Figure 3.9) draws is that the Bedelle groundwater flow takes place at three levels: a shallow local system within upper basalt, an intermediate system within medium basalt, and a deep regional flow system within lower basalt. These paths are very much determined by the steep and rugged landscape as well as the vertical and horizontal positioning of the volcanic rock layers. The interplay of permeable basalt layers, sporadic low-permeability zones, and intrusive barriers culminates in a pattern of groundwater movement that is complex yet predictable across the Bedelle volcanic terrain.

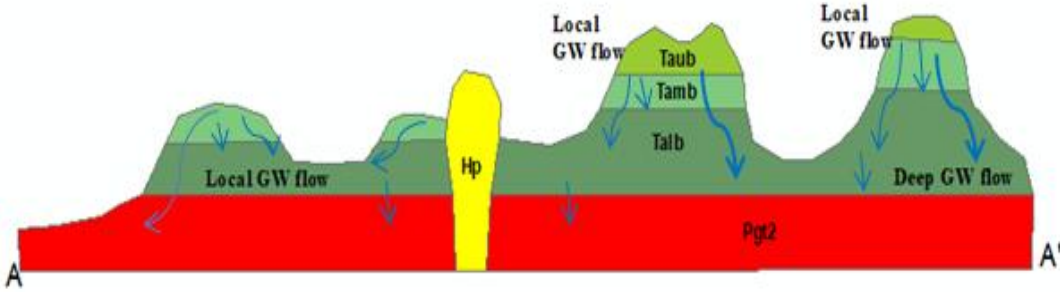


Figure 3.9 Hydrogeological Cross-Section of the Study Area (Jiri Sima,2018)

3.1.7. Land Use Landcover

The land use land cover classification map of Ethiopia was used for this study which is collected from the Ethiopian Ministry of Water and Energy. It shows a detailed classification of the LULC for the whole country (Ethiopia). Figure 3.10 represents the land cover classification condition of the Dabena watershed. This land cover classification has seven classes (Cultivation, Grassland, Highland Bamboo, Natural Forest, Shrubland, Water and Wood land).

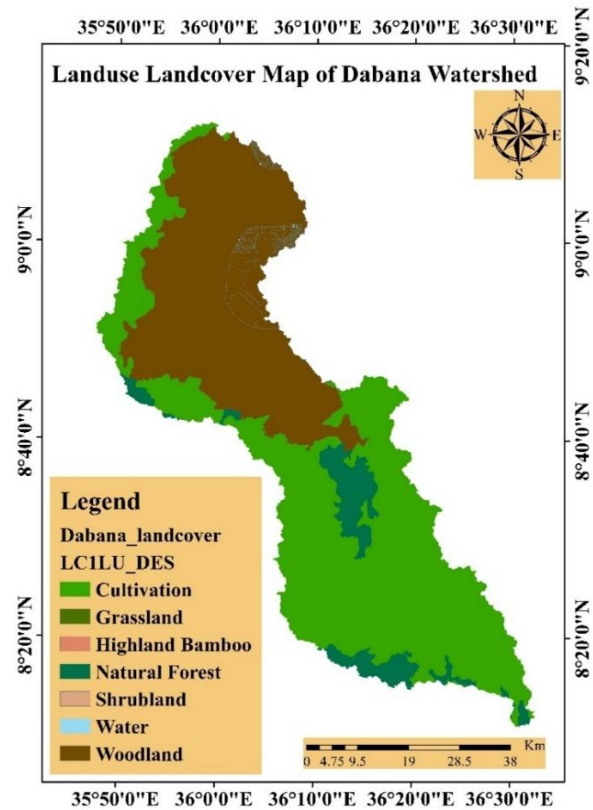


Figure 3.10 Landuse Landcover Map of the Dabana Watershed. (Source: MOWE)

3.1.8. Soil

The soil map of Ethiopia was collected from the Ministry of Water and Energy and clipped for the study area. The soil types clipped in the study area are identified as Dystric Gleysols, Dystric Nitisols, Eutric Cambisols, Eutric Fluvisols, Eutric Nitisols, Leptosols, Orthic Acrisols, and Orthic Luvisols. As shown in Figure 3.11, Dystric Nitisols and Eutric Nitisols are dominant, covering about 46% and 20% of the Dabena watershed, respectively.

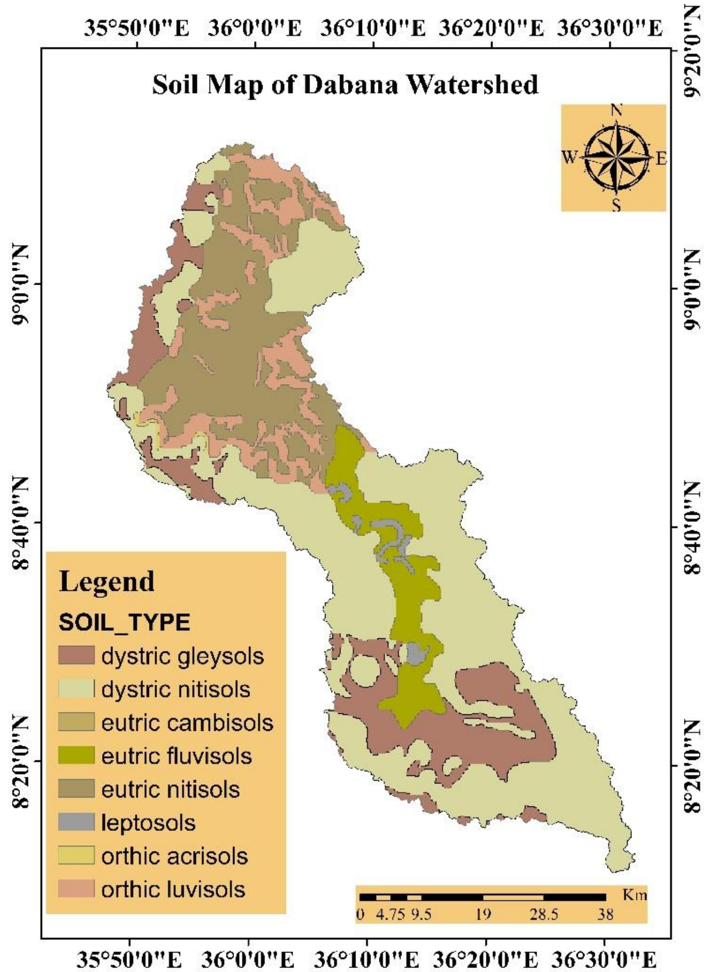


Figure 3.11 Soil Map of Dabana Watershed (MOWE)

3.1.9. Socio-Economy of Dabana Watershed

Dabena River Watershed is an important water system that supports a diverse range of water users, including domestic, farmers, and industry. The Watershed exhibits a diverse socio-economic profile shaped by intensive agricultural activity, high population growth and emerging industrial development. The urban and rural areas of the Watershed are densely populated. These urban and rural communities rely heavily on the domestic water supply from the Dabena River for household use and sanitation. In addition to agricultural and domestic needs, the area has a single industrial operation: the Bedele brewery, which extracts water directly from the Dabena River.

3.2. Data Quality control

For a variety of reasons, including damage or malfunction in the gauging station throughout the measurement period, the missing data can disrupt the continuity of recorded data. Therefore, before starting any model simulation, it is essential to make sure that the data are homogeneous, consistent, sufficient, and complete with no missing information. If there is any missing data, the data filling techniques should be used to estimate it. Inaccurate data produces inconsistent and unclear conclusions that can be at odds with reality.

3.2.1. Filling Missing Data

The quality of the available data determined the accuracy of the findings. Therefore, it is vital to look for missing data and discrepancies before using the data gathered for analysis. For missing meteorological data computation, the XLSTAT 2018 tool (software) was used. Most XLSTAT functions give options for dealing with missing data. Missing values can be classified into three types: data missing entirely at random (MCAR), data missing at random (MAR), and data not missing at random (NMAR). The approach included in the XLSTAT tool matches the MCAR and MAR scenarios. This tool uses advanced missing value treatment methods to help you complete or clean your dataset. The numerous methods/approaches available in XLSTAT, based on the need for data, are Remove observations with missing values, the nearest neighbour methods, the mean imputation method, and the NIPALS algorithm. The nearest neighbour method is applied for this study

3.2.2. Checking consistency of data

In addition to filling in missing data, inconsistency issues should be addressed, since data due to instrument malfunction may cause records to fail for continuity. This study employed the double mass curve analysis method in order to ensure the consistency of the rainfall data. A plot of cumulative rainfall data (Figure 3.12) at a particular station was frequently compared to the cumulative average at neighbouring stations in order to assess the consistency of rainfall data.

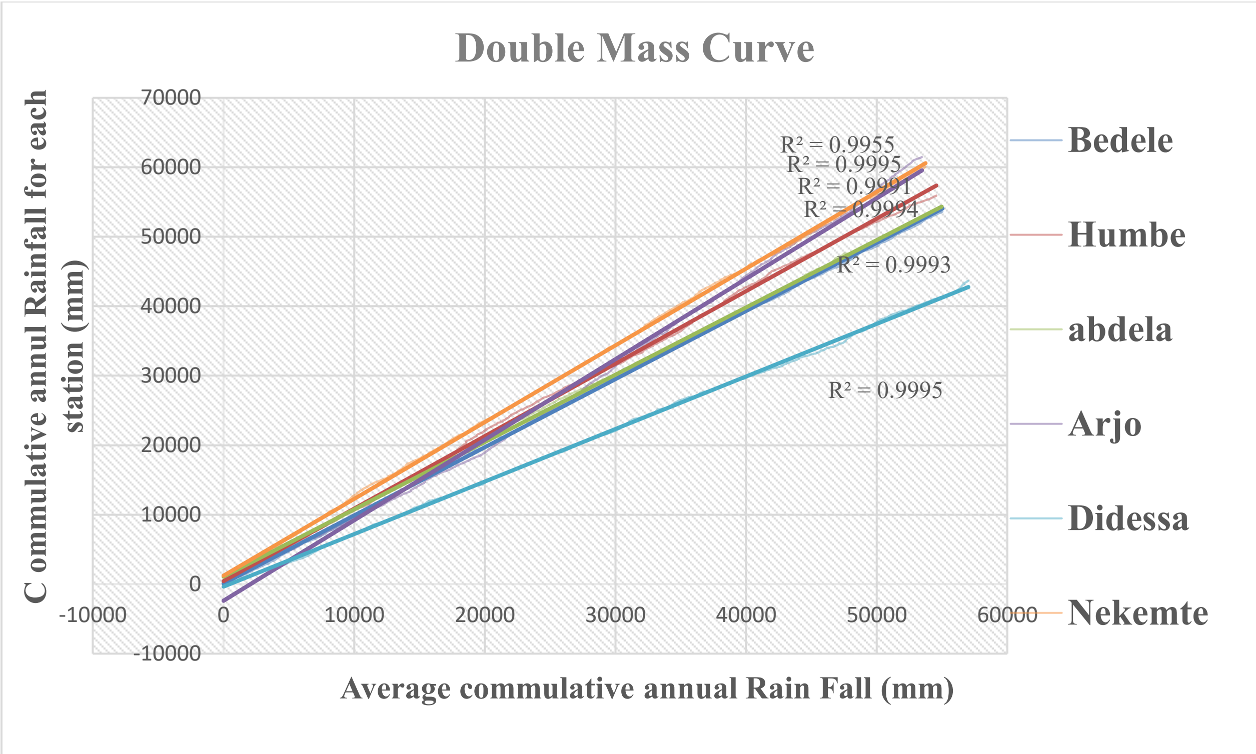


Figure 3.12. Double-Mass Curves and Consistency in Rainfall Data

3.3. Research Methodology

3.3.1 Water Balance calculation using WetSpass-M Model

The WetSpass-M model will be used as a methodology for the Dabena watershed to simulate the monthly, seasonal, and annual fluctuations in surface runoff, actual evapotranspiration, and groundwater recharge. Hydro-meteorological and biophysical data related to the watershed are typically the two fundamental input parameters required to run the WetSpass-M model. The data must be prepared in the required grid and database file (DBF) formats.

Three crucial steps were engaged in this study. To gather as much knowledge as possible about the topic, the first step was to evaluate the literature that was currently available. After that, the spatial data was gathered and prepared for recharge modeling. All of the inputs for the WetSpass-M model were constructed using the collected data, which included topographical, meteorological, soil, and landuse. ArcGIS 10.8 software demonstrated effectiveness for digital data preparation, manipulation, and analysis. These data were adjusted and processed for the raster grid cell.

In WetSpass-M model modelling frame, Water balance components of vegetated, bare-soil, open-water and impervious surfaces are used to calculate the total water balance of a raster cell using the Eqs. (1)–(3).

$$ETraster = av\,ETv + asEs + aoEo + aiEi \tag{1}$$

$$Sraster = avSv + asSs + aoSo + aiSi \tag{2}$$

$$Rraster = avRv + asRs + aoRo + aiRi \tag{3}$$

where ETraster, Sraster, Rraster are the total evapotranspiration, surface runoff, and groundwater recharge of a raster cell, respectively, each having a vegetated, bare-soil, open-water and impervious area component denoted by av, as, ao, and ai, respectively. The computation of the water balance of each of the previously mentioned raster cell components begins with precipitation; subsequent processes, including interception, surface runoff, evapotranspiration, and recharge, proceed in a systematic fashion.

3.3.1.1 Input Data for WetSpass-M Model

Both meteorological (rainfall, temperature, wind speed, and PET) and physical (land-use land cover, soil and slope, and groundwater level) data are required as input parameters for the WetSpass-M model. In general, parameter tables and grid maps have been prepared for the WetSpass-M model. GIS grid maps include information such as rainfall, PET, average temperature, wind speed, GWD, slope, soil type, and topography, Weather the information about soil properties and land use included in the parameter table of the model.

Attribute tables were used to connect these tables to the maps. Rooting depth, leaf area index (LAI), vegetation height, canopy cover, and many other variables related to land use type are included in the land use attribute table. Field capacity, wilting point, and permeability are among the soil characteristics included in the soil parameter table for each type of textural soil. Because a certain combination of slope, land use, and soil type will produce a fixed fraction of runoff regardless of location, the runoff attribute is thought to be universal(Amiri et al., 2022).

The interpolation method is used because it can be quickly and simply built using sparse and limited measurement data for a particular goal. Raster interpolation techniques include Kriging, Spline, and Inverse Distance Weighting (IDW). The Inverse Distance Weighting (IDW) method was applied in a spatial ArcGIS toolbox for this study. It is the most popular approach since it is easy to implement and usually yields positive outcomes.

During simulation, coherent outputs were produced by resampling the model input grid maps to a spatial resolution of 30 m. For the model, hydro-meteorological and biophysical maps were created, resampled to a resolution of 30 meters, and converted to ASCII files. The preparation, resolution, and sourcing of the WetSpass-M model data are explained here.

3.3.1.1.1 Meteorological Data Input

A daily observation of 6 meteorological stations that were evenly distributed over a period of 28 years (1993–2020) collected from the Ethiopian National Meteorological Agency (NMA), were used to compile the mean monthly rainfall. Rainfall data were provided by a total of 6 stations, maximum and minimum temperature data were provided by 4 stations, and due to the unavailability of recent wind speed data, daily wind speed data of 5 stations were downloaded from Power Access Climate Data (https://power.larc.nasa.gov). The study area experiences a small rainy season from March to the end of April after dry weather from October through February. The months of May to September are the main wet season.

The Hargreaves equation (Hargreaves & Samani, 1982), which is suitable in areas where only temperature data is available for climatic analysis, was used to compute the PET due to a lack of data. If there is not enough meteorological data for the Penman-Monteith methodology, the FAO recommends using the Hargreaves method(Allen et al., 1998) as a backup option for predicting PET. The Hargreaves Equation was utilized in this study to compute PET using DrinC software.

Meteorological variables are usually recorded at meteorological stations and the resulting data is only precise for that particular spot. These variables are required in hydrology and water resource management applications. Spatial interpolation can be used to estimate meteorological variables at various stations. The Inverse Distance Weighting IDW method was applied to prepare the meteorological data input for the model.

Every month, for each climate parameter, twelve raster maps were produced, bringing the total to 48 maps. All these rasters were then changed into American Standard Code for Information

Interchange (ASCII) files to ensure their accurate entry into the model. To facilitate model operation, these rasters were made with a cell size of (30 m x 30 m).

3.3.1.1.2 Physical Data Input

Topography and Slope

The elevation of the Dabana watershed ranges from 1136 to 2525 meters above mean sea level, and it is characterized by many forms of topography. While the western portion of the downstream and the western portion of the midstream region have undulating topography with extremely steep slopes, the eastern portion of the downstream and a portion of the midstream region were distinguished by flat slopes. There are mild to moderate slopes upstream of the watershed.

Topographically high locations are often regarded as recharge areas, while topographically low areas are considered discharge areas. Higher altitude locations had higher recharge rates than the remainder of the lowland areas. The local ground flow direction changes within small areas due to topography effects at shallow depths, whereas the regional groundwater flow displays a general direction at depths. Surface water infiltration is directly impacted by the slope gradient. While a high slope gradient reduces groundwater recharge because of excessive surface runoff, a low slope gradient restricts water flow and thus increases infiltration rate(Amiri et al., 2022). The watershed slope map is produced from topography map in a direct manner, by means of an ArcMap 10.4 “derive slope” module. The slope ranges from 0° to 50°, with a mean of 10° and a standard deviation of 5. Figure 3.13 show the slope map of the Dabena watershed.

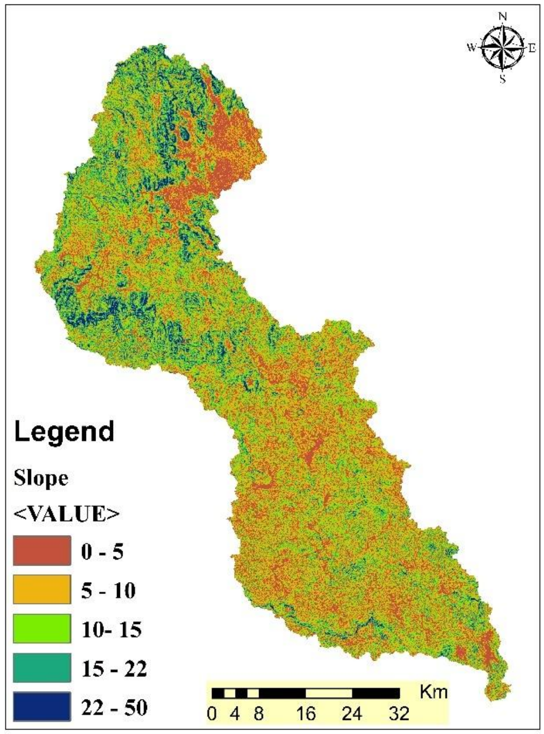


Figure 3.13 Slope Map of the Study Area generated from SRTM30

Soil Texture

Soil texture is an important factor in the control of runoff and recharge among the physical properties of soil. Permeability of the soil which especially depends on soil's capability for infiltration, is the main reason for both the possible quantity of water that might be retained in the soil and the extent to which the water will flow into deep layers being very harsh. The soil texture in the studied area has been classified into two main types according to the USDA methods: clay loam and clay. Majority of the land is made up of clay soil. The WetSpass-M model has developed the attribute table required for the recognition of various soil types from biophysical maps. The texture class provided by the USDA has been made in relation to the model code. Lastly, the raster grid map has been transformed into ASCII format so as to let the model processing work at a 30m*30m resolution.

Landuse Landcover

Land use is one of the major characteristics that control the surface runoff process and thus affect the infiltration (recharge), evapotranspiration, and erosion. The different types of land use or vegetation significantly alter the recharge, runoff and evaporation rates owing to their varying leaf area indices, root depths and sizes (Batelaan & De Smedt, 2001a). It is a very sensitive parameter for estimating recharge with the help of WetSpass-M modeling technique

The water balance of the study area is calculated by dividing each raster cell of the model into fractions corresponding to the four main land use/land cover types: impervious area, bare soil, open water, and vegetated area. The vegetation land-use land cover class is indicative of all the different types of vegetation, such as forests, bushes, and woods, croplands, and others. 'Bare soil land use' is the name of the land cover class that shows exposed surfaces and bare soils. 'Open water land use' is the term that encompasses all surface water bodies that are in lakes, rivers, and reservoirs. Human-made structures are the most common type of impermeable land cover in urban areas and settlements with low infiltration.

The study area was classified into four categories according to the land use and land cover classification, namely; cropland, grassland, forest, and water bodies. For each land-use or land cover, the model includes a code for local land-use diversity, and fractions of land-use are applied as the weighting variables to compute the water balance at the grid cell level.

Depth to Groundwater

The depth of groundwater (static water level) is one of the main input parameters of the WetSpass-M model used to estimate the recharge of the study area. The well depth and static water levels have been extracted from existing archives of the Buno Bedele Zone Water and Energy Bureau, which included 10 inventoried wells construction completion reports, and 10 hand-dug well depths to ground level were measured directly using a deep meter. ArcGIS 10.8 applied the Inverse Distance Weighting (IDW) spatial interpolation technique for interpolating groundwater level. The majority of the borehole data indicate that the static water level is the shallow aquifer. Figure 3.14 shows the depth to groundwater level map of the study area.

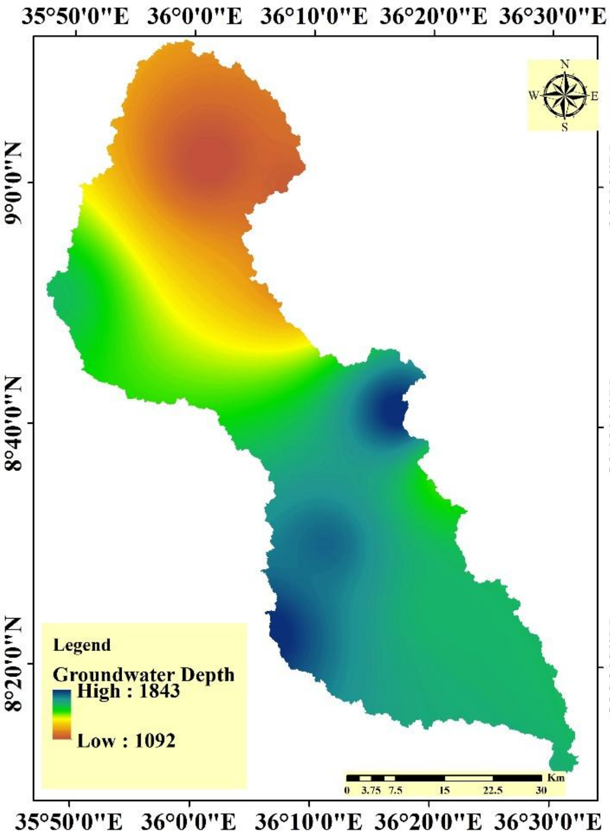


Figure 3.14 Dabana Watershed Groundwater Depth Map.

Parameter Table/Lookup Tables

To operate properly, the WetSpass-M model necessitates various biophysical parameter tables in addition to grid maps, such as monthly rainfall days, land use/land cover, and soil parameters. The parameter tables were produced in a fitting and required table format (TBL). The model user manual and literature reviews were employed to adjust and create parameter values for the Dabana watershed characteristics. After the required grid maps (ASCII format) and parameter tables were ready, the model was run.

3.3.2 Calibration, Validation and Sensitivity Analysis of Wetspass-M Model

The WetSpass-M model underwent manual calibration by employing a trial-and-error technique until the simulated hydrological outputs matched the observed data for groundwater recharge (base flow) and direct runoff. Through the iterative processes, significant changes were introduced to the critical parameters such as interception (a), evapotranspiration (α), surface runoff (LP), runoff delay factor (x), and base flow factor (β). The adjustments of each parameter were performed very carefully in order to comply with the physical characteristics of the Watershed and to provide a better representation of the water balance components in the model.

The calibration was considered to be effective if the model outputs closely corresponded to the observed runoff data at the monitoring station. The goodness-of-fit measurement system was used to judge performance. The parameter optimization was regulated by the extent of conformity between the predicted and actual values, thus allowing the model to accurately simulate both the spatial and temporal variations of hydrological processes. Although there were no automated calibration tools available, this manual method still managed to increase model accuracy, particularly in areas with limited data, thus proving its worth in this aspect.

The analysis of the sensitivity of the WetSpass-M model which has been calibrated has shown that even minor variations in certain parameters can have a great impact on the performance of the model. In order to this, the value of individual parameters was changed one at a time while the other parameters remained at their calibrated values. This was done by gradually increasing and decreasing the value of the parameter by a certain percentage. In every simulation, each model parameter value increased by 1% from the lower range to the upper range. The model showed sensitivity to the various parameters, with the evapotranspiration coefficient (α) and the surface runoff coefficient (Lp) giving the most significant response. This underlines the necessity of performing accurate calibration in a meticulous manner especially for the parameters controlling water loss and runoff generation as they are the ones that directly impact the precision of the hydrological components simulated.

To validate the WetSpass-M model, streamflow data was used to assess its ability to simulate both surface runoff and groundwater recharge. Hydrological data was sourced from the Ethiopian

Ministry of Water and Energy (MoWE), which granted access to the flow data recorded between the years of 2000 and 2017 at the Dabana nr Buno Bedele station located in the watershed.

The validation was conducted based on the premise that the groundwater discharge to rivers is equal to the groundwater recharge which is seen in the stream baseflow. The SepHydro tool (https://sephydro.hydrotools.tech/pageMain.php), which uses the Lyne & Hollick recursive digital filter method, an accepted technique for differentiating baseflow from total streamflow, was used for baseflow separation in the study. The method was picked for its reliability and simplicity thus making it possible to accurately extract the baseflow component from the observed streamflow data. The resulting baseflow estimations were a strong support for the validation of the model's groundwater recharge outputs.

3.4 Hydrologic Modelling Using SWAT

A watershed is a basic unit of hydrologic behavior. It is, on the ground surface, a geographical unit that enables the examination of the hydrological cycle and its components. A watershed is usually defined as the region that, according to geography, seems to provide all the water through a specific point in a river. A watershed includes both its natural and man-made sides, such as surface and underground features, climate and weather, geologic and topographic conditions, soil and plant characteristics, and land use. Hydrological characterization of a watershed involves studying how water behaves in a given location. This includes investigating how much rain falls, how water moves across land and into rivers, how it enters into the ground, and how plants use water. The primary objective of the SWAT modeling is to simulate the rainfall runoff to get a better understanding of the watershed hydrology and to control the water resources in the watershed.

The Soil and Water Assessment Tool (SWAT) is a model that simulates the hydrology of the watershed. It is a deterministic hydrologic model, and it is a physically-based semi-distributed model that operates on a continuous time scale. SWAT model operates on a daily time step and predicts the impact of land management in large complex watersheds with varying soils, land use and management conditions. SWAT involves detailed knowledge on the weather, soil properties, topography, vegetation, and land management, rather than merely using regression equations to define the relationship between input and output variables. For the physical representation of the watershed, SWAT required the following data: topography (Digital Elevation Model), climate (daily measured and monthly statistical weather data), flow data, and soil and land use data (maps and physical parameters).

3.4.1 Water Balance Using the SWAT Model

The water balance is the primary driver of the entire watershed hydrologic cycle. The hydrologic cycle simulated by SWAT is based on the following water balance equation:

$$SWt = SWo + \sum_{t=1}^{t}(Rday - Qsurf - Ea - Wdeep - Qgw) \quad (4)$$

Where: SWt is the final soil water content (mm), SW_0 is the initial soil water content (mm) Rday is the amount of precipitation in a day (mm) Qsurf is the amount of surface runoff in a day (mm) Ea is the amount of evapotranspiration in a day (mm) Wdeep is the amount of water entering the vadose zone from the soil profile in a day (mm) Qgw is the amount of return flow in a day (mm).

3.4.1.1 Preparation of SWAT Input Data

3.4.1.1.1 Digital Elevation Model (DEM)

The spatial data (DEM) of the Dabena watershed with a resolution of 30*30m (SRTM) was acquired from the United States Geological Survey (USGS) (https://earthexplorer.usgs.gov/) and it was utilized for the purpose of watershed delineation and for the calculation of sub-basin parameters. Furthermore, this data was applied for slope classification, which in turn constituted the foundation for the generation of Hydrological Response Units (HRU). See Figure 3.15

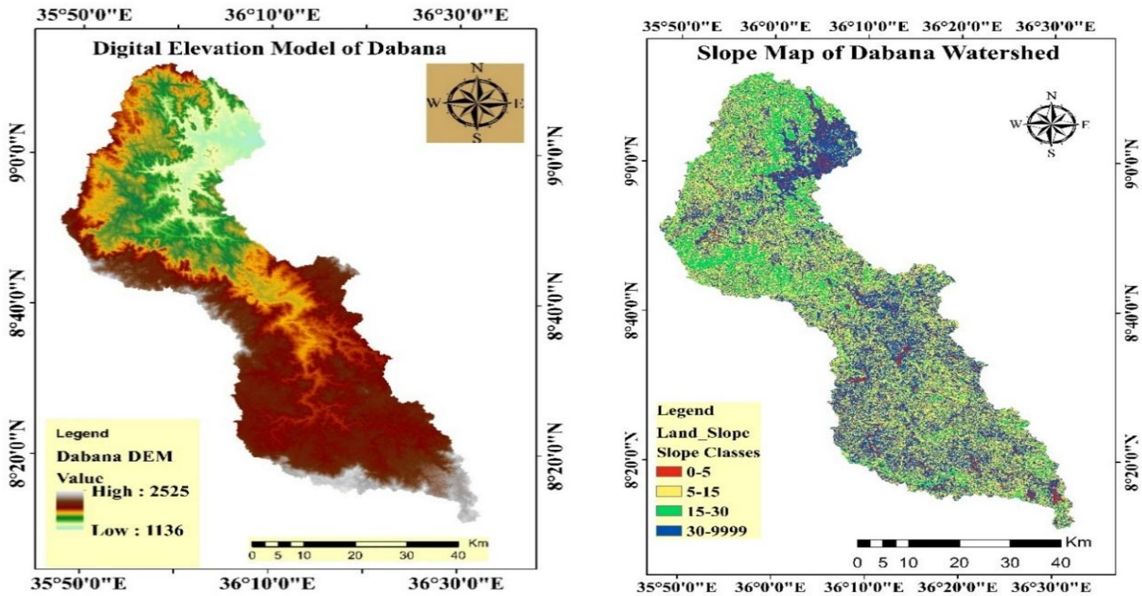


Figure 3.15 Digital Elevation Model and Slope Map of Dabana Watershed

3.4.1.1.2 Land Use

The land use map of Ethiopia was first clipped and then it was dissolved over the Dabana watershed. The clipped land use map was then employed for SWAT land use reclassification. As per the SWAT classification of land use, the watershed consisted of four categories. These categories were Agricultural Land - Generic (AGRL) covering 51.74% of the total area, Forest Mixed (FRST) with 48.17%, Range-Grasses (RNGE) taking up 0.07% and water (WATR) accounted for 0.015%.

3.4.1.1.3 Soil

The SWAT model demands the fundamental physical-chemical characteristics of the soil types, for instance, texture, chemical composition, physical properties, and available moisture content, hydraulic conductivity, bulk density, and organic carbon content of various layers. (Dibaba et al., 2020). In this research, the principal soil types that were gathered from the Ministry of Water and Energy are missing this information. Thus, the digital soil map of the world that was created by the Food and Agriculture Organization of the United Nations (FAO-UNESCO) was obtained from (https://data.apps.fao.org/map/catalog/srv/eng/catalog.search#/metadata/446ed430-8383-11dbb9b2-000d939bc5d8). Then, the MWSWAT extension was added in MapWindow GIS for SWAT hydrologic modelling. Based on the SWAT reclassification, the Watershed has two soil categories (Figure 3.16). These are Bh12-3c-31 with an area of 70.6% and Ne13-3b-158- 29.4%. Based on their texture, Bh12-3c-31 was classified as clay loam, whereas Ne13-3b-158 was classified as clay.

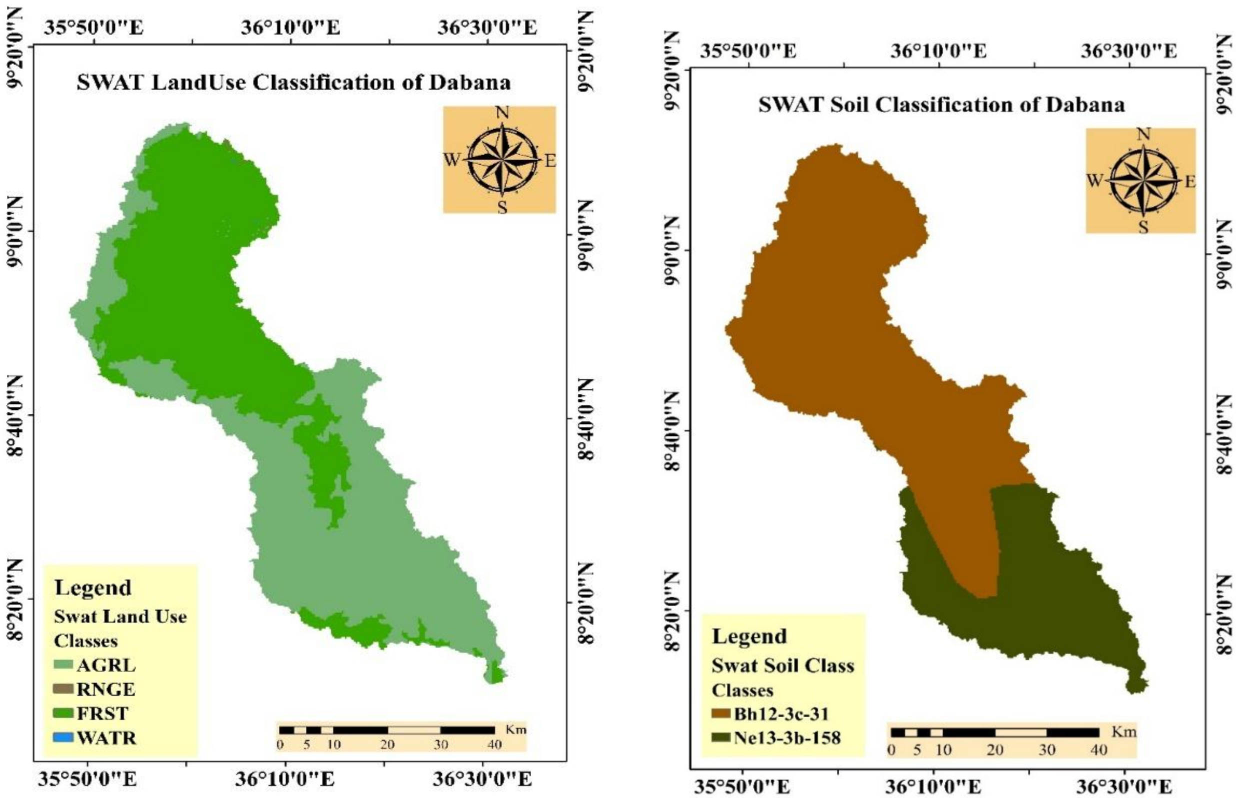


Figure 3.16. SWAT Land use and Soil Classification of Dabana Watershed

3.4.1.1.4 Meteorological data

The SWAT model used climate data with varying data lengths as input, including rainfall, solar radiation, wind speed, relative humidity, and maximum and minimum temperatures. In and around the Dabena watershed, there are six weather stations. It is important to note that not every meteorological station had the capacity to provide synoptic data; yet, Bedele station was one such synoptic station (having all types of climatic data) that was used for the generation of the weather data base consisting of the other five meteorological stations which lacked complete climate data. After the WGEN parameters were computed, the location table corresponding to the SWAT format was prepared and then uploaded to the model. The SWAT model receives the data of each climatic variable from the weather station closest to the meteorological stations where it is measured. The meteorological data were collected over the period of 1993 to 2020.

3.4.1.1.5 Hydrological (streamflow) data

SWAT demands the daily temporal stream flow data for the physical hydrological model to calculate the flow. SWAT has been using this data as an input for the investigation of the hydrological characteristics of the Dabana watershed. Observed values of water discharge (1990-2017) were collected from Dabana near Buno Bedele station and have been used for model calibrations and validations.

3.4.2. SWAT Model Setup

The Arc SWAT extension of SWAT version 2012 was utilized for model configuration. Initially, a new SWAT project was created and saved, after that the delineation of watershed was done. It is very important to have a clear understanding of the hydrological cycle and to be able to predict hydrological parameters accurately for proper planning and efficient water usage. Calibrate and validate the model to determine its ability to accurately predict streamflow. A SWAT model has been developed across the Dabena watershed using a digital elevation model, land use information, and soil data.

3.4.2.1 Watershed delineation

To determine the watershed, automatic watershed delineation was used. he 30*30m DEM was subsequently incorporated into the ArcSwat model and the stream network was established by utilizing a threshold area that indicates the source of the stream. Finally, the watershed outlet was selected to define the basin. Based on this, the total area of the watershed was 3,225.98 km2

3.4.2.2 Hydrological Response Unit (HRU) Determination

The watershed was then divided into sub-basins as the following step in the watershed simulation setup. The sub-basins have a geographical location in the watershed and are spatially related to one another. Once the watershed is delineated, the user is able to simulate one soil, land use, and management plan for every sub-basin or can further break the sub-basins into several hydrologic response units. Hydrological response units refer to portions of a sub-basin that have distinct land use, management, and soil characteristics.

The slope was classified after loading the prepared land use and soil map in the defined watershed. The multiple slope option was taken, that is, four classes (0-5, 5-15, 15-30, and above 30). The land use, land cover, soil map, and slope classifications were reclassified according to the parameters in the SWAT database. After that, all of these physical characteristics were overlaid to define HRU. The HRU was determined by taking into account the threshold levels. In the various HRU definitions threshold levels were used to exclude the minor land uses, soils, and slope classes in each sub-basin. The sub-watershed was divided into areas with different combinations of land use, soil, and slope thus it was possible to study the variations in streamflow and evapotranspiration for different cover, soil, and slope. Generally, it is suggested that the threshold levels of 20% for land use and land cover, 10% for soil, and 20% for slope, which are the default settings, are adequate for most applications. In this instance, land use thresholds were adjusted to 20%, soil to 10% and slope to 20%. In the end, the watershed was divided into 87 HRUs consisting of 25 sub-basins.

3.4.2.3. Uploading Weather Data

The SWAT model analyzes the various components of the hydrological process using physical data from the watershed, as well as energy and moisture information. Temperature, precipitation, relative humidity, wind speed, and solar radiation are all essential climatic variables for the SWAT model hydrological analysis. Weather data from the Watershed's study areas was imported into the SWAT database, which provided energy and moisture data. SWAT requires a station with complete weather data to act as a weather generator for other stations that don't have complete data because not all stations provided complete weather data. For the model to connect each sub-watershed to the crucial station, exact location of the weather stations is also essential. The weather data from the weather stations was utilized for additional simulation when the locations of the stations were entered into the interface.

3.4.2.4 Potential Evapotranspiration Estimation

The SWAT calculate diverse components of the watershed water balance using data from models and weather stations. The "Edit SWAT Inputs" menu enables modifications to the model databases and existing watershed files. One crucial component of the water balance is potential evapotranspiration (PET). The PET is the one that could be evaporated and transpired by plants if water is not limited. The Soil and Water Assessment Tool (SWAT) employ several approaches to compute PET: the Penman-Monteith (PM) method, which requires comprehensive daily climatic data; the Hargreaves (HG) method, which uses maximum and minimum temperatures and is noted for its ease of use; and the Priestley-Taylor (PT) method, which relies primarily on solar radiation. Hargreaves method is selected for this study because it needs only air temperature for PET calculation in the SWAT database.

3.4.3. SWAT Simulation

The SWAT model simulation of the water movement through the hydrologic cycle can be represented as the flow of water through the stream system of the watershed to the outlet. The input files were organized, and the model that was planned to run was finally simulated. SWAT modeling is dependent on daily weather data which include precipitation, temperatures (maximum and minimum), solar radiation, wind speed, and relative humidity. SWAT simulation was conducted over 28 years, including a 3-year warm-up period, at six meteorological stations (Bedele, Abdela, Humbe, Didessa, Arjo, and Nekemte) from January 1, 1993, to December 31, 2020, based on data availability.

3.4.4 Sensitivity Analysis, Calibration and Validation of the SWAT Model

3.4.4.1 Sensitivity Analysis

Sensitivity analysis is a necessary step in SWAT model development since it determines which parameters have significant effects on model outputs. Identifying these sensitive parameters allows users to prioritize them during the calibration process, enhancing the model's accuracy and efficiency. Sensitivity analysis is a technique for calculating the rate that which model output changes in response to variations in model inputs (parameters). It is necessary to identify important parameters and the level of precision needed for calibration(Arnold et al., 2012). It is also a measure of how changing one parameter affects another; it takes less time for calibration and validation process; it improves the accuracy of calibration, since uncertainty is reduced; and it controls the simulated process behavior by the most sensitive parameters, thus minimizing the number of parameters in the calibration step(Gassman et al., 2014).

Flow simulation takes into account various hydrological input parameters, including those related to groundwater (.gw), management (.mgt), soil (.sol), hydrological response units (.hru), routing (.rte), sub-basins (.sub), and other hydrological and Watershed practices. To determine the values for these parameters, their impact on flow was assessed through sensitivity analysis. For this aim, the Sequential Uncertainty Fitting (SUFI-2) method, which was embedded in SWAT-CUP, is a widely used method that iteratively fits the model to observed data in order to assess parameter sensitivity and uncertainty. By progressively reducing the range of parameter values, SUFI-2 prioritizes the most sensitive parameters, thereby improving the accuracy and reliability of the SWAT model in simulating hydrological processes within the watershed. It took multiple iterations for the SUFI-2 to get results that were satisfactory. For the new parameters to be used in the following iteration, each iteration provided recommended values. Finally, the values of the percent of bias, coefficient of determination, Nash–Sutcliffe, and other statistical parameters related to uncertainty analysis generated acceptable results(Daniel, 2024).

4.4.4.1.1 Sensitive parameters measurement in SWAT-CUP

Sensitivity analysis is used to measure sensitive parameters in SWAT-CUP, usually with techniques such as SUFI-2. The technique is changing key model parameters consistently and measuring their impact on model outcomes. Sensitivity is measured using statistical measures like the t-statistic, which shows relative parameter importance, and the p-value, which shows parameter significance. Then, to guide model calibration and enhance performance, parameters are rated according to their sensitivity.

The t-stat and p-value are statistical metrics utilized in sensitivity analysis in SWAT-CUP to assess how model parameters affect results. Each parameter's corresponding importance is shown by the t-statistic; larger absolute values indicate greater sensitivity. The statistical significance of the parameter is measured by the p-value; smaller values (usually less than 0.05) indicate greater impact on the behavior of the model. These indicators work together to prioritize adjustments during model calibration by controlling the ranking of parameters.

The SWAT-CUP was run monthly from the period 01 January 1993 to 31 December, 2017. The first 3 years from 01 January 1993 to 31 December 1996 were used for model warm-up. Based on research conducted in the watersheds of the Blue Nile basin close to the Dabena watershed, the initial 18 parameters were selected. They were also chosen following the SWAT model simulation, taking into account the scenario (default) outcomes from the Txt-In-Out folder. The table below (Table 3.1) provides detailed information on several hydrological parameters and their sensitivity expression.

Table 1 3.1. SWAT-CUP Parameters Selected for Sensitivity Analysis

Parameters	Description	Absolute SWAT value	Category
LAT_TTIME	Lateral flow travel time	0-180	.hru
CN2	SCS runoff curve number	35-98	.mgt
GWQMN	Treshold depth of water in the shallow aquifer required for return flow to occur (mm)	0 – 5000	.gw
GW_REVAP	Groundwater "revap" coefficient	0.02 - 0.2	.gw
RCHRG_DP	Deep aquifer percolation fraction	0 – 1	.gw
CH_K2	Effective hydraulic conductivity in main channel alluvium	-0.01 – 500	.rte
CH_N2	Manning's "n" value for the main channel	-0.01 - 0.3	.rte
SLSUBBSIN	Average slope length.	10 – 150	.hru
SOL_AWC	Available water capacity of the soil layer	0 – 1	.sol
CANMX	Maximum canopy storage	0 – 100	.hru
HRU_SLP	Average slope steepness	0 – 1	.hru
EPCO	Plant uptake compensation factor	0 – 1	.hru
ESCO	Soil evaporation compensation factor	0 – 1	.hru
SOL_ALB	Moist soil albedo	0 - 0.25	.sol
ALPHA_BF	Baseflow alpha factor (days)	0 – 1	.gw
GW_DELAY	Groundwater delay (days)	0 – 500	.gw
REVAP_MN	Threshold depth of water in the shallow aquifer for "revap" to occur (mm).	0 – 500	.gw
SOL_K	Saturated hydraulic conductivity.	0 - 2000	.sol

.gw=ground water, .hru=hydrologic response unit, .mgt=management, .rte =routine, .sub =subbasin, .sol =soil.

3.4.4.2 Model Calibration and Validation

Calibration is the procedure of altering the model parameters based on sensitivity results to make sure that the SWAT model accurately simulates observed data, such as streamflow, sediment transport, or water quality. It is the idea is to better parameterize a model for a specific set of local conditions through the comparison of the model prediction with the observed data, thereby decreasing the uncertainty in the prediction (Arnold et al., 2012; Dibaba et al., 2020). This includes comparing model outputs obtained from historical meteorological data to recorded streamflow. Model calibration had been conducted for the period of 15 years from 1996-2010 with three years warm-up period of 1993, 1994 and 1995 and it involved fine adjustments to sensitive parameters, as already indicated in the sensitivity analysis.

Validation is a further step that evaluates the model's reliability with an independent dataset that was not utilized during calibration, keeping the calibrated parameters constant. It is the process of testing a calibrated model against an independent set of measured data without any additional adjustments in order to use it to estimate the effectiveness of future potential management practices (Dibaba et al., 2020). This is the last phase of hydrological modeling, to check the performance of the model for simulated flows in different periods than the calibration periods of 2011 to 2017, and ultimately to compare the simulated flow with the observed streamflow data for the validation period. In general, the R^2 was the objective function used in SWAT-CUP (SUFI-2) for the calibration and validation of the SWAT model in this study, because it is very frequently used; the best objective function assists in evaluating how well the model imitates the observed patterns during the calibration and validation phases.

3.4.3.3 Model Performance Evaluation

The performance of the SWAT model was assessed through a combination of statistical measures and graphical methods that compared the simulated data with the observed data. R^2, NSE, and PBIAS are statistical techniques that express how well the model simulation performs with the measured streamflow (Abbaspour et al., 2015).

Coefficient of Determination (R^2): indicates the percentage of the measured data variance that the model can account for, and it is frequently used for evaluating models. It is not sensitive to proportional and additive variations between observed data and model predictions, and it is oversensitive to high extreme values (outliers) (Moriasi et al., 2007). It indicates the correlation between the simulated and observed data. It is defined as the squared value of the coefficient of correlation according to Bravais- Pearson. It is calculated as:

$$\mathbf{R^2} = \frac{\sum_{i=1}^{n}\left[(O_i - O_{avg})(S_i - S_{avg})\right]^2}{\sqrt{\sum_{i=1}^{n}(O_i - O_{avg})^2}\sum_{i=1}^{n}(S_i - S_{avg})^2} \qquad (5)$$

Where, R^2 is the coefficient of determination, Oi is the ith observed parameter, Oavg is the mean of the observed parameters, Si is the ith simulated parameter, Savg is the mean of model-simulated parameters, and n is the total number of events.

The coefficient of determination (R^2) s defined as the square of the ratio between the covariance and the product of the standard deviations of the observed and predicted values. Hence, it measures the total dispersion relative to the dispersion of the observed and predicted series. R^2 ranges from 0 to 1, showing to what degree the prediction has accounted for the observed dispersion. In terms of values, zero means there is no correlation at all, while one means that the prediction is as dispersed as the observation.

Nash–Sutcliffe efficiency (NSE): is a normalized statistic that assesses how the residual variance compares to the variance of the measured data in terms of their relative magnitude. NSE is one of the most widely used measures and it gives detailed information about the reported values. It is also the most suitable objective function for representing the total fit of a hydrograph. By virtue of the squared differences it becomes less sensitive to extreme high values (Daniel & Abate, 2022; Moriasi et al., 2007). NSE indicates the degree to which the trends in the observed data are mirrored by the simulated data within a specified time period and time interval. The NSE is a scale from ∞ to 1. Performance levels between 0 and 1 are considered acceptable while the performance indicated by NSE 0 is judged as totally unacceptable. It’s calculated as:

$$NSE = 1 - \frac{\sum_{i=1}^{n}(O_i - S_i)^2}{\sum_{i=1}^{n}(O_i - O_{avg})^2} \qquad (6)$$

Where NSE is the Nash–Sutcliffe efficiency coefficient, Oi is the ith observed parameter, Oavg is the mean of the observed parameters, Si is the ith simulated parameter, and n is the total number of events.

Percent bias (PBIAS): assesses the average bias of the gestures in the simulated data in comparison to the observed data. In general, the differences in the streamflow values during the different auto calibration methods are greater in dry years than in wet years. This is a point that needs to be considered when performing a split-sample assessment, one part being for calibration and the other for validation (Santhi et al., 2001). It characterizes the percent mean deviation between observed and simulated flows. The best PBIAS value is 0, and values of low magnitude show that the model simulation is accurate. Positive values show that the model is underestimating and negative values show overestimation by the model.

$$PBIAS = \frac{\sum_{i=1}^{n} O_i - \sum_{i=1}^{n} S_i}{\sum_{i=1}^{n} O_i} \times 100 \tag{7}$$

Where PBIAS is the percent bias, Oi is the ith observed parameter, Si is the ith simulated parameter, and n is the total number of events.

The general performance rating criteria developed for calibration and validation of the SWAT model for this method are given in Table 3.2.

Table 2Table 3.2: SWAT Model Performance Evaluation Formula

R^2	NSE	PBIAS	Performance rating
R2 > 0.70	0.75 < NSE ≤ 1	PBIAS<±10	Very Good
0.60 < R2 ≤ 0.70	0.65 < NSE ≤ 0.75	± 10 ≤ PBIAS	Good
0.50 < R2 ≤ 0.60	0.5 < SE ≤ 0.65	±15 ≤ PBIAS < ±25	Satisfactory
R2 < 0.50	NSE < 0.5	PBIAS ≥ ±25	Unsatisfactory

3.5 Water Allocation Using WEAP

The Water Evaluation and Planning (WEAP) model is one of the most widely used tools for decision-making regarding the modeling and analysis of water resource systems in different scenarios. In this research, WEAP was utilized for assessing the water resource distribution in the watershed area by integrating hydrological information from SWAT (Soil and Water Assessment Tool). The streamflow data of the SWAT simulation performed on a monthly basis was taken as the primary supply input for WEAP, which led to a better representation of the hydrological behavior of the basin.

3.5.1 Input Data for WEAP Model

This study uses hydrological time series data, water demand data, water supply schemes and their locations, as well as a GIS vector map of the Dabana Watershed and river system. Both current and future projects are taken into account in the model.

Population data

Population data forms the foundation of WEAP model input data. The Central Statistical Agency has provided the population data for the Watershed towns in the year 2020. The population count in the watershed area was approximately 509,478 at the time of the current account, and the average basin population growth rate was found to be 3.2%. By applying this growth rate, the population of the watershed is projected to be 1,319,166 in 2050. The total consumptive water demand was thus calculated on the basis of the population of towns in 2020.

Hydrological Data

Output from the Soil and Water Assessment Tool (SWAT) was used to provide necessary hydrologic data for the WEAP model. At first, SWAT was applied to simulate hydrological processes in the watershed such as streamflow, surface runoff, groundwater recharge, and evapotranspiration, by using climate, land use, and soil data. The flow series generated by SWAT provided the inflow values at key river nodes and reservoirs, which were then imported into WEAP as the primary source inputs.

Water Demand Data

In the study area, the water demand was determined mostly by domestic water demand (both urban and rural), irrigation water demand, industrial water demand, and environmental water requirement. The water demand figures for this study were drawn from the water abstraction data sourced from various water user's offices. These data consist different surface abstraction points along major rivers and its tributaries, covering both permitted and unpermitted abstractions. These points represent various uses including domestic, irrigation and industrial. This data is important for modeling sectoral water requirements.

3.5.2. Sectoral water demand estimation

In order to evaluate and have a full understanding of the current and future water demands together with the supplied amount of Dabena watershed, sectoral water requirement data were drawn from various sources. The water demand estimation for different water use is done according to the data that is gathered from different water user sectors.

Water requirement for domestic

Water requirement for domestic is the amount of water utilized daily per person the amount of required water for household use. The water per person per day in the study area was estimated by applying the updated standard for water requirement of Ethiopian second Growth and Transformation Plan (GTP-II, which is from 2015 to 2020) by the new method. According to the recently updated GTP-II water need standard, it varies from 40 to 100 lpcd depending on the size of the urban population and 25 lpcd in rural areas until 2020. The master plan study determined the average water requirement of urban and rural, and even categorized them according to the number of inhabitants. The following table shows the average water requirement per capita of towns classified by category.

Table 3Table 3.3: Population Size and Average Per Capita Demand for Town

Town Category	Population size	Per capita demand (l/c/day)
1	> 1,000,000	100
2	100,000 – 1,000,000	80
3	50,000-100,000	60
4	20,000 - 50,000	50
5	<20,000	40

Source: GTP-II, water sector document.

Agricultural water demand

Agricultural water demand in the study area was calculated using the average irrigation duty (l/s/ha) for the major crops grown under various irrigation schemes. Irrigation duty represents the continuous flow rate of water needed to irrigate one hectare of land, providing a direct assessment of crop water requirements. A standard representation was produced by computing the mean of duty values for different crops and schemes, considering the differences in cropping patterns, irrigation methods, and scheme efficiencies in order to ensure that the spatial distribution of irrigated land follows locally validated planning data, the command area assigned to each woreda (demand site) was calculated using data from the official assessment of the irrigation potential of the zone. Most of the irrigation technology applied in the study area was furrow irrigation method, therefore, the maximum irrigation duty was taken. The sectoral irrigation demand was calculated by multiplying the average duty by the total irrigated area for each crop. The table below shows the different irrigation duties for each irrigational demand sites.

Table 4Table 3.4 Irrigation Duty and Command Area for Each Demand Site

No.	Woreda (demand sites)	Irrigation duty (l/s/ha)	Command area (ha)
1	Bedele	1.59	20620
2	Chora	1	18068
3	Dabo	1	12366
4	Dega	1.58	7470
5	Meko	1.37	2329
6	Gechi	1.1	3598

Source: Buno Bedele Zone Irrigation Office

Water Requirement in Industry

The requirement for industrial water in the area studied was indicated by the withdrawal claims of Bedele Brewery, which is the company that gets about 5,614 hectolitres daily (204911 m^3/yr), according to the direct data of the company. This figure reflects the total water consumption in the production of the brewery, which comprises of cleaning, brewing, and other activities.

Environmental Flow Requirement

The environmental flow requirements for the river were assessed at three critical points; one upstream (EFR1), one midstream (EFR2), and one downstream (EFR3) by using flow duration curve (FDC) analysis covering the period of 1997 to 2020. The flow duration curve is a statistical tool that shows for each flow magnitude the percentage of the time it is equaled or exceeded, thus reflecting the variation and consistency in river discharge over the specified time period. For this analysis, the Q95 flow was chosen as the environmental flow requirement, which is defined as a discharge equal to or exceeding 95% of the time. The Q95 results show that the minimal environmental flow is 0.8053 m^3/s at the upstream part, 3.338 m^3/s at the middle stream section, and 3.875 m^3/s at the downstream section.

3.5.3. Current Water Demand

The WEAP model defines current water demand as the baseline or reference-year estimate of water usage in a variety of sectors, including domestic, agricultural, industrial, and environmental requirements. It represents the amount of water required to sustain current socioeconomic activity within current climate and infrastructure restrictions. Additionally, in all scenarios, the Current Accounts are taken to be the beginning year. WEAP calculates this demand using characteristics such as population size, irrigated area, production from industry, and per capita water consumption, which are linked by the relationship between activity level and unit water usage rate. As a result, using typical water use methodologies for each disaggregated level, the user can determine appropriate activity levels, such as persons, heads, and hectares of the command area and multiplying them by the suitable yearly rate of water use for each action. The monthly supply and demand specifications for the first year of the study have been recorded in the Current Accounts. The first year of the research was 1996, and the last year of the scenario was determined to be 2050. Therefore, all the existing data about the water supply and demand that was collected was recorded in the current accounts.

3.5.4 Future Water Demand

Future water need is a representation of the anticipated water consumption in different sectors that will occur in the future. This will happen in various ways according to the shifts in socioeconomic, technical, and climate conditions. To obtain the future demand numbers through scenario analysis, there are various characteristics that pertain to the different scenarios such as population increase, land use change, irrigation expansion, and efficiency improvements, which are dependent on each of the different futures. The usual way for future demand estimation is done through annual growth rates or policy changes that are applied to current account demand of the base year. For instance, a growing population or economic activity could mean more water needed while on the other hand, conservation efforts or technological advancements may lead to reduce per capita use. WEAP provides the opportunity for users to create many scenarios, such as the typical case, high growth, and focusing on efficiency, so the influence of different assumptions on water supply and sustainability can be investigated. In the present research, the development of six scenarios was a step towards an analysis of water demands in the future based on different conditions.

3.5.5. WEAP Model Setup

WEAP consists of five main perspectives: schematic, data, results, overviews, and notes. The schematic view is a GIS-based tool that makes it easy to arrange system elements such as demand nodes, rivers, reservoirs, Watersheds, transmission links, return flows, and more. The data view provides users with the ability to create variables and relationships, insert mathematical formulas, and link to Excel. The results view shows all model outputs in charts, tables, and on the schematic, thus providing a complete and adjustable display. The overview shows an immediate, brief overview of the most important system indicators. The note view is the last one and it allows you to record your data and assumptions.

3.5.5.1. Configuration Of WEAP Model

The Schematic View is the initial point of all activities with WEAP. It is derived from the setup "area". It consists of the physical parts of the water demand-supply system, their spatial linkages, time period, units, and hydrologic patterns. The schematic view in WEAP illustrates the limitations of watersheds, rivers, demand sites, and Watersheds. WEAP relies on GIS maps of rivers and Watersheds in order to locate streams.

The Project Area was created using the create-area menu item. The GIS-based vector boundary, river shape data and each sub-basin for the Dabena River Basin were imported to the Project Area for orientation and refinement of area boundaries. This supplied an outline for the Schematic, which is utilized for system configuration. The major river channels were digitized, beginning at the upstream and moving downstream. The WEAP data tree was used to enter monthly average head flow data from the Dabena river and its tributaries, including minimum environmental flow requirements, return flow, and transmission links for demand sites and supply sources. Figure 3.17 shows the schematic view of WEAP model.

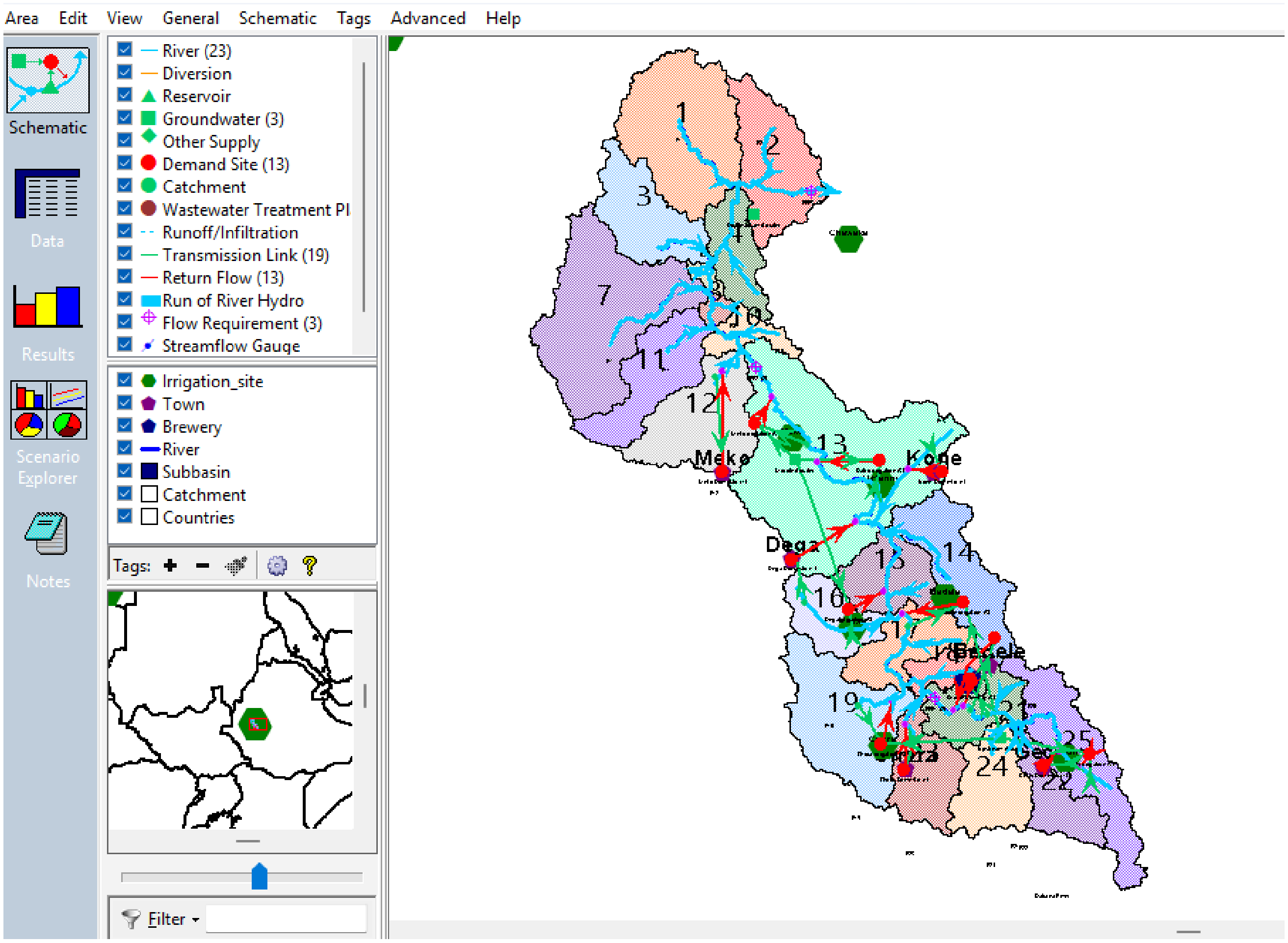


Figure 3.17. WEAP Model Schematic View of Dabena Watershed and Demand Nodes

The water allocation priorities have been established according to the demand sites that were input into the schematic. The demand priorities decide how the scarce resources have to be distributed among the various demand areas. Priority demand sites will receive the supply first. The water demand was calculated for each demand location by entering the Annual Activity Level, Annual Water Use Rate, and Consumption. Figure 3.17 shows the final demand site schematic map, which includes various levels of disaggregation for each site.

Demand Sites

A demand site means a group of water users that use the same distribution system and are in a specific area or have a common extraction point. The demand sites in the study area were merged into sixteen groups for the establishment of the WEAP model. Out of these, thirteen demand sites were using surface water while the remaining three were allocated for environmental flow requirement. Each demand site has a pipeline to its source and, where applicable, a return line directly to a river except for the environmental flow requirement.

Annual Activity Levels

The yearly demand shows the water requirements for every specific demand. On a separate note, loss, reuse and efficiency are accounted for. In each of the demand locations, the water consumption was calculated by going through the whole activity level and then multiplying it with the monthly use rate variation. According to the WEAP model, demand analysis is based on Activity Levels that allow measuring social and economic activity.

Annual Water Use Rate

The Water Use Rate is a metric that shows the average yearly water use for each unit of activity. WEAP reveals the denominator to highlight the ratio per unit instead of the total water consumption. For this research, annual water use rates for each person, hectare, and year were computed, converted into m^3 per year, and introduced into the WEAP model.

Priorities for Water Allocation

The recommendation for the priority assignment of each demand varies from 1 to 99. Water in the system at level 1 is the highest priority. WEAP gave priority to fulfilling all demands of this level first and then to other priority demands. Water is distributed to the demand locations by the model according to these priority levels. The model supplies water simultaneously to all sites with the highest priority (level one), and if the system has any water left, it then starts delivering to the lower priority levels.

3.5.6. Scenario Development

Scenarios are self-consistent narratives that describe how a future system could develop over time in a specific socioeconomic context and under specific policy and technological constraints. WEAP allows user to create scenarios and compare them to determine their water consumption, costs, and environmental implications. All scenarios begin with a common year in which you record your Current Accounts data. Scenarios are effective tools for exploring "what if" questions by changing key assumptions regarding future water resource development and management options.

In this Study, six scenarios were evaluated using the WEAP model to determine whether the existing water resources will meet the rising water demands in Dabena Watershed in a way that is sustainable and fair to ecosystems and different socio-economic groups. The model was set to examine the impacts of water resource management scenarios on water resources availability for domestic use, irrigation, industrial and ecosystem protection. The proposed scenarios are presented in the following sections. All other scenarios were configured based on the baseline scenario (SC1), which encompassed all present-day water abstractions.

SC1: Baseline Scenario (Current situation)

Baseline (or reference) Scenario is the beginning point against which all other scenarios are measured. It covers current conditions and trends, such as population growth, water demand patterns, infrastructure, and climate, without proposing new policies or making significant adjustments. It is the current scenario depicting what is happening on the ground. Therefore, all alternate scenarios derive from this baseline. In this scenario, the irrigated land in the future (2021-2025) remains the same as current data, which is 64,451ha based on the real data on the ground. Domestic demand sites for different stations (towns) vary according to their growth rate of each town. The table below (Table 3.5) shows the current and future population size with the recommended growth rate for each domestic demand station or town.

Table 5Table 3.5 Current and Future population size and the growth rate of towns of the watershed

Demand sites (towns)	Current population (2020)	Growth rate (%)	Future population (2050)
Bedele	137,723	3.9	417,693
Chora	136,609	3.1	331,116
Gechi	95,805	3.1	232,215
Dabo	56,582	3.3	145,073
Dega	53,639	3.1	130,012
Meko	29,120	2.7	63,057

SC2: Irrigation Expansion

This scenario explains how the expansion of irrigated land affects irrigation water demand. This scenario simulates the new demand created after new settlers started massive irrigation development and the strategic transition from rainfed agriculture to irrigated system in the Dabena watershed. The key assumption is that irrigated land area will further expand by 1% growth rate each year following the baseline period. This figure is determined by FGD with local experts and considering historical trends in the watershed. This is fundamentally aligned with Ethiopian Ten-Year Development Perspective Plan (2021-2030) and is further justified by Abbay River Basin Integrated Development Master Plan (BCEOM, 1998), which designates Didhessa sub-basin as high priority corridor for irrigation expansion. This growth path is supported by physical evidence. (Moisa et al., 2022), identified 67.8% of the Didessa sub-basin as suitable land for irrigation while (Dawit et al., 2020) confirmed that the basin possessed sufficient hydrological resources to enable development beyond one million hectares. Accordingly, it is expected irrigated area to increase from 64,451ha to 86,870ha (approximately 50% of the current rainfed agricultural land) by 2050. This gradual increase signifies anticipated agricultural growth, leading to higher water withdrawals for crop requirements. This scenario shows that larger irrigation areas consume more irrigation water (See table below).

Table 6Table 3.6: Irrigation expansion in each Irrigated Area

Demand sites (towns)	Current irrigated area(ha) (2020)_	Future irrigation(ha) (2050)
Bedele	20,620	27,793
Chora	18,068	24,353
Gechi	3,598	4,850
Dabo	12,366	16,667
Dega	7,470	10,068
Meko	2,329	3,139
Total	**64,451**	**86,870**

SC3: Groundwater Use

The exploration of this scenario was considered a viable strategy to fulfill the increasing demands for irrigation water and support various economic activities. In the WEAP model the irrigation demand sites were connected to groundwater nodes to abstract additional water resources. In this scenario, the maximum storage capacity of the watershed (V) is calculated using the following equation (Todd & Mays, 2004).

$$V = A * h * sy \tag{8}$$

Where A= Area of the watershed, h = Aquifer thickness and sy = Specific yield.

The area of the watershed multiplied by saturated aquifer thickness and the specific yield. The area of the watershed is 3225 km^2, based on available well completion report in the watershed the average saturated aquifer thickness of the watershed is 126 m. Depending on the lithology of the well in the watershed the most part of the area is dominated by volcanic rock (rhyolite, ignimbrite, trachyte, scoraceous basalt, river gravel, etc.). According to (Kebede et al., 2025) the estimated Sy value they choose for their study falls within the permissible range of the previously calculated value in volcanic geology, which is between 6.7 and 11.2%, depending on this range the specific yield for this study is assumed to be 0.07(7%). The maximum storage capacity of the watershed is 28.45 BM^3, this value represents the maximum capacity of the watershed to hold available water and it's divided in to three aquifers which is upstream, midstream and downstream. The groundwater is abstracted from upstream and middle stream because there are no demand sites in the downstream of the watershed. The initial storage was assumed to be 70% of maximum storage capacity of the watershed following Texas Water Development Board methodology (25%-75% is recoverable range) (Robert G., 2014). This value has been set to represent the specific hydrogeological characteristics that exist in the Dabena watershed. the scientific validity of this assumption finds support through the observation that wetlands exist throughout the are and the river maintains continuous flow which demonstrates thst the water table reaches its maximum saturation level. The combination of strong bedrock foundations, high annual rainfall and the topography of the area creates an environment where aquifers maintain their full water capacity throughout the year.

The WEAP model needed a maximum withdrawal which was established for the groundwater node to maintain its physical and hydrological accuracy. In this scenario, the key assumption is that 10% of the initial active storage is abstracted over the analysis period. This determined limit was approximately equal to 40% the average annual estimated recharge of the study area. This threshold was selected to align with the principle of sustainable groundwater management, ensuring that abstraction does not exceed the renewability of the resource to avoid long-term depletion(Alley & Leake, 2004). Limiting abstraction to 40% of the annual recharge also aligns with sustainability framework proposed by (Gleeson et al., 2012), by reserving 60% of the annual replenishment to maintain hydraulic gradient which supports dry-season baseflow to river network and prevents groundwater mining which occurs when basins exceed their renewable limits. This scenario answered the question "what will happen if we use additional water resource to satisfy each water requirement? and also, the impact of groundwater use or abstraction on unmet demand was assessed.

SC4: Combined Impacts

In this scenario, the combined impact of irrigation expansion and enhanced groundwater use is assessed against the baseline scenario. Expansion in irrigated land in the study are requests more water than the baseline. So, in this scenario the abstraction of groundwater resources will be expected to minimize the unmet demand for irrigation in some amount or it may satisfy all the demand by delivering the supply.

SC5: Irrigation Priority

In accordance to the Ethiopian Water Policy (MoWE,1999), domestic demands and irrigation water use are given top priority in the scenario development followed by environmental flow requirements, and industrial use. This means that in times of scarcity, domestic and agricultural requirements come first. In the baseline scenario irrigation was given third priority following the environmental flow requirements. Therefore, this scenario assesses the impact of moving current irrigation needs to the top priority. It functions as a stress-test assessment, which evaluates the maximum water flow capacity of the watershed area. The model assesses its capacity to fulfill all agricultural water requirements through its top irrigation priority system, which determines whether domestic and industrial water needs remain unfulfilled.

SC6: Environmental Flow Requirement (EFR) Priority

In this scenario, environmental flow requirements are given the highest allocation priority, followed by domestic and irrigation demands, and finally industrial use. This scenario evaluated what happened if the environmental flow demand was met first, above all other demands. While there is an ongoing debate regarding the mandatory inclusion of environmental flow (EF), this study acknowledges that national policy currently prioritizes productive water use for development. Therefore, this scenario is not presented as a management requirement, but as a sustainability sensitivity test. This study determines the minimum ecological flow requirements needed to assess the hydrological buffer of Dabena River. The scenario stablishes the baseline data to understand how much water can be abstracted for other water demand sites without harming the ecosystem of the river.

CHAPTER FOUR: RESULTS AND DISCUSSION

4.1 WetSpass-M Model Sensitivity Analysis

For an accurate water balance evaluation of a watershed, the model demands certain parameters and input variables. It is a must to carry out a sensitivity analysis of all the parameters and input variables before the WetSpass-M model's parameters are applied. This is done to know the response of the model regarding the change in the parameters. The global (alpha coefficient, Lp coefficient, interception, and average intensity) and local (slope, land use, and soil factor) WetSpass-M model parameters were subjected to sensitivity analysis. By adjusting one model parameter while keeping the rest unchanged for each simulation, the sensitivity analysis of recharge-related model parameters was completed. To reach simulation results in the upper range, in every simulation, every model parameter value from the lower range increased by 1%.

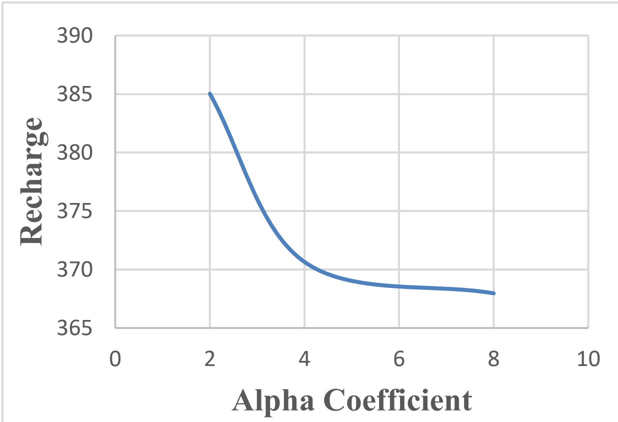
The hydrologic outputs from the WetSpass-M Model, including recharge and runoff, react differently to variations in each global parameter. The sensitivity analysis of the Alfa coefficient demonstrates its role as primary calibration parameter that governs Actual Evapotranspiration measurements. The total annual AET increased when the Alfa value was raised. The atmosphere required more water, which caused both groundwater recharge and surface runoff to decrease. The hydrological pattern shows that the increased Evapotranspiration leads to decreased water surplus which affects both surface and subsurface flow systems.

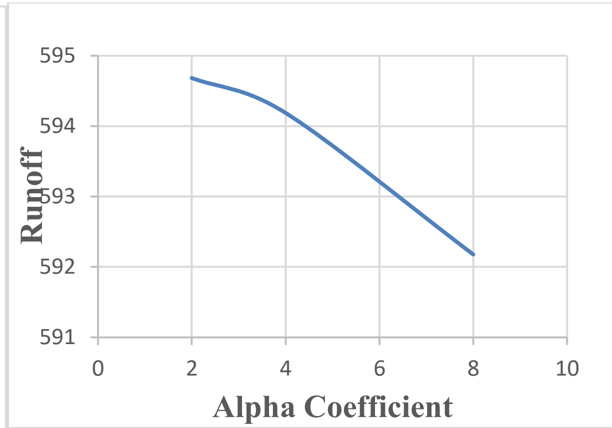
The Lp coefficient serves as the primary parameter for partitioning available water between the surface and subsurface. The model outputs indicate a clear inverse relationship between these two components as Lp adjusted. Increasing the Lp value resulted in a rise in annual surface runoff. Conversely, the annual groundwater recharge decreased. The Lp coefficient correctly predicts runoff potential because higher Lp values cause the watershed to overflow its boundaries as a surface flow which restricts deep percolation and aquifer recharge.

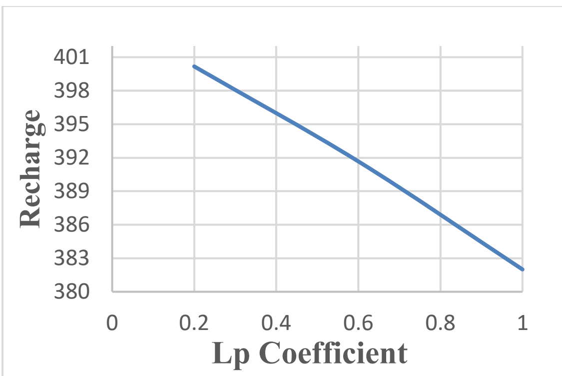
The sensitivity measurements of Average intensity (mm/h) shows that rainfall rates directly affect how much water the soil can absorb. The model showed a sharp increase in annual surface runoff when the intensity increased. The same period experienced a major decrease in annual groundwater recharge. The phenomenon occurs because soil systems reach their maximum infiltration capacity during periods of heavy rainfall. The process begins with fast runoff which leads to increased water discharge from the system before any water has time to percolate in to the earth and replenish underground sources.

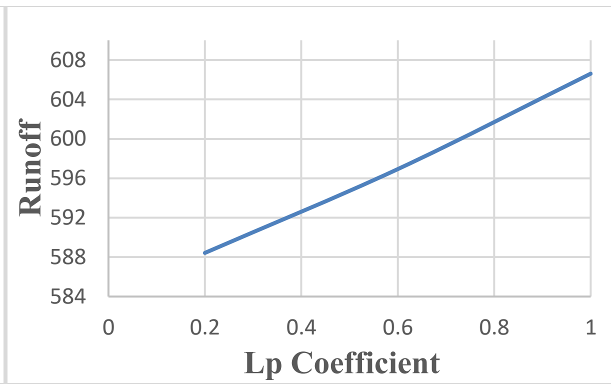
Finally, the interception ("a") parameter measures the percentage of rainfall that vegetation canopy takes up and then loses through evaporation before reaching the ground. The result shows that increasing the interception parameter results in both major water balance elements experiencing negative response effects. The initial evaporation loses increase because higher interception value creates greater evaporation. The net precipitation that reaches the ground decreases because of its reduction, which leads to a corresponding decrease in available water volumes for both surface and groundwater systems.

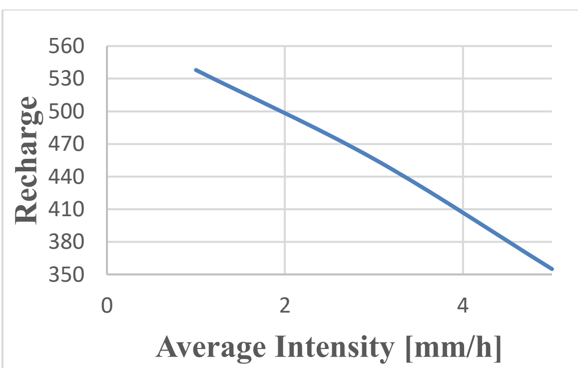
It can thus be concluded that structural parameters like Lp and alpha regulate model behavior, whereas climatic drivers like intensity have a more powerful effect on hydrological responses. Rainfall intensity is readily recognized as the most sensitive parameter within the WetSpass-M model. It has a significant impact on both recharge and runoff: an increase in intensity leads to a sharp decrease in recharge and an equally significant rise in runoff. It directly controls how much precipitation gets divided in to surface runoff and groundwater recharge. When the rainfall intensity gets over-estimated, the model basically makes water fall too quickly for the soil to take it up, and then the surface runoff rise steeply, with a major decrease in groundwater recharge. That reduced recharge then shows up as low recharge values right at the aquifer nodes that are imported into the WEAP allocation model. So, what happens is that the aquifer supply doesn't get enough water, and WEAP ends up producing this artificial water deficit across the whole system. Since the WEAP depends on those physical constraints, the decline in groundwater availability moves through the allocation ledger, and it the triggers unmet water demands for essentially every connected uses. This can seriously inflate water scarcity, especially in those critical dry seasons, when river flows are already at their lowest point. This very strong and opposing reaction reflects that the intensity of rainfall has a very strong influence on the distribution of water compared to other parameters like alpha, interception or Lp that have soft and gradual effects. Figure 4.1 shows the sensitivity of WetSpass-M model to global parameter.

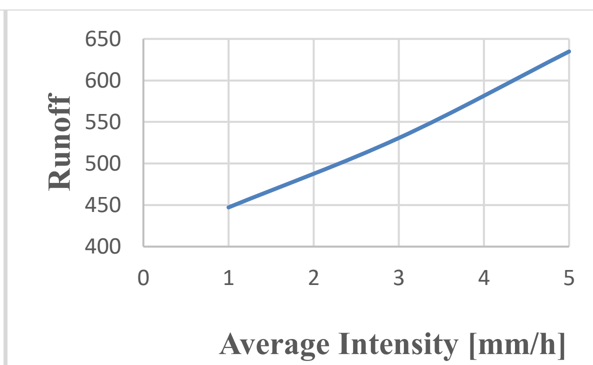

Recharge
390
385
380
375
370
365
0
2
4
6
8
10
Alpha Coefficient

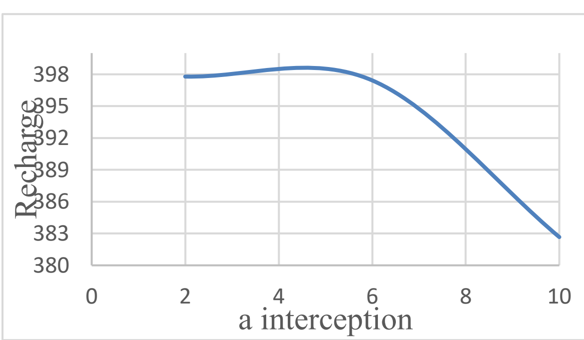

Runoff
595
594
593
592
591
0
2
4
6
8
10
Alpha Coefficient


Recharge
401
398
395
392
389
386
383
380
0
0.2
0.4
0.6
0.8
1
Lp Coefficient


Runoff
608
604
600
596
592
588
584
0
0.2
0.4
0.6
0.8
1
Lp Coefficient


Recharge
560
530
500
470
440
410
380
350
0
2
4
Average Intensity [mm/h]


Runoff
650
600
550
500
450
400
0
1
2
3
4
5
Average Intensity [mm/h]


Recharge
398
395
392
389
386
383
380
0
2
4
6
8
10
a interception

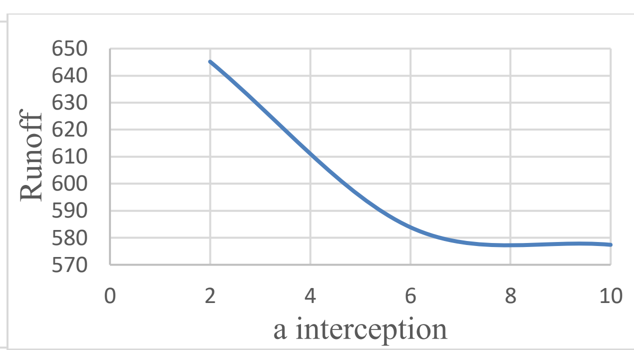
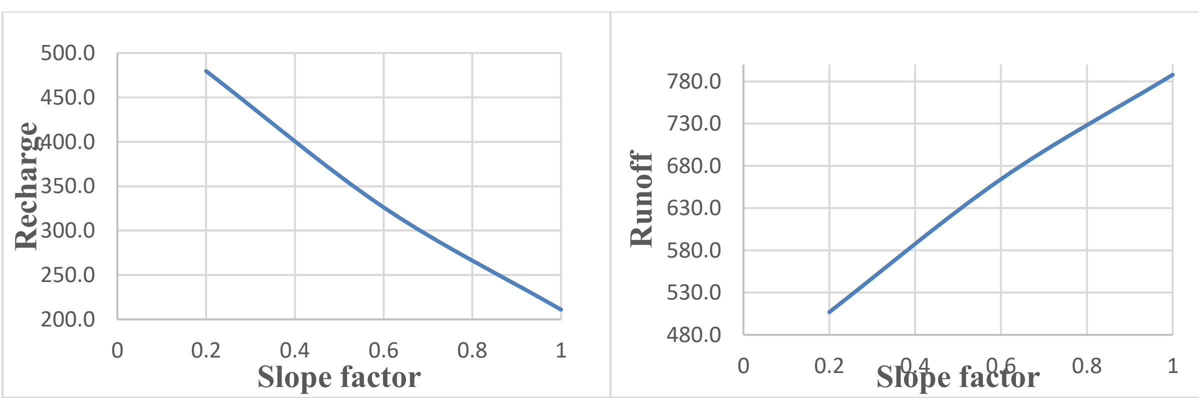

Runoff
650
640
630
620
610
600
590
580
570
0
2
4
6
8
10
a interception

Figure 4.1 The WetSpass-M model's sensitivity to global parameter variations. (a)interception parameter, The average intensity factor, alpha and LP coefficient

In general, the sensitivity analysis of the WetSpass-M model to global parameters indicates that it is highly sensitive to the average intensity parameter across all ranges. It also shows moderate sensitive to Lp coefficient across all range value of the parameter. In contrast, the model shows sensitive to alpha coefficient for less than 4 range (<4) and less sensitive for a range of greater than 4 (>4). Similarly, the model shows less sensitivity to the interception parameter when it is less than 6 range (<6), but it becomes sensitive to a range greater than 6 (>6).

The sensitivity analysis of the model to local parameters (slope, land use, and soil factors) shows a significant inverse relation between runoff and recharge for every parameter. An increase in each factor results in a significant decrease in recharge and a steep increase in runoff of corresponding magnitude. Among the factors, soil factor has the largest sensitivity with a decrease of about 66% in recharge and an increase of over 60% in runoff within its range. The slope factor also impacts the water balance, as it illustrates that steeper terrains favor surface flow and thereby reduce infiltration. The land use factor behaves in an analogous manner, where it can be interpreted that areas covered with impervious or runoff-prone plantings do not allow for any water to be stored in the ground. In summary, soil properties are the primary determinant in the distribution of water, with slope and land use following closely behind. Figure 4.2 reveals the sensitivity of the model to local parameter. WetSpass-M model demonstrates noticeable sensitivity to changes across all local parameters.



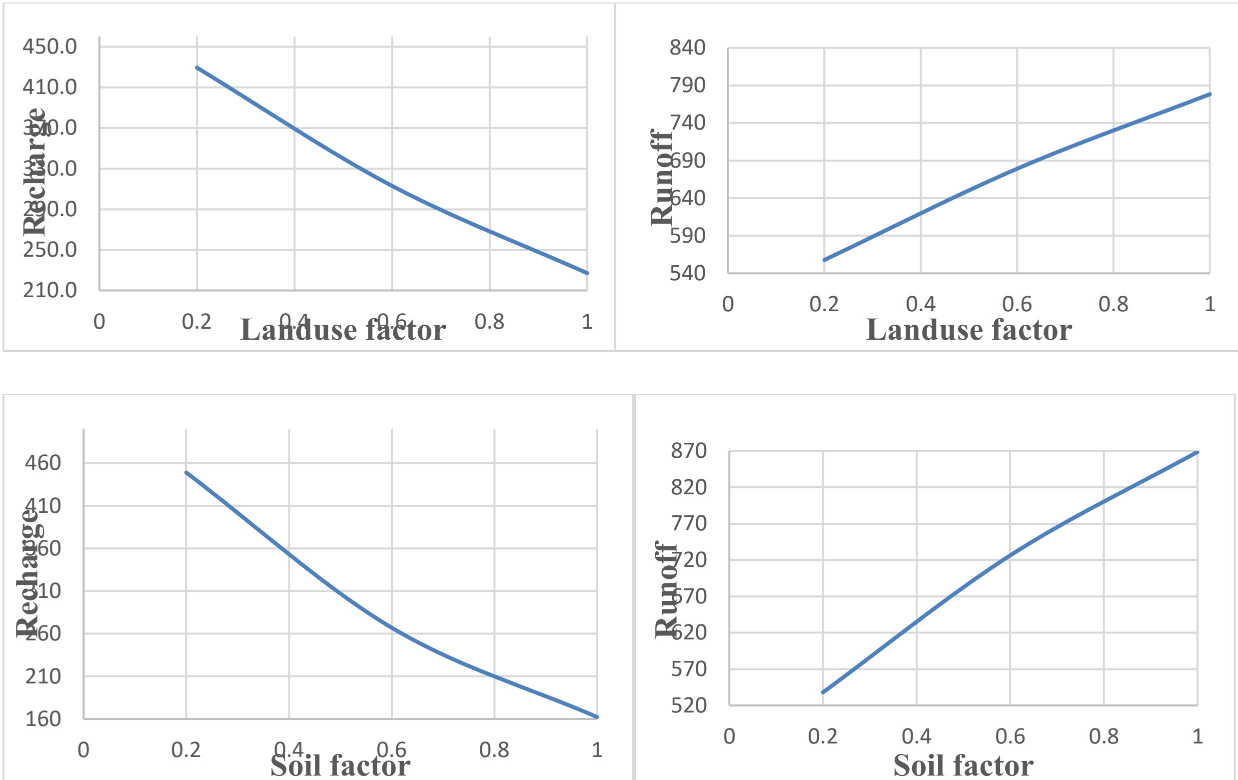


Figure 4.2 The WetSpass-M model's sensitivity to local parameter variations Slope, land-use factor, soil factor

4.2 WetSpass-M Model Calibration and Validation

The model results were manually calibrated in order to change the default parameters of the model assigned with their corresponding range values to suit the output accordingly. The parameters are namely: alfa coefficient, "a" interception, Lp coefficient and runoff delay factor "x". The parameters were optimized until they agreed with the base flow generated by separating the discharge using baseflow separation techniques and the measured discharge at the Dabana River. River flow from the watershed is determined by baseflow and surface runoff, which corresponds to the long-term average seasonal river discharge of the watershed. The results of the model were calibrated using 18 years' average monthly stream flow data (1996–2017) from Dabana river gauging stations (Dabana nr Buno Bedele), which can represent the entire Dabana watershed.

Figure 4.3 shows the comparison of simulated and observed baseflow and surface runoff.

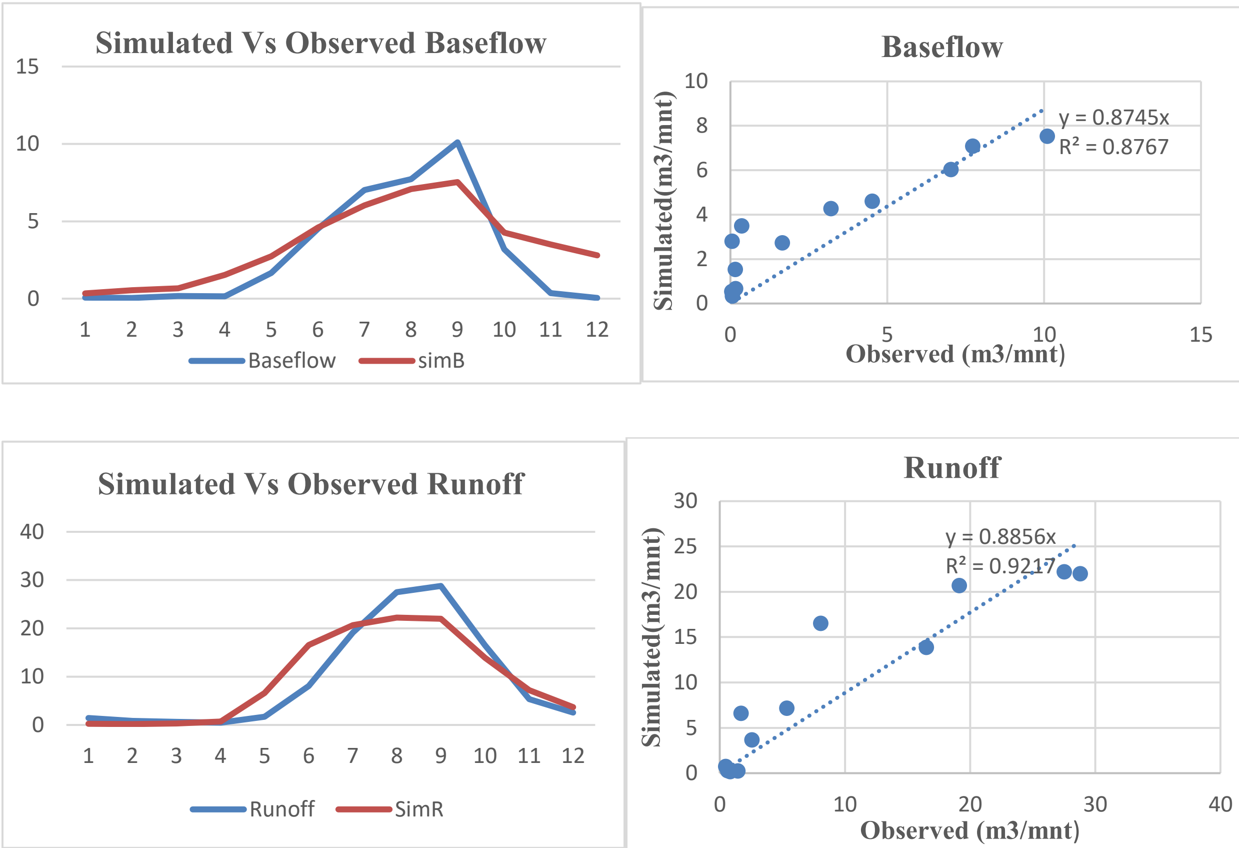


Figure 4.3 Model performance evaluation and comparison of the WetSpass-M simulated (recharge and runoff) and (recharge and runoff) from baseflow separation

The figure shows the comparison between runoff and baseflow from the model and from base flow separation from stream flow by SepHydro (R^2=0.86, NSE =0.85 for Runoff and R^2 =0.86, NSE = 0.79 for baseflow) shows that model simulates a typical recharge for the Dabana watershed.

4.3 Outputs of WetSpass-M Model

The model accurately represents the Dabana watershed. This is because the model being spatially and temporally distributed and also depicting all the features of the watershed (physical, climatic, and hydrological) and demonstrating changes in the components of the water balance of the watershed spatially and temporally. The main output of the model is the monthly water balance components of the watershed. The results are in the form of raster grid maps where each pixel illustrates the various water balance components of the Dabana watershed with their respective magnitudes.

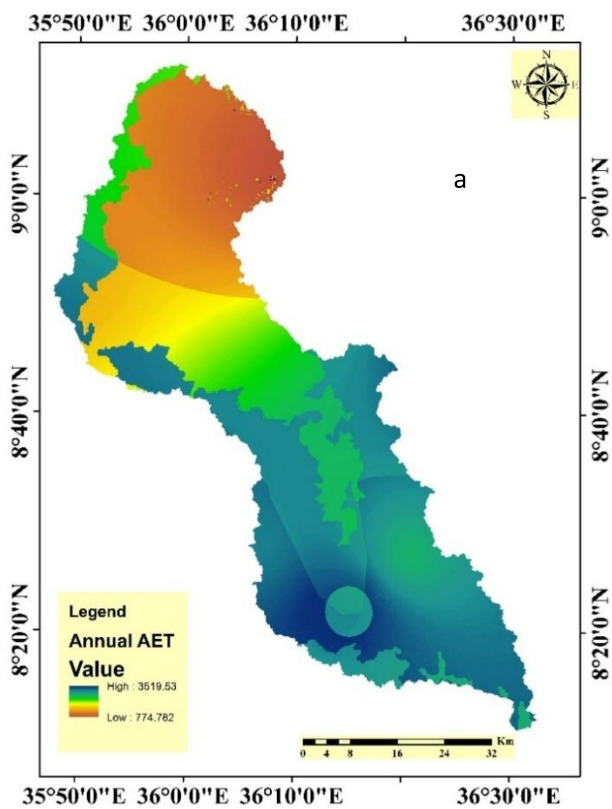
4.3.1 Actual Evapotranspiration (AET)

The model estimates AET as evaporation from bodies of water, evaporation from soil, transpiration from plants, and interception loss by vegetation. AET is a vital factor of the water balance in the groundwater recharge estimation process in the Dabena watershed. The findings revealed that the watershed loses water through evapotranspiration during a year in the range of 790.55 to 3609.78mm, the average being 961.6mm. This water loss represents 49% of the total precipitation in the watershed. This high evapotranspiration was primarily caused by the geographically varied land use and cover types, as well as the strong radiation and dry wind. The Dabana watershed is largely sheltered by various vegetation, including shrubs, trees, and crops. This improves evapotranspiration by lowering surface runoff in the watershed.

Similar findings have been identified in many Ethiopian watersheds. For instance, (Woldu et al., 2024) discovered that 47% of the mean annual rainfall was AET in the Upper Awash basin. Similarly, AET was found to represent 53% of total rainfall in Lake Tana basin (Yenehun et al., 2022), 36.4% of total annual rainfall was AET in Jedeb watershed, Upper Blue Nile basin(Asrade et al., 2024).

Every month, the WetSpass-M model predicts actual evapotranspiration. To determine seasonal values for the watershed's water balance components, data gathered monthly must be summed over the summer (May-September) and winter (October-April) seasons. Similarly, the average values for the various components of water balance have been calculated by adding the monthly results. The AET in the summer is 648.2mm with a standard deviation of 43.94, whereas the average AET in the winter is 313.35mm with a standard deviation of 49.06. The yearly AET of the watershed is estimated to be 961.6mm on average, with a minimum of 790.55 mm and a maximum of 3609.78mm. The wet season accounts for about 68.9% of the annual evapotranspiration, with the dry season releasing the remaining 31.1%.

The variance is caused by the variation in rainfall and other factors between the two seasons. The Decreased evapotranspiration during the winter months is caused by the soil moisture deficit, which manifests when precipitation is insufficient. Because crops and vegetation required more water during the dry season, water consumption increases. On the other hand, high soil moisture, healthy vegetation, and other land covers, together with a high length, intensity, and amount of precipitation dispersion, all contribute to higher evapotranspiration throughout the summer. The southern, western, and eastern regions of the research area have relatively high levels of evapotranspiration, whereas the central and northern regions have medium and low levels. There is less precipitation in the lower portion of the watershed due to its low evapotranspiration value, and vice versa. Changes in land use and cover are also connected to this. Figure below (figure 4.4 shows the annual and seasonal AET



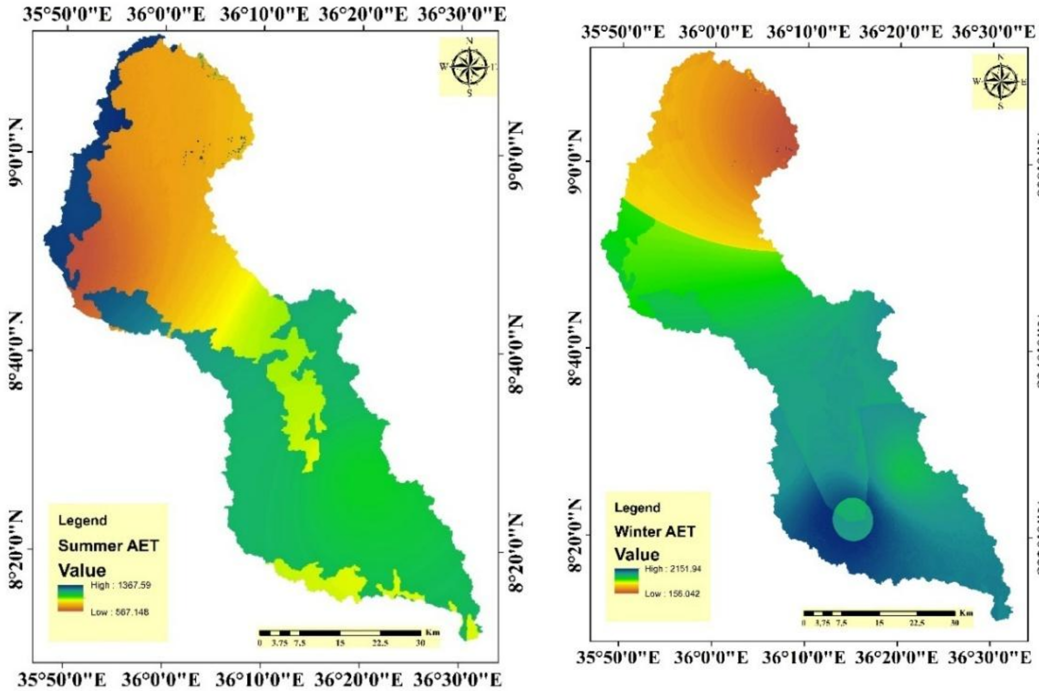


Figure 4.4 Annual AET, Summer AET, Winter AET

4.3.2. Surface Runoff

The WetSpass-M model depends on several f input variables and parameters to estimate monthly surface runoff. Slope, soil texture, vegetation type, and other weather factors are all taken into consideration by the model in the watershed. Runoff in the Dabena watershed has a very high range of variation, depending on the above-mentioned input variables. The spatial and seasonal SV values of surface runoff in the Dabena watershed are also very different during the rainy and dry months. According to the model results, the Dabena watershed's annual runoff value ranges from 139.15 mm to 1903.12 mm, with a mean of 523.74 mm. The typical number represents around 27% of the annual rainfall of the watershed.

The runoff of the watershed value varies seasonally by 487.5 mm during the summer (May to September) and 36.2 mm during the winter (October to April). The summer (wet) seasons account for 93% of the annual runoff, with the winter (dry) seasons accounting for the remaining 7%. The runoff coefficients have a significant impact on the runoff value. The runoff coefficient is greatly affected by variations in soil moisture, infiltration capacity, land use/cover, and rainfall volume and intensity. Rainfall is primarily responsible for the seasonal variation in the Dabana watershed. In the summer, rainfall exceeds soil infiltration capacity, leading to substantial surface runoff. The annual and seasonal runoff of the Dabena watershed is shown on figure below (Figure 4.5)

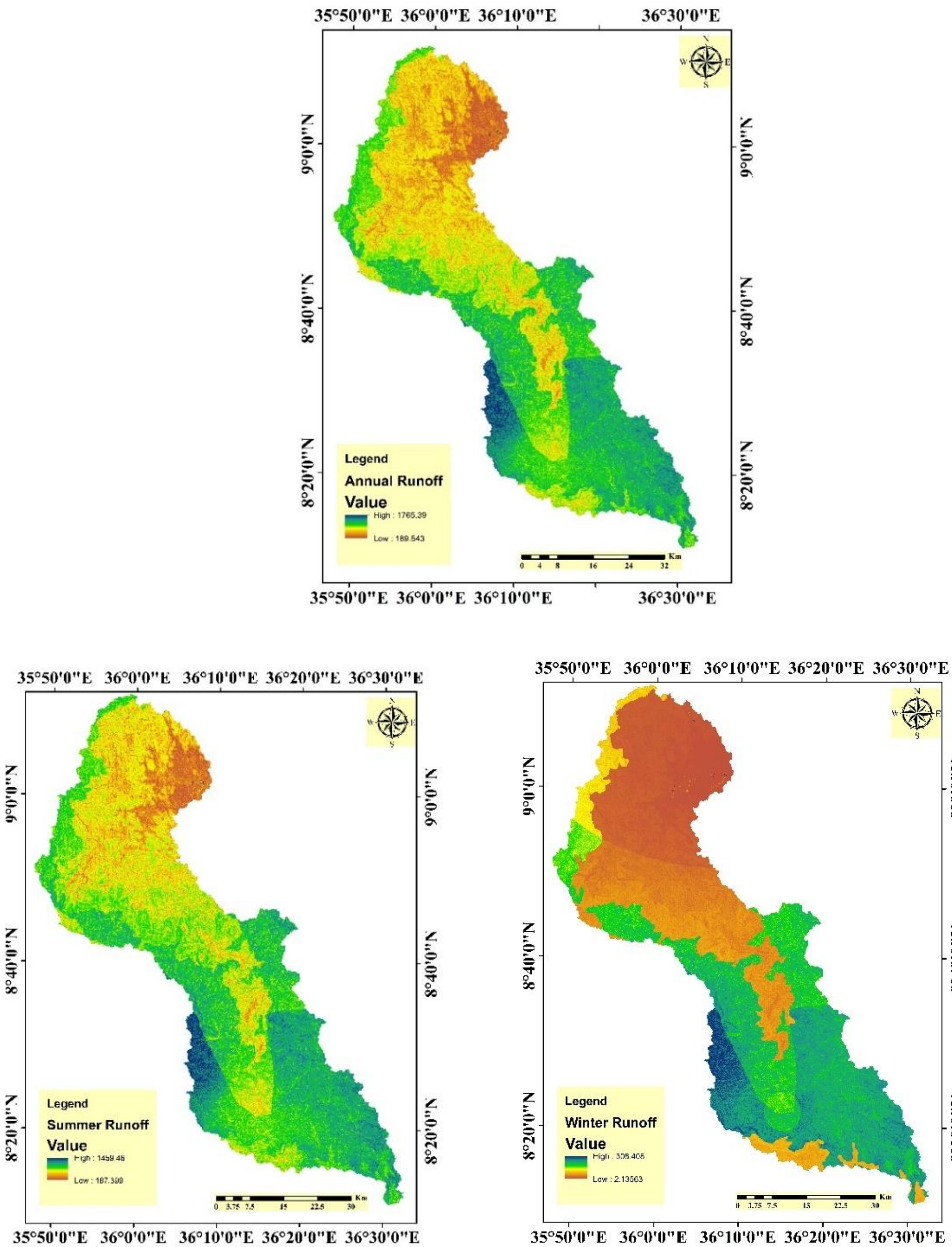


Figure 4.5 Annual Runoff, Summer Season Runoff and Winter Season Runoff.

According to above figure (Figure 4.5) the eastern and southern regions of the watershed experience high runoff because the soil consists clay. The rainwater cannot enter the earth because the clay material creates an impermeable barrier which prevents any water movement. The absence of forest roots in the agricultural area prevents soil penetration which leads to water runoff across the surface. The northern and central regions experience significantly reduced runoff. The area contains clay loam soil which provides better drainage because its composition includes sand that enables water movement through the soil. The areas maintain forest coverage which designates them as a forested region. The tree roots absorb rainwater and direct into the earth instead of allowing it to flow away. Even where the land is steep, the forest and the loamy soil work together to stop water movement.

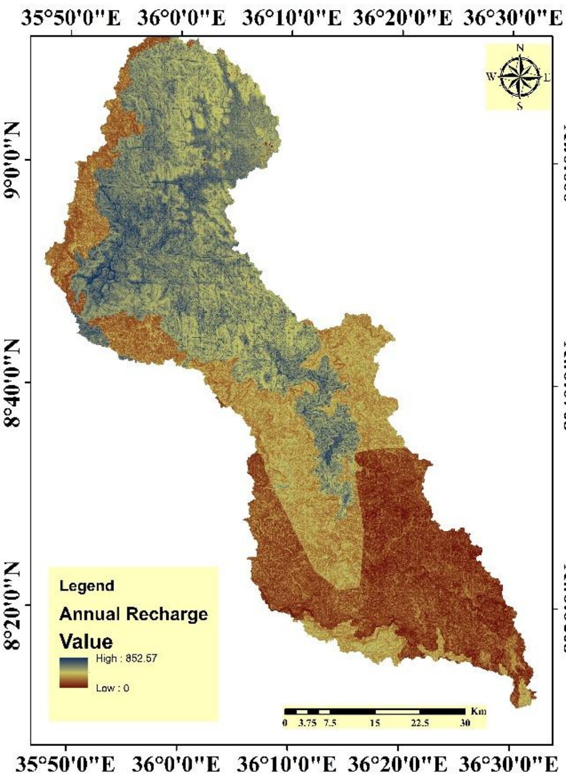
4.3.3. Groundwater Recharge

Groundwater recharge is influenced by a variety of factors, including soil texture, slope, land use, and groundwater level(Al Kuisi & El-Naqa, 2013). It is possible to apply diverse models to evaluate the recharge in a certain range according to the real situations present. In this scenario, the model computes the monthly long-term spatiotemporal distribution of groundwater recharge of the Dabena watershed by subtracting surface runoff and evapotranspiration from precipitation. The model estimates monthly groundwater recharge based on various input parameters. Recharge is estimated as the residual of precipitation-derived water balance components. This element makes it adaptable and sensitive to changes in various input variables and model parameters.

$$P - ET - Sy - R = 0 \tag{9}$$

Where P is precipitation, ET evapotranspiration, Sy surface runoff and R recharge.

Based on the model findings, The annual groundwater recharge in the Dabena watershed ranges from 0 to 849.74mm, with a mean of 478.12mm and a standard deviation of 122.77. The estimated mean annual groundwater recharge is estimated to be equivalent to 1,542,418,352m3/year. This accounts 24% of the total annual rainfall. Summer (May to September) accounts for approximately 76% (366.3mm) of the overall annual groundwater recharge of the watershed, while only 24% (111.82mm) of the recharge occurs in the dry (October to April) season. The temporal variation is caused by different climatological and biophysical input parameters, mainly rainfall. Summer season has the highest duration, intensity, and amount of precipitation distribution, and soil moisture which together speed up the groundwater recharge process. The mean annual and seasonal groundwater recharge of Dabena watershed is shown in figure below (Figure 4.6)



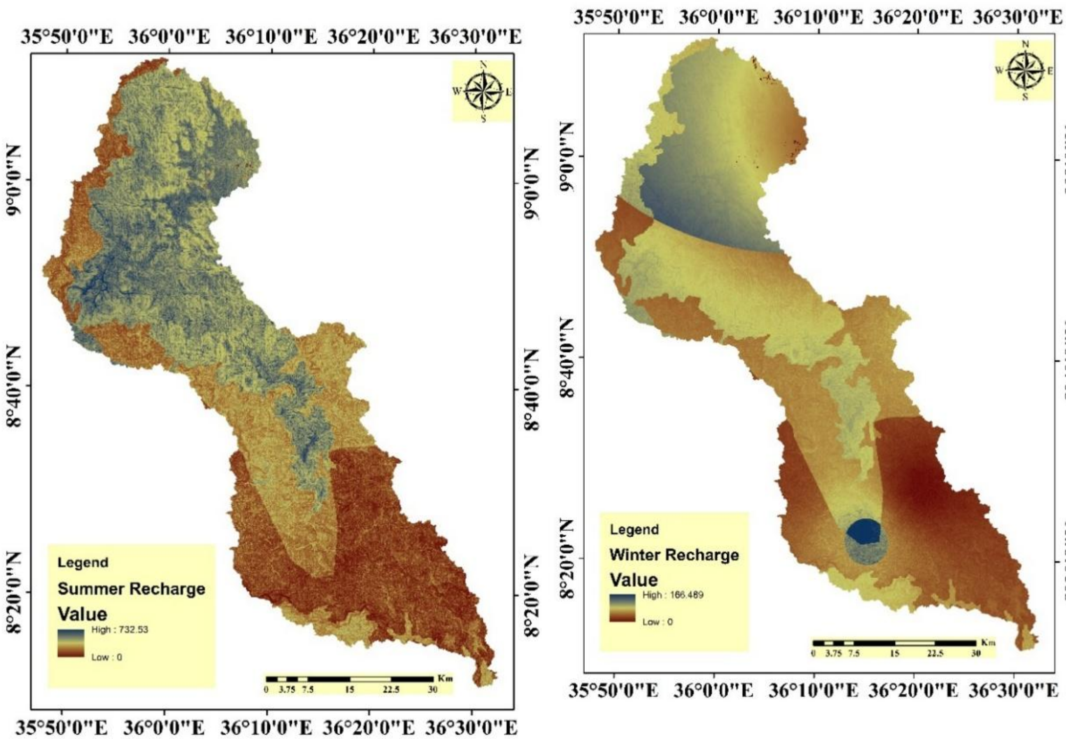


Figure 4.6 Annual Recharge, Summer Recharge and Winter Recharge

The spatial distribution of the groundwater recharge in the Dabena watershed is primarily governed by interaction between soil textures and land cover. The WetSpass-M model result shows that, the northern and central part of the watershed contain highest annual recharge rate. The high-recharge zone directly connects to clay-loam soil textures and forest land use. The forested are contain clay-loam which enables infiltration because its sand and silt components produce larger pore spaces than clay materials. Deep root systems of the forest create natural pathways which enable rainwater to move through the surface and reach aquifer.

The southern and eastern section of the study area are characterized by low recharge. Clay soils that dominate the area together with agricultural land use create conditions which lead to this significant decline in groundwater recharge. The tiny flat particles of clay create a dense layer that prevents water from moving downward because of its poor permeability. The surface becomes a seal because agricultural practices lead to soil compaction while they lack the deep-root structures which exist in forests. The result of this process shows that surface water will flow away from the area instead of soaking in to the ground which explains the low recharge on the area.

4.4 Sensitivity Analysis of SWAT Model

SWAT-CUP (SUFI-2) was used to examine sensitive parameters affecting the output of hydrological model output and their ranks. The most sensitive parameter in the watershed has a low p-value and a high absolute value (t-Stat). The hydrological model was calibrated and validated using parameters with medium, high, and extremely highly sensitive values that have a considerable effect on the output (Daniel & Abate, 2022). In the global sensitivity of SWAT-CUP, their sensitivity range was represented by the t-statistic and p-value. Parameters ranging from extremely sensitive to the least or insignificantly sensitive parameters were shown in the global sensitivity grid view and map view. As a result, the sensitivity analysis was performed using the Sufi-2 technique. A total of 18 parameters were examined for the sensitivity analysis, with an ending simulation number of 500, beginning with simulation 100.

After 500 iterations of SWAT sensitivity analysis for flow calibration, 18 parameters were identified as sensitive to varying degrees. The researcher chose 16 parameters out these 18 parameters because two of them are not that much sensitive. In descending order, the sensitive parameters are shown in table below (Table 4.1). Therefore, the eight most sensitive hydrological parameters in the Dabana catchment are: GW_DELAY.gw (Groundwater delay in days), RCHRG_DP.gw (Deep aquifer percolation fraction), CANMX.hru (Maximum canopy storage), LAT_TTIME.hru (Lateral flow travel time), GW_REVAP.gw (Groundwater "revap" coefficient), CN2.mgt (SCS runoff curve number), SOL_AWC(..).sol (Available water capacity of the soil layer), and ALPHA_BF.gw (Baseflow alpha factor in days). The results show that the watershed's hydrological process is mostly determined by the activity of each of these variables. The groundwater delay in days (GW_DELAY.gw) was found to be an extremely highly sensitive parameter in the watershed.

Table 7Table 4.1. The SWAT model Sensitivity Parameters

Rank	Parameter name	t-Stat	P-value
1	V__GW_DELAY.gw	-23.23	0.000

2	V__RCHRG_DP.gw	-15.78	0.000
3	V__CANMX.hru	7.61	0.000
4	V__LAT_TTIME.hru	-3.998	0.0001
5	V__GW_REVAP.gw	-3.786	0.0002
6	R_CN2.mgt	3.0388	0.0025
7	R__SOL_AWC(..).sol	2.3026	0.022
8	V__ALPHA_BF.gw	-2.189	0.029
9	V__GWQMN.gw	-1.859	0.064
10	V__EPCO.hru	-0.8211	0.412
11	V__CH_N2.rte	0.714	0.4756
12	V__ESCO.hru	-0.595	0.552
13	R__SOL_ALB(..).sol	-0.4889	0.625
14	V__CH_K2.rte	-0.424	0.672
15	V__HRU_SLP.hru	-0.304	0.761
16	V__SLSUBBSN.hru	-0.132	0.895

Here, R represents multiplying a current parameter value by (1 + fitted value), and V represents replacing a current parameter value with a fitted value.

4.4.1. Sensitive Parameters Fitted Value

The fitted values for sensitive parameters are the optimal values obtained from the SWAT-CUP calibration process. During calibration, these parameters are modified within predefined ranges to reduce the difference between observed and simulated outputs, thus improving model accuracy. The fitted value is the best estimate for each sensitive parameter based on the observed data and the model setup. The fitted value of every parameter and its maximum and minimum ranges are revealed in Table 4.2.

Table 8Table 4.2. Fitted Values of SWAT Parameters

Parameter name	Minimum	Maximum	Fitted Value
GW_DELAY.gw	0.00	100.00	19.700001
RCHRG_DP.gw	0.00	0.60	0.211800
CANMX.hru	0.00	40.00	25.879999
LAT_TTIME.hru	40.00	100.00	68.379997
GW_REVAP.gw	0.02	0.10	0.078160
CN2.mgt	-0.10	0.10	-0.079000
SOL_AWC(..).sol	-0.20	0.10	-0.088100
ALPHA_BF.gw	0.20	0.60	0.414800
GWQMN.gw	0.00	1600.00	270.399994
EPCO.hru	0.40	1.00	0.795400
CH_N2.rte	0.01	0.200	0.063390
ESCO.hru	0.30	0.80	0.657500
SOL_ALB(..).sol	-0.20	-0.001	-0.164777
CH_K2.rte	300.00	500.00	338.200012
HRU_SLP.hru	0.400	1.00	0.475000
SLSUBBSN.hru	10.00	100.00	71.470001

4.5. SWAT Model Calibration and Validation

From 1996 to 2017, 16 sensitive characteristics and SWAT-CUP (SUFI-2) on monthly time steps were chosen in order to calibrate and validate the SWAT model. 15 years flow gauging periods (1996 to 2010), were chosen for the calibration period. The remaining 7 years, i.e., from 2011 to 2017, were used to validate the model that was measured at the Dabena near Buno Bedele station in the Dabena watershed. Figure 4.7 &4.8.

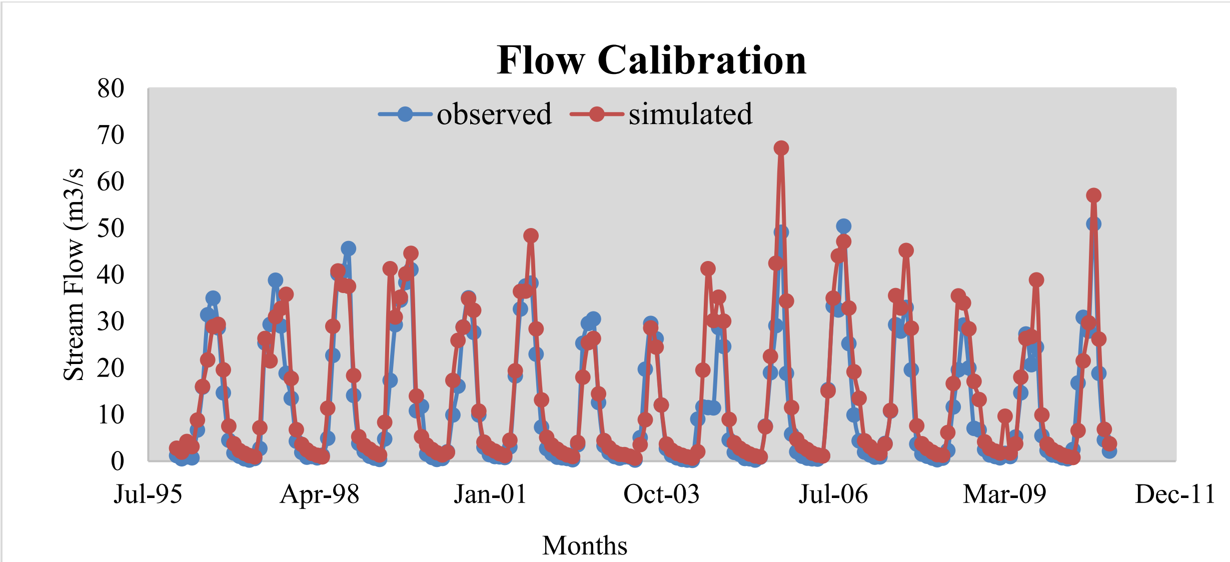


Figure 4.7. Calibration Results of Monthly Observed and Simulated Stream Flow Hydrograph

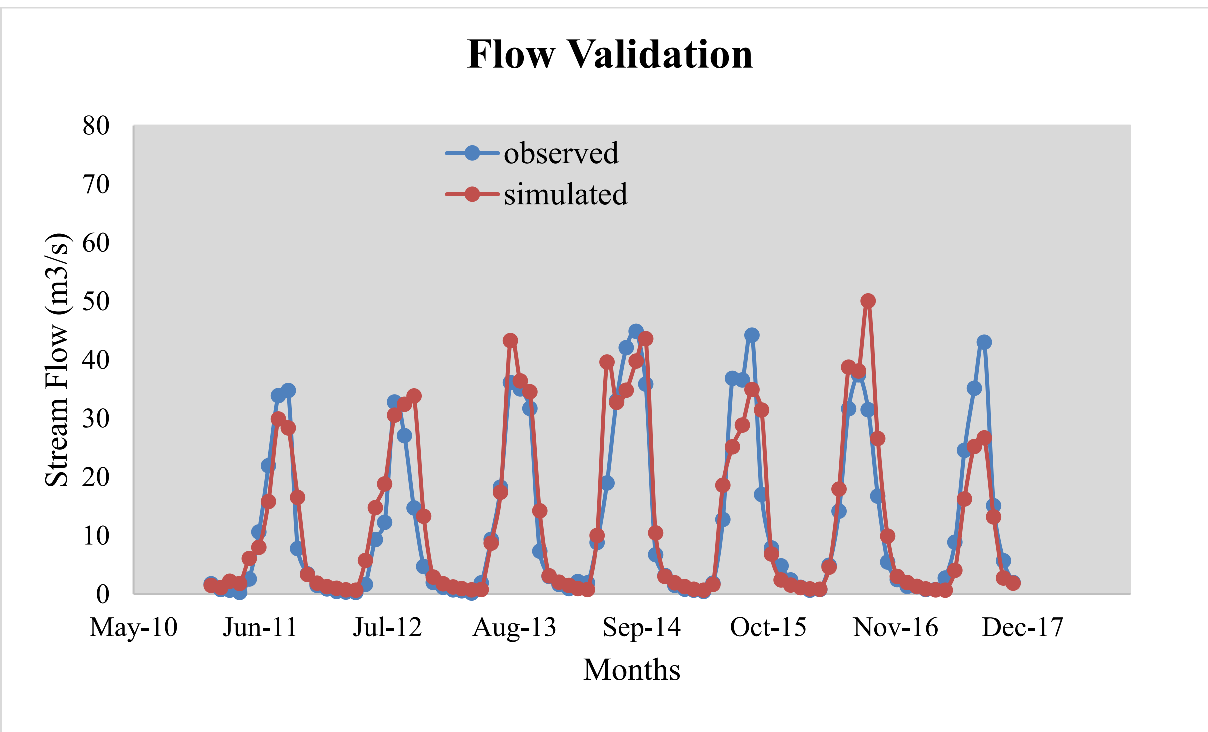


Figure 4.8. Validation Results of Monthly Observed and Simulated Stream Flow Hydrograph

The calibration results for the mean streamflow indicated that the SWAT model could describe the observed streamflow with R^2, NSE, and PBIAS values of 0.87, 0.8, and -21.1, respectively. In the same way, the mean monthly streamflow validation shows R2, NSE, and PBIAS values of 0.83, 0.82, and -6.8, respectively. In addition, the P-factor and r-factor statistics indicate 0.86 and 0.81 during calibration and 0.74, and 0.77 during validation, respectively. The summary stat of SWAT model calibration and validation results are presented in Table 4.3.

Table 9Table 4.3. Summary Stat of SWAT Model Performance

	Evaluation parameters					Mean Flow (m3/s)	
	R2	NSE	PBIAS	P-factor	r-factor	Observed	Simulated
Calibration	0.87	0.8	-21.1	0.86	0.81	11.7	14.17
Validation	0.83	0.82	-6.8	0.74	0.77	12.22	13.06

Overall, the SWAT model attained a good fit between observation and simulation in the Dabana nr Buno Bedelle station of the Dabana watershed.

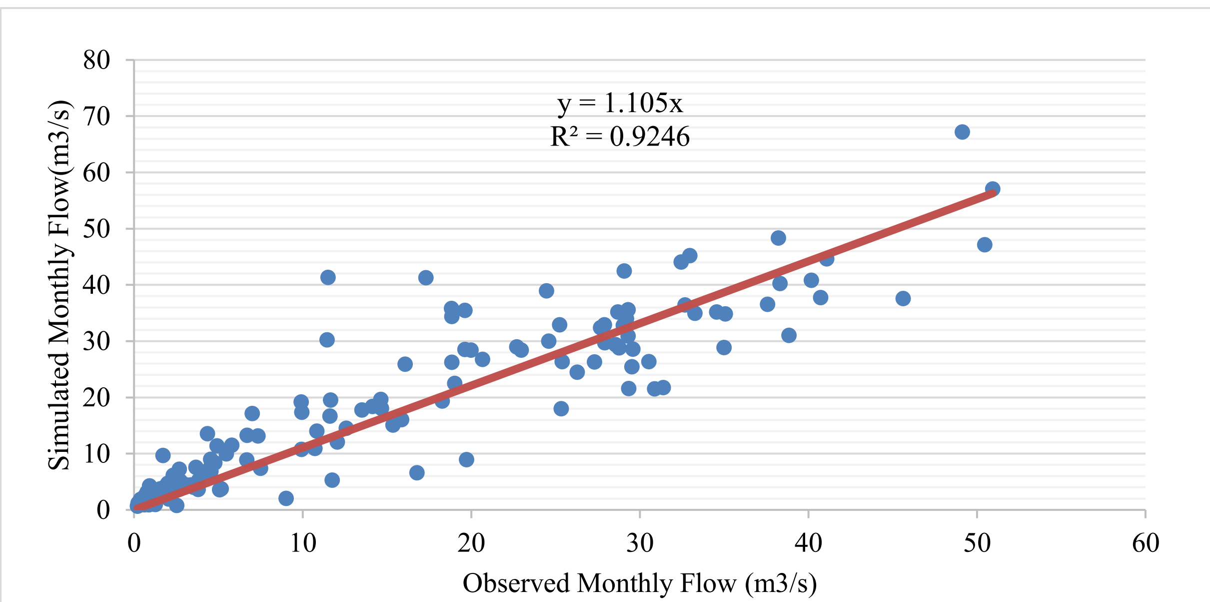


Figure 4.9. Fit Line Stream Flow Simulation and Observation for the Calibration Period

The overlay plot of observed and predicted flow for the monthly timestep is illustrated in Figure above (Figure 4.9). The plot indicates a slight overestimation of the year's maximum flow in 2006 and 2010, as well as a little underprediction of the year's minimum flow in 2002. The monthly data of the observed and simulated calibration reveals that the measured and simulated flows are mostly in great agreement.

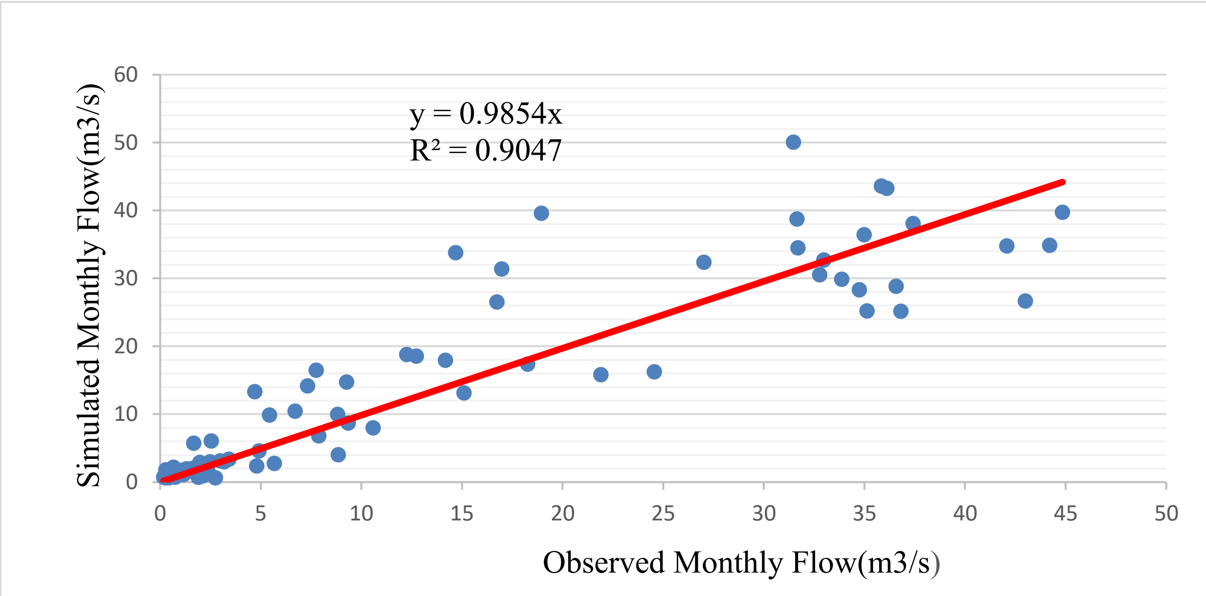


Figure 4.10. Fit Line Stream Flow Simulation and Observation for the Validation Period

The outcome for simulated flow calibration and validation as confirmed by NSE, R2, and PBIAS, the hydrographs are well-captured and the correlation between the measured and simulated value is generally in very good condition. The model evaluation guidelines were followed to produce an acceptable result. See the above figure (Figure 4.10)

4.6. Water Balance of Dabana Watershed

The Water Balance Components were created using the SWAT model. The following elements were considered: rainfall, ET, runoff, baseflow, and groundwater recharge. The total precipitation in the watershed during the time step, the actual evapotranspiration from the watershed, and the net amount of water that leaves the basin and contributes to the rich (water yield) are the three main components of the water balance of the watershed. Water yield takes into account surface runoff, lateral flow, groundwater, and transmission losses in stream flow. The equation of water balance is as follows:

$$P - Q - ET - Base\ flow \pm \Delta TWS - (other\ components) = 0 \qquad (10)$$

where P stands for precipitation, Q indicates runoff, ET refers to evapotranspiration, and TWS represents for change in terrestrial water storage. Other components include soil moisture, glacier water, shallow and deep ground water storage, and soil moisture.

The calibrated and validated SWAT model was used to determine various water balance components in the Dabena watershed. PET, evaporation and transpiration, precipitation, and the average curve number, Runoff from the surface, evaporation from the shallow aquifer, lateral flow, recharge to the deep aquifer, and percolation to the shallow aquifer are the most important water balance factors taken into account. This research concluded that a well-calibrated watershed model can provide significant help in water balance analysis at the watershed level. The figure below (Figure 4.11) depicts the quantitative diagram representation of the hydrologic cycle. It is the hydrologic component generated from the SWAT model. The water balance of the Dabena watershed included PET 1781.1mm, Evaporation and transpiration 721.9mm, Precipitation 1833.3mm, Average curve number 77.91, Surface runoff 465.81mm, Revap from shallow aquifer 34.63mm, Percolation to shallow aquifer 566.07mm, Lateral flow 79.57mm, and recharge to deep aquifer 32.73mm.

The higher rate of percolation indicates that the Dabena watershed is functions as a recharge dominated system with high infiltration capacity. The soil-vegetation system of the watershed functions as a natural reservoir which directs water downwards to underground storage instead of allowing it to flow out through surface drainage. The major implication of this dominated percolation is the sustenance of robust baseflow, which ensures the perennial nature of Dabena river in dry season. The annual recharge rate indicates that the shallow aquifer experiences continuous replenishment which creates strong hydrological security and resilience against seasonal rainfall changes.

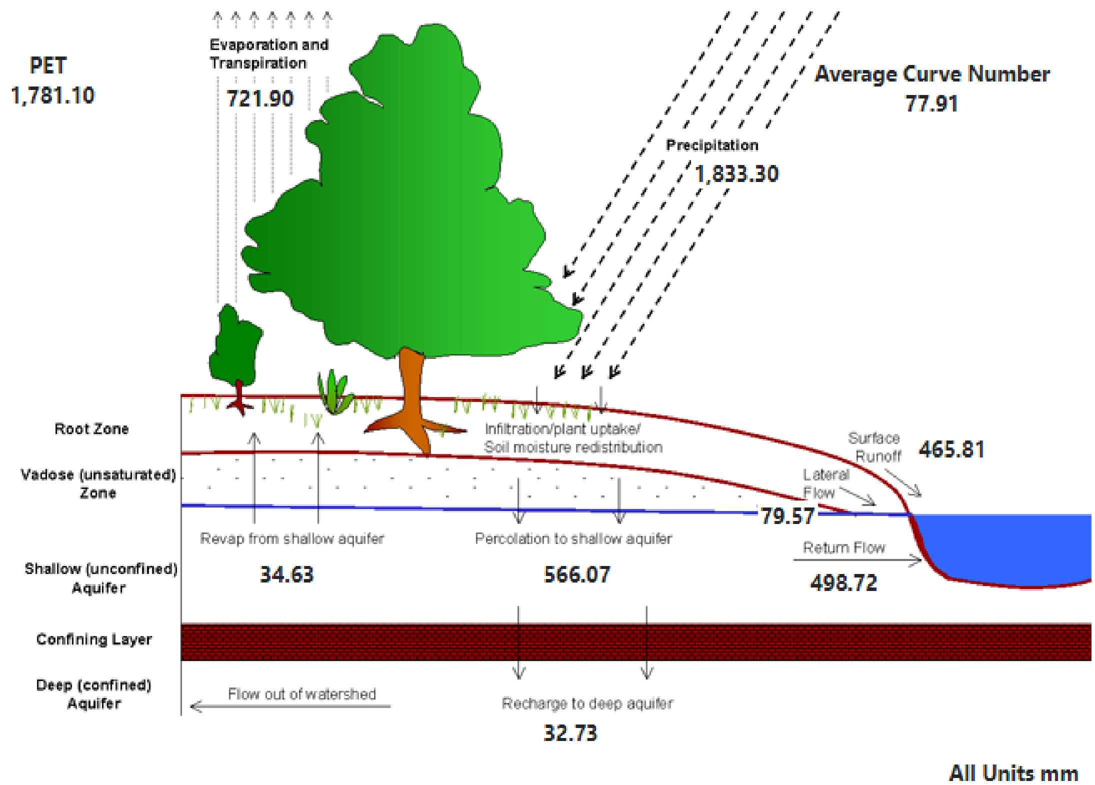


Figure 4.11. Water Balance of Dabana Watershed.

4.7. WEAP Model Scenario Analysis and Results

The WEAP Model provides a simulation of water allocation in a river basin via supply and demand balancing. Its working is based on a sequential mass balance for controlling inflows, withdrawals, return flows, and storage dynamics at every node. The model presents the locations of demand, reservoirs, rivers, and transmission links spatially thus taking into account the interactions of the sectors and regions. This modern scenario like irrigation expansion and population growth assessment of water availability, reliability, and environmental flow requirements in the watershed.

4.7.1 SC1: Baseline Scenario

Water Demand in the Baseline Scenario

In the baseline scenario, the annual water demand for all demand sites is 2.61 BMC. The analysis of water demand reveals that irrigation constitutes the largest demand sector. The highest water demand is evaluated on Bedelle irrigation demand site which accounts 39% of the annual water demand in the study area followed by Chora and Dabo irrigation sites. The overall water demand for all irrigation sites in the watershed is 2591.34 MCM, Domestic water demand evaluated to be 14.88 MCM, as well, water requirement for industrial purpose is 0.22 MCM. See table below

Table 10Table 4.4 Annual Water Demand on Base Year in Baseline Scenario

Water Demand (not including loss, reuse and DSM) (Million Cubic Meter)				
Scenario: SC1: Baseline, 1996, All Branches				
Branch	Industrial	Irrigation	Domestic	Sum
Jan	0.02	777.40	1.26	220.76
Feb	0.02	777.40	1.18	206.52
Mar	0.02	518.27	1.26	220.77
Apr	0.02	129.57	1.22	213.64
May	0.02	0.00	1.26	220.77
Jun	0.02	0.00	1.22	213.64
Jul	0.02	0.00	1.26	220.77
Aug	0.02	0.00	1.26	220.77
Sep	0.02	0.00	1.22	213.64
Oct	0.02	77.74	1.26	220.77
Nov	0.02	129.57	1.22	213.64
Dec	0.02	181.39	1.26	220.77
Sum	0.22	2591.34	14.88	2606.44

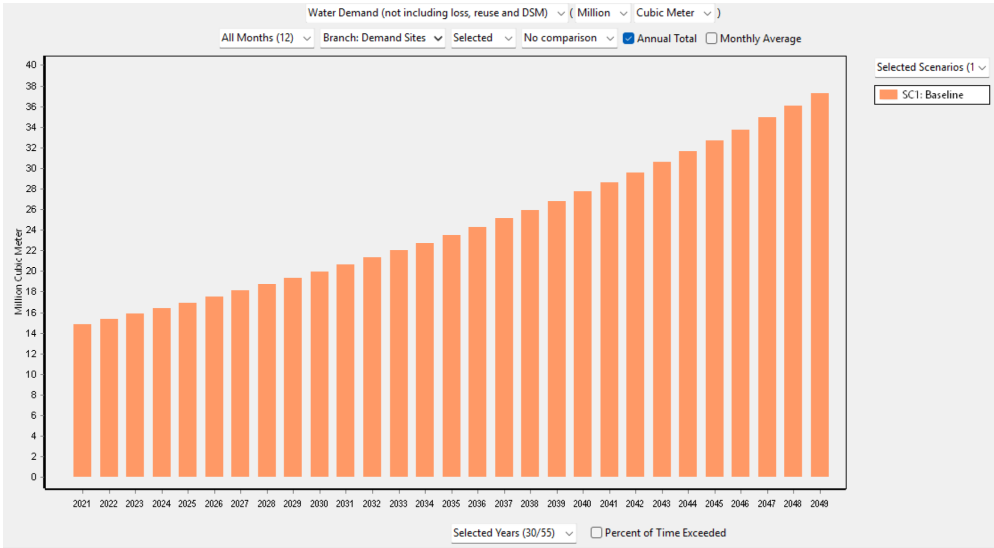


Figure 4.12 Domestic Water Demand in Baseline Scenario

The figure above (Figure 4.12) illustrates that how domestic water demand increases from base year to the last year of the future water demand year 2050. The current account domestic water demand was 14.88 MCM on base year and it increased to 38.52 MCM on 2050. The future water demands for irrigation and industrial remains the same with the base year water requirement. Generally, the overall water demand for all demand site is increased to 2.63BCM in 2050. The future water demand for the period of (2021–2050) for all demand sites is 78.49BCM.

Supply Delivered in the Baseline Scenario

Total net amount of water required to meet all demand sites in the current account is 2.61 BMC. The total supply delivered in this current year is 0.38BCM. The all water demands for domestic demand sites were satisfied because it's given the highest priority. But, for the irrigation demand sites the total required amount of water is 2.6BCM and the amount of supply delivered is 0.28BCM. the amount of water supply delivered for industrial water demand is 0.14MCM. The future supply delivered of all demand sites is 9.43BCM.

Unmet Demand in the Baseline Scenario

Unmet demand is defined as the quantity of water that falls short of the demand. In the present year, the unmet demand for domestic water consumption is very 7.25MCM. The unmet demand on domestic water is very small when compared to the unmet demand on the irrigation water requirement. The overall unmet demand for 2020 is 2.23BCM. The unmet demand evaluated on irrigation and industrial demand sites accounts 69.05BCM and 0.06MCM respectively for the period of (2021–2050). The available water resource is first supplied to domestic and the remain amount of water is share for rest demand sites based on their priority rank. The result indicate that the Dabena watershed is already facing supply-demand gaps during the low-flow periods.

Instream flow requirement

On baseline scenario, the instream flow requirement was measured to be 25.5MCM, 105.6 MCM and 122.5MCM on upstream, middle stream and downstream respectively. The amount water delivered for environmental flow requirement meets most of the demand across the river basin. However, in February and March, a small amount of unmet demand for environmental flow requirement is observed in this scenario.

4.7.2 SC2: Irrigation Expansion with Baseline Scenario

This scenario describes the future irrigation water demand for the period of 2021–2050 in Dabena watershed. This scenario gives a clear answer for the question "what will happen to future irrigation water demand if irrigated land will be expanded by 1% each year after the current account year?".

Water Demand in Irrigation Expansion Scenario

The total future water demand for irrigation demand site is evaluated to be 91.04BCM. It increased from 77.74BCM to this value from Baseline Scenario. The water demand for the remaining water demand sites like domestic and industrial remains the same with the baseline scenario, because the only change assessed in this scenario was the expansion of irrigated land in the study area. Therefore, the overall total future (2021-2050) water demand for all demand site is 91.79BCM. Figure 4.13 and Table 4.5 show the irrigation water demand in irrigation expansion scenario.

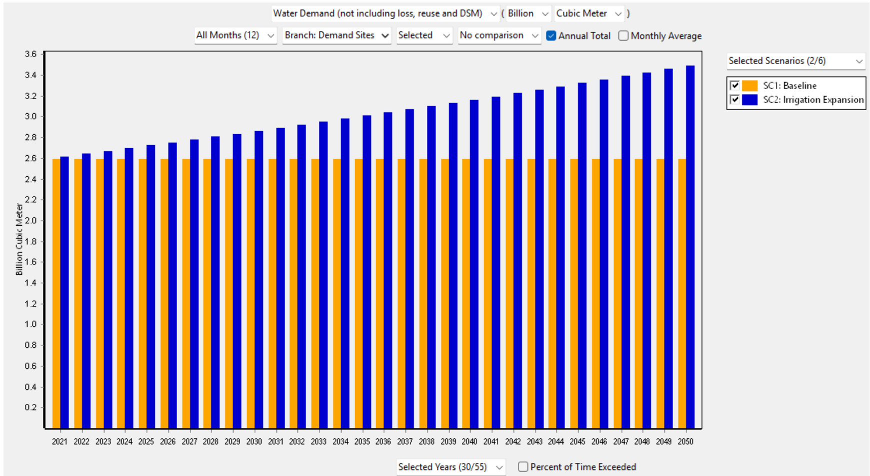


Figure 4.13 Irrigation Water Demand in Baseline and Irrigation Expansion Scenario

Table 11Table 4.5 Monthly Irrigation Water Demand

Water Demand (not including loss, reuse and DSM) (Billion Cubic Meter)							
Scenario: SC2: Irrigation Expansion, Selected Years (30/55), Selected Branches (6/13)							
Selected Branch	Bedele	Chora	Dabo	Dega	Gechi	Meko	**Sum**
Jan	10.90	6.01	4.11	3.92	1.32	1.06	27.31
Feb	10.90	6.01	4.11	3.92	1.32	1.06	27.31
Mar	7.26	4.00	2.74	2.62	0.88	0.71	18.21
Apr	1.82	1.00	0.69	0.65	0.22	0.18	4.55
May	0.00	0.00	0.00	0.00	0.00	0.00	0.00
Jun	0.00	0.00	0.00	0.00	0.00	0.00	0.00
Jul	0.00	0.00	0.00	0.00	0.00	0.00	0.00
Aug	0.00	0.00	0.00	0.00	0.00	0.00	0.00
Sep	0.00	0.00	0.00	0.00	0.00	0.00	0.00
Oct	1.09	0.60	0.41	0.39	0.13	0.11	2.73
Nov	1.82	1.00	0.69	0.65	0.22	0.18	4.55
Dec	2.54	1.40	0.96	0.92	0.31	0.25	6.37
Sum	36.32	20.02	13.70	13.08	4.39	3.54	91.04

Supply Delivered in Irrigation Expansion Scenario

The total annual water delivered to meet water requirement in irrigation expansion scenario is 9.99BCM which accounts 11% of the total water demand. From this water delivered around 9.24BCM water is supplied for irrigation water demand as shown on below table (Table 4.6).

Table 12Table 4.6. Supply Delivered in Irrigation Expansion Scenario

Supply Delivered (Billion Cubic Meter) **Scenario: SC2: Irrigation Expansion, Selected Years (30/55), Selected Branches (6/13)**							
Selected Branch	Bedele	Chora	Dabo	Dega	Gechi	Meko	**Sum**
Jan	0.22	0.11	0.12	0.04	0.03	0.03	0.55
Feb	0.20	0.08	0.11	0.03	0.02	0.03	0.48
Mar	0.55	0.18	0.25	0.07	0.07	0.06	1.18
Apr	0.46	0.17	0.26	0.07	0.05	0.07	1.07
May	0.00	0.00	0.00	0.00	0.00	0.00	0.00
Jun	0.00	0.00	0.00	0.00	0.00	0.00	0.00
Jul	0.00	0.00	0.00	0.00	0.00	0.00	0.00
Aug	0.00	0.00	0.00	0.00	0.00	0.00	0.00
Sep	0.00	0.00	0.00	0.00	0.00	0.00	0.00
Oct	1.09	0.58	0.41	0.36	0.13	0.11	2.68
Nov	1.11	0.39	0.55	0.17	0.13	0.14	2.50
Dec	0.36	0.15	0.14	0.06	0.04	0.04	0.79
Sum	3.99	1.66	1.84	0.81	0.47	0.47	9.24

Unmet Demand in Irrigation Expansion Scenario

The simulation outcomes for the period of 2021-2050 demonstrates that Dabena watershed experiences a major shortage of water supply under this scenario. The total cumulative unmet water which is not delivered for required water demand is quantified at 81.81BCM, which accounts for approximately 89% of the total required water demand. This amount of scarcity of water found on irrigation demand sites. The irrigation sector experiences complete supply failure because existing hydrological conditions prevent access to additional water resources. The model indicates a reliability of only 11% which means that most irrigation demand locations will experience persistent water scarcity throughout the entire projected timeline. This result show that implementing the exist irrigation expansion plan without securing additional water resources will result in full agricultural production failure. An 89% deficit represents a major gap which demonstrates the fundamental difference between what policy aims to achieve and what the water resource situation allows. With present available water resources, the Dabena watershed will be unable to supply required irrigation water for the period of 2021-2050.

4.7.3 SC3: Groundwater Use with Baseline Scenario

The result of this scenario show that using groundwater resources as a management solution leads to major changes in how water flows through the watershed. The use of groundwater is projected to result a significant reduction of unmet demand by 99.9% decreasing from 69.06BCM to 0.01BCM in the period of 2021-2050. It was also revealed that the implementation of this management option will result a 100% reduction for all irrigation demands because the groundwater nodes were connected to irrigation demand sites only. Small amount (7.25 MCM) of unmet demand is discovered on domestic water demand (see Figure 4.14). Since the groundwater is utilized exclusively for irrigation demand sites, this unmet demand is observed on domestic water demand, even though it's not linked to domestic consumption. Mostly, this scenario presents a potential to water scarcity challenges in the study area.

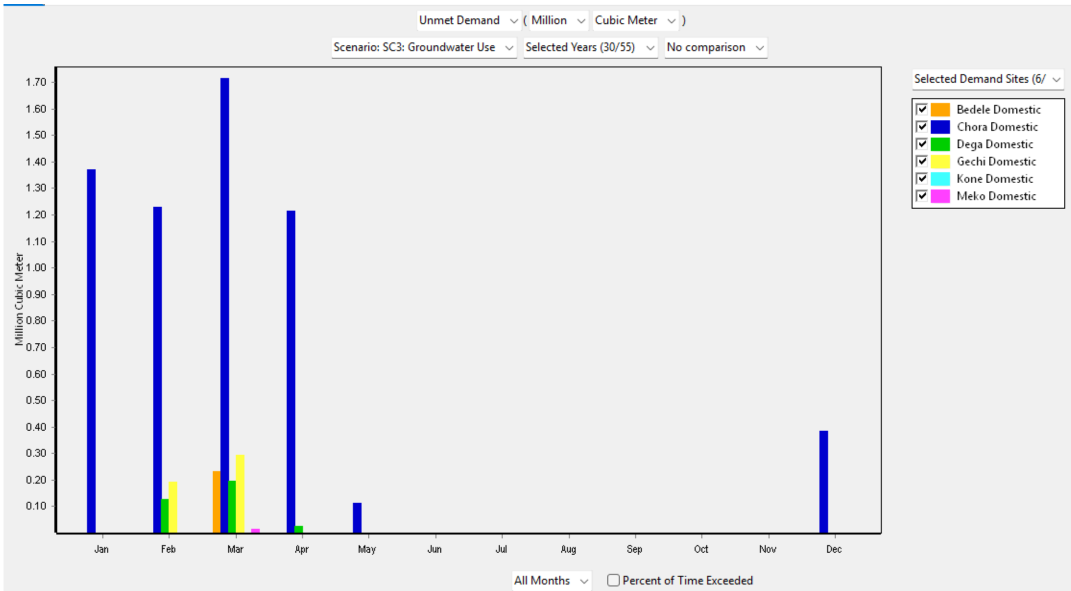


Figure 4.14 Unmet Demand for Domestic Demand Sites in Groundwater Use Scenario

4.7.4 SC4: Combined Impact Scenario

In this scenario, the combined impact of the above three scenarios (baseline, irrigation expansion and groundwater use scenarios) was assessed. It also highlights cumulative effects of water availability and demand across the watershed. Together, these scenarios illustrate how expanding irrigation and relying on groundwater abstraction affects the unmet demands when compared to the baseline condition. The total water demand in this scenario for future water demand is evaluated to be 91.79BCM in the period of 2021-2050. This water demand is increased from 78.49BCM to 91.79BCM due to expansion in irrigated land in SC2.

Unmet demands in baseline and irrigation expansion scenarios reduced by 99.9% in groundwater use and combined impact scenarios on irrigation demand sites. But there is still small amount of unmet demand observed on domestic and environmental flow requirements. As mentioned above this is due to the abstraction of groundwater for irrigation demands only. Figure 4.15 shows how groundwater uses and combined impact scenarios affects the unmet demand on irrigation demand sites.

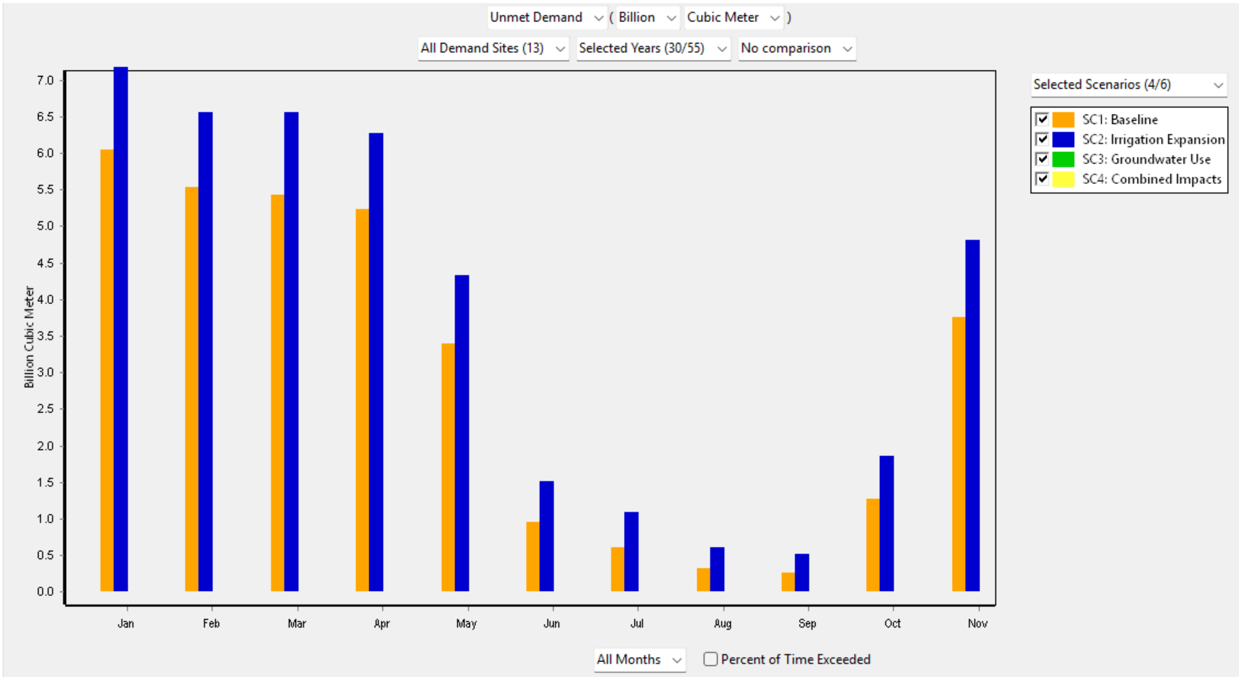


Figure 4.15 Unmet Demands for Each Scenario (Baseline, Irrigation Expansion, Groundwater Use and Combined Impact)

4.7.6 SC5: Irrigation Priority with Baseline Scenario

The irrigation priority scenario discovers the implications of assigning higher allocation priority to irrigation demand sites compared to other sectors. This scenario evaluated how prioritizing agricultural water use affects domestic water demand and environmental flow requirement. The water demand in this scenario is the same with the water demand in baseline scenario. The only thing that was changed is the allocation priorities for domestic and irrigation water demand.

In this scenario, the total unmet demand for domestic increased significantly in the baseline scenario rising from 7.25MCM to 267.83MCM. Conversely, the unmet demand for irrigation demand sites decreased slightly from 69.05BCM to 67. 63BCM. Figure below (Figure 4.16 &4.17) shows how prioritizing irrigation affects the unmet demand of domestic and irrigation water demand in baseline and irrigation priority scenarios.

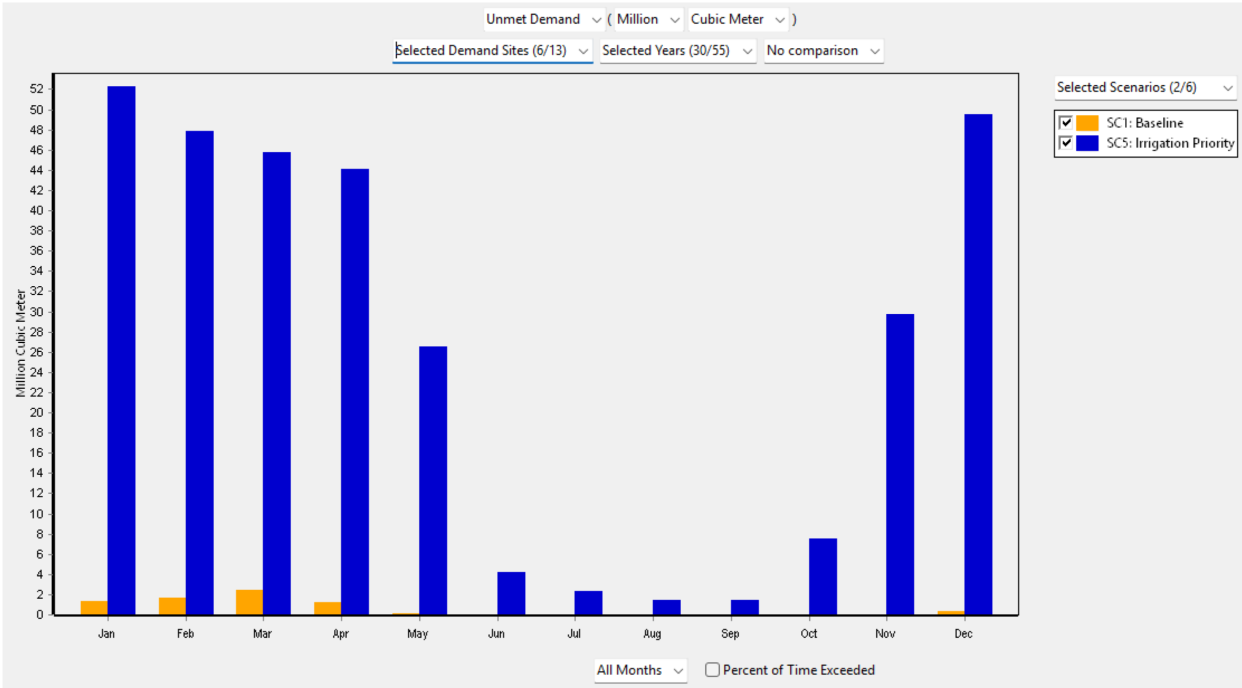


Figure 4.16 Domestic Unmet Demand Under Baseline and Irrigation Priority Scenarios.

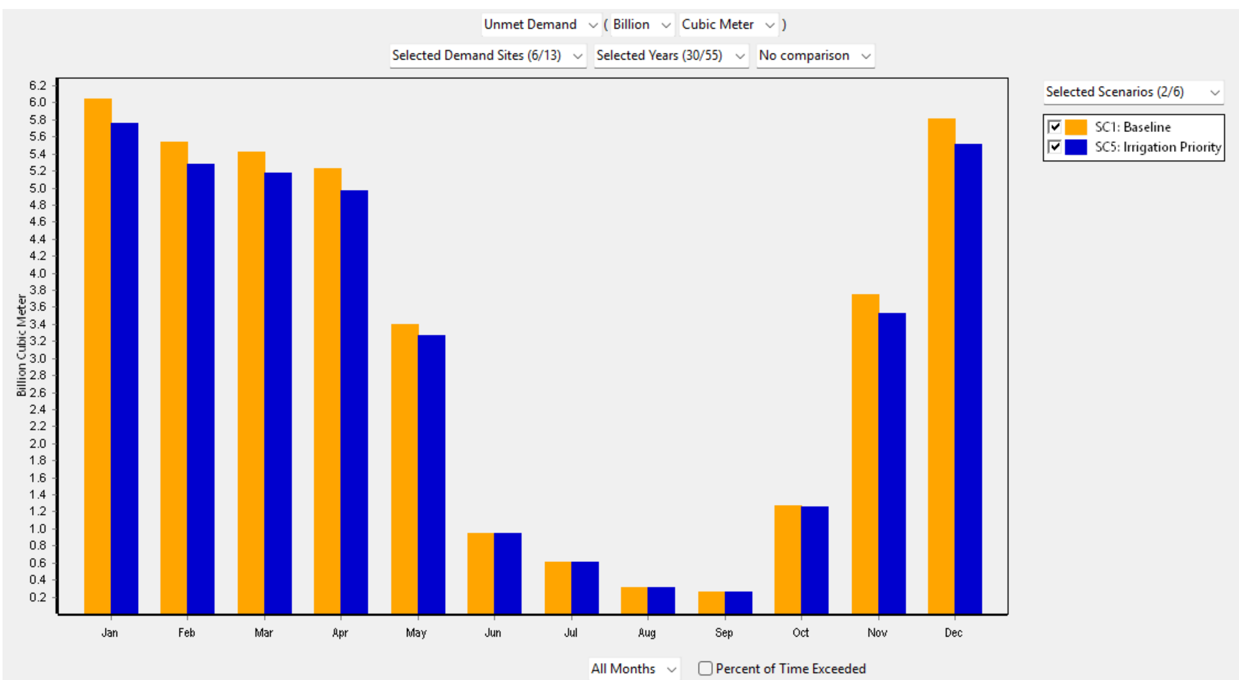


Figure 4.17 Irrigation Unmet Demand Under Baseline and Irrigation Priority Scenarios.

4.7.7 SC6: Environmental Flow Requirement (EFR) Priority with Baseline Scenario

In this scenario, the allocation priority for Environmental flow requirement was set equal to that of domestic water demand. Domestic and EFR are both given the highest priority. The ecological requirements are treated with the same rank as basic human consumption in the water allocation framework. Similar to the irrigation priority scenario, this scenario had a great impact on unmet demand for domestic water demand. The unmet demand for domestic water consumption was 7.25MCM in the baseline scenario and it increased to 45.39MCM in the EFR priority scenario. This scenario reduces the flexibility to satisfy domestic water demand specially during dry season. As a result, domestic water shortages become more significant in this scenario compared to baseline. See figure below

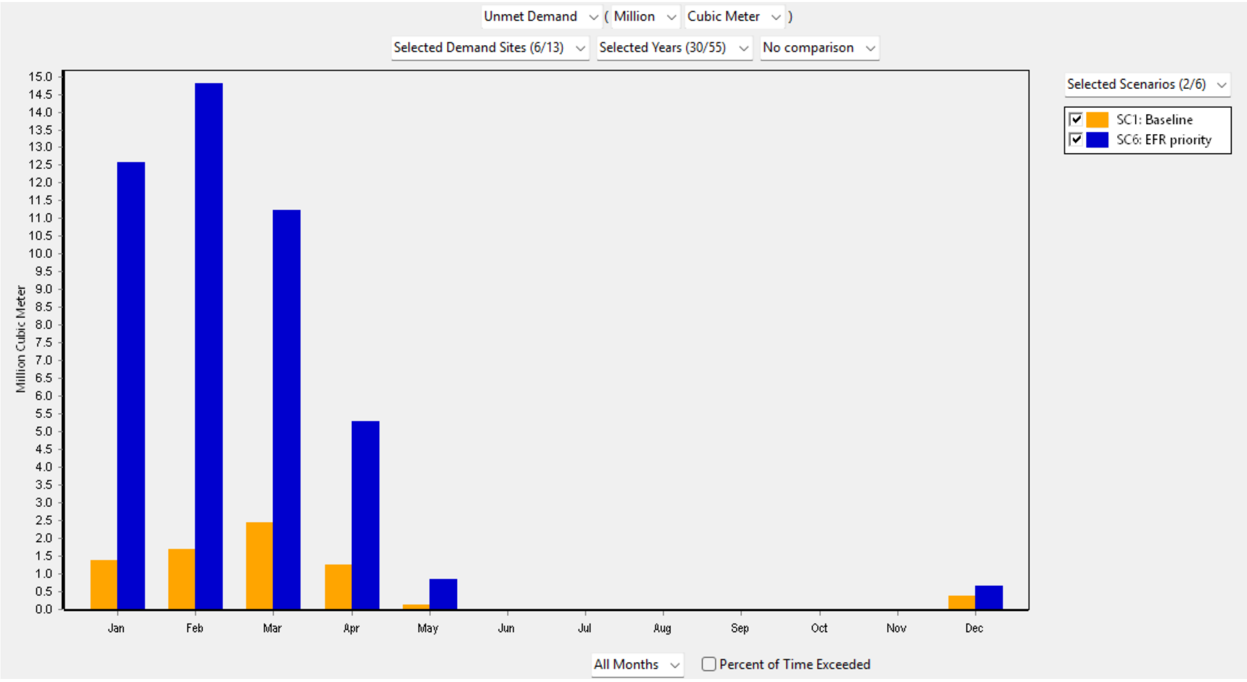


Figure 4.18 Domestic Unmet Demand Under Baseline and EFR Priority Scenarios.

CHAPTER FIVE: CONCLUSION AND RECOMMENDATION

5.1 CONCLUSION

This thesis aimed to conduct the evaluation of available water resources including surface and groundwater resources and development of allocation strategies for different water users within Dabena watershed by combining hydrological modeling and allocation tool. Surface water availability was assessed using SWAT model which provided insights into streamflow dynamics and the hydrological character of the watershed. Groundwater recharge was quantified using WetSpass-M model, enabling a better understanding of subsurface contribution to overall water balance components. Finally, the available water resources quantified using above two hydrological models allocated for different water users, ensuring that domestic, agricultural, industrial and environment flow requirements using WEAP model.

The knowledge of hydrological processes and the creation of proper hydrological models for a watershed are the prime factors in the implementation and management of water resources programs. In this study, the surface water resource of Dabena watershed is simulated using SWAT model. The sensitivity analysis, calibration and validation of the model turned out to be effective in evaluating the performance and applicability of SWAT model. As per the sensitivity analysis result with the discharge data eight parameters were identified to be the most sensitive hydrological parameters in the watershed. Among them, the groundwater delay in days (GW_DELAY.gw) was ranked as the most sensitive parameter in the watershed.

The SWAT model performance for calibration and validation was evaluated using statical and graphical method. R^2, NSE, and PBIAS has given a high value of 0.87, 0.8, and -21.1, respectively for calibration and 0.83, 0.82, and -6.8 respectively for validation. This value indicates the excellent performance of the SWAT model as it successfully represents the observed and simulated streamflow of the Dabena watershed very closely. The water balance of the Dabana watershed included PET 1781.1mm, Evaporation and transpiration 721.9mm, Precipitation 1833.3mm, Average curve number 77.91, Surface runoff 465.81mm, Revap from shallow aquifer 34.63mm, Percolation to shallow aquifer 566.07mm, Lateral flow 79.57mm, and recharge to deep aquifer 32.73mm.

The monthly water balance component of the Dabena watershed has been simulated using the physically based water balance model WetSpass-M. The WetSpass-M model is very sensitive to local factors and moderately to less sensitive to global parameters, according to a manual examination of the model's sensitivity to both local and global parameters. The model results were calibrated using 18 years' mean monthly river flow data (1996–2017) with correlation of R2=0.86, Nash-Sutcliffe Efficiency (NSE) =0.85 between observed surface discharge and simulated surface runoff. Additionally, the recharge simulation of the model was validated with estimated recharge using baseflow separation, digital recursive method with a correlation of R2=0.86, Nash-Sutcliffe Efficiency (NSE) =0.79.

The study findings indicated that the watershed loses a minimum and maximum of 790.55 and 3609.78mm of water by evapotranspiration each year, with an average of 961.6mm. This represents for 49% of total rainfall in the watershed. The yearly groundwater recharge of the Dabana watershed ranges from 0 to 849.74mm as a minimum and maximum value respectively, with a mean of 478.12mm and standard deviation of 122.77. The computed mean annual groundwater recharge amounts to 1,542,418,352m3/year which is a corresponding figure in terms of volume. This is equal to 24% of the total yearly precipitation. The annual runoff value in the Dabana watershed is minimum at 189.5mm and maximum at 1765.4mm, with an average of 532.8 mm. The average value corresponds to nearly 27% of the yearly total precipitation in the watershed.

The WEAP model was successfully used to model the optimum allocation of available water resources for different water users. In the current research, the hydrological model results of SWAT for the Dabena Watershed are employed as the data input to the WEAP model to analyze the interplay of water demand and supply across various scenarios. The demand assessment was conducted across various sectors, including domestic, irrigation and industrial water use. In this study, six scenarios were developed to see the changes on supply delivered and unmet demands for various water demand sites.

On the baseline scenario, the unmet demand evaluated on irrigation and industrial demand sites accounts 69.05 BCM and 0.06MCM respectively. On SC2, the total future water demand for irrigation demand site is increased from 77.74BCM to be 91.04BCM, compared Baseline Scenario.

The third scenario was Groundwater use and this scenario revealed that the implementation of this management option will result a 100% reduction for all irrigation demands because the groundwater nodes were connected to irrigation demand. Unmet demands in baseline and irrigation expansion scenarios reduced by 99.9% in groundwater use and combined impact scenarios on irrigation demand sites.

In the irrigation priority scenario, the total unmet demand for domestic increased significantly in the baseline scenario rising from 7.25MCM to 267.83MCM. Conversely, the unmet demand for irrigation demand sites decreased slightly from 69.05BCM to 67. 63BCM. Lastly, in the EFR priority scenario, the unmet demand for domestic water consumption was increased from 7.25MCM in the baseline scenario and it increased to 45.39MCM. Generally, Different recommended water allocation processes were discussed to help understand the existent shortages and excesses of water within the study area.

In conclusion, this study achieved its goals and managed to solve the watershed water conflicts by integrating hydrological models. In order to meet the objectives, the study used WetSpass-M model to map spatio-temporal groundwater recharge, SWAT to simulate daily streamflow and WEAP to merge that water supply information with human water demand. This overall approach seems to solve the main issue in the Dabena watershed; a serious dry season water shortage caused by an upstream industrial site that diverts big volumes from the upper river, so downstream towns and irrigation sites end up short of water. And by calculating the timing and exact volume of that shortage, the research goes beyond simple assumptions. It also evaluates updated management ideas that prioritize domestic water first and it shows with some clarity how much water can be allocated safely to the brewery plus the irrigation sites without basically draining the downstream communities and affecting the ecosystem. In the end, the study gives local water bureaus a straightforward, data guided instrument for more equitable allocation and to reduce seasonal conflicts.

5.2 RECOMMENDATION

The findings of this study can be considered as an initial study of water resource management in Dabena watershed. based on the findings from the two hydrological model SWAT and WetSpass-M, Dabena watershed have sufficient water resources if it is distributed properly and fairly among different water users. Therefore, the following recommendation have been made.

- This study will be useful as a basis for future research as well as planning, development, and management activities related to water resources.
- Establish a well spatially distributed groundwater monitoring stations(boreholes) to understand seasonal fluctuation of groundwater and enhance groundwater quantification in the watershed.
- Strategies that increase water usage efficiency, such as the combined use of surface and groundwater (SC3), should serve as the foundation for decisions about water resource development projects and management options.
- Surface water harvesting to enhance water resources and to mitigate water shortage.
- Adopt efficient irrigation technologies together with distribution infrastructure upgrades to achieve minimum water losses while delivering maximum water productivity across all sectors.
- Integrate updated data and emerging trends to refine future water demand projections ensuring that sectoral demands are anticipated and managed effectively.
- Involve local communities, farmers, industries and policymakers in allocation decisions to improve acceptance and compliance.
- Further study should be conducted focused on improving model accuracy by addressing data limitations, such as those related to climate and streamflow and enhance the parametrization of surface water-groundwater interaction.

REFERENCES

(GSE), G. S. o. E. (2006). Hydrogeology and Hydrochemisry of Nekemte and Arjo area. Sheet Number: NC37-9 and NC37-13.

Abbaspour, K. C., Rouholahnejad, E., Vaghefi, S., Srinivasan, R., Yang, H., & Kløve, B. (2015). A continental-scale hydrology and water quality model for Europe: Calibration and uncertainty of a high-resolution large-scale SWAT model. *Journal of Hydrology*, *524*, 733-752.

Abdollahi, K., Bashir, I., Verbeiren, B., Harouna, M. R., Van Griensven, A., Huysmans, M., & Batelaan, O. (2017). A distributed monthly water balance model: formulation and application on Black Volta Basin. *Environmental Earth Sciences*, *76*(5), 198.

Abu-Saleem, A., Al-Zu'bi, Y., Rimawi, O., Al-Zu'bi, J., & Alouran, N. (2010). Estimation of water balance components in the Hasa basin with GIS based WetSpass model.

Adgolign, T. B., Rao, G. S., & Abbulu, Y. (2016). WEAP modeling of surface water resources allocation in Didessa Sub-Basin, West Ethiopia. *Sustainable Water Resources Management*, *2*(1), 55-70.

Adgolign, T. B., Rao, G. V. R. S., & Abbulu, Y. (2015). WEAP modeling of surface water resources allocation in Didessa Sub-Basin, West Ethiopia. *Sustainable Water Resources Management*, *2*(1), 55-70. https://doi.org/10.1007/s40899-015-0041-4

Agarwal, A., de los Angeles, M. S., Bhatia, R., Chéret, I., Davila-Poblete, S., Falkenmark, M., Villarreal, F. G., Jønch-Clausen, T., Kadi, M. A., & Kindler, J. (2000). *Integrated water resources management*. Global water partnership Stockholm.

Agarwal, A., Patil, J. P., Goyal, V., & Jayakumar, K. (2018). A review on WEAP21 model for managing water resources. *J Indian Water Resour Soc*, *38*(4), 38-44.

Ahmed, R., & Sajjad, H. (2018). Analyzing factors of groundwater potential and its relation with population in the Lower Barpani Watershed, Assam, India. *Natural Resources Research*, *27*(4), 503-515.

Akanksha D Salvi, R. T., PM Ingle, ST Patil, SS More, Aniket A Kale. (2024). Surface water assessment methods and tools for water. *International Journal of Research in Agronom*, 7(12): 113-120.

Al Kuisi, M., & El-Naqa, A. (2013). GIS based spatial groundwater recharge estimation in the Jafr basin, Jordan: Application of WetSpass models for arid regions. *Revista mexicana de ciencias geológicas*, *30*(1), 96-109.

Alamanos, A., & Koundouri, P. (2024). Future Challenges of Water Resources Management. In *Elgar Encyclopedia of Water Policy, Economics and Management* (pp. 87-93). Edward Elgar Publishing.

Allen, R. G., Pereira, L. S., Raes, D., & Smith, M. (1998). Crop evapotranspiration-Guidelines for computing crop water requirements-FAO Irrigation and drainage paper 56. *Fao, Rome*, *300*(9), D05109.

Alley, W. M., & Leake, S. A. (2004). The journey from safe yield to sustainability. *Groundwater*, *42*(1), 12-16.

Amarasinghe, U. A., & Smakhtin, V. (2014). *Global water demand projections: past, present and future* (Vol. 156). IWMI.

Amiri, M., Salem, A., & Ghzal, M. (2022). Spatial-temporal water balance components estimation using integrated GIS-based Wetspass-M model in Moulouya Basin, Morocco. *ISPRS International Journal of Geo-Information*, *11*(2), 139.

Andualem, T. G., & Demeke, G. G. (2019). Groundwater potential assessment using GIS and remote sensing: A case study of Guna tana landscape, upper blue Nile Basin, Ethiopia. *Journal of Hydrology: Regional Studies*, *24*, 100610.

Arjoon, D., Tilmant, A., & Herrmann, M. (2016). Sharing water and benefits in transboundary river basins. *Hydrology and Earth System Sciences*, *20*(6), 2135-2150.

Armas Vargas, F., Nava, L. F., Gómez Reyes, E., Olea-Olea, S., Rojas Serna, C., Sandoval Solís, S., & Meza-Rodríguez, D. (2023). Water and environmental resources: A multi-criteria assessment of management approaches. *Water*, *15*(16), 2991.

Arnold, J. G., Moriasi, D. N., Gassman, P. W., Abbaspour, K. C., White, M. J., Srinivasan, R., Santhi, C., Harmel, R., Van Griensven, A., & Van Liew, M. W. (2012). SWAT: Model use, calibration, and validation. *Transactions of the ASABE*, *55*(4), 1491-1508.

Arnold, J. G., Srinivasan, R., Muttiah, R. S., & Williams, J. R. (1998). Large area hydrologic modeling and assessment part I: model development 1. *JAWRA Journal of the American Water Resources Association*, *34*(1), 73-89.

Ashaolu, E., Olorunfemi, J., Ifabiyi, I., Abdollahi, K., & Batelaan, O. (2020). Spatial and Temporal Recharge Estimation of the Basement Complex in Nigeria. *West Africa. Journal of Hydrology*.

Ashaolu, E. D., Olorunfemi, J. F., Ifabiyi, I. P., Abdollahi, K., & Batelaan, O. (2020). Spatial and temporal recharge estimation of the basement complex in Nigeria, West Africa. *Journal of Hydrology: Regional Studies*, *27*, 100658.

Asrade, T. M. (2024). Groundwater potential mapping and its sustainable management using AHP and FR models in the Jedeb watershed, Upper Blue Nile Basin, Ethiopia. *Water Supply*, *24*(10), 3617-3638.

Asrade, T. M., Tadesse, K. B., Kerebih, M. S., & Ayinalem, S. B. (2024). Assessment of Groundwater Recharge Using WetSpass-M and MODFLOW Coupling in Jedeb Watershed, Upper Blue Nile Basin, Ethiopia. *Air, Soil and Water Research*, *17*, 11786221241253325.

Awasthi, N., & Kumar, M. (2021). Soil and water assessment tool (SWAT) modelling: a review. *International Journal of Innovative Science and Research Technology*, *6*(8), 1084-1087.

Baker, A. T., Olla, O. O,Bello, L, A,Ilevbaoje, O. O,Salman, S. I and Nurudeen, H. (2024). A Review of Water Resources Evaluation using GIS and Remote Sensing. *World Journal of Sensors Network Research*.

Balata, E. E., Pinto, H., & da Silva, M. M. (2022). Latent dimensions between water use and socio-economic development: A global exploratory statistical analysis. *Regional Sustainability*, *3*(3), 269-280.

Batelaan, O., & De Smedt, F. (2001a). WetSpass: a flexible, GIS based, distributed recharge methodology for regional groundwater. Impact of Human Activity on Groundwater Dynamics: Proceedings of an International Symposium (Symposium S3) Held During the Sixth Scientific Assembly of the International Association of Hydrological Sciences (IAHS) at Maastricht, The Netherlands, from 18 to 27 July 2001,

Batelaan, O., & De Smedt, F. (2001b). WetSpass: a flexible, GIS based, distributed recharge methodology for regional groundwater modelling. *IAHS PUBLICATION*, 11-18.

Batelaan, O., & De Smedt, F. (2007). GIS-based recharge estimation by coupling surface–subsurface water balances. *Journal of Hydrology*, *337*(3-4), 337-355.

BCEOM. (1998). Abbay River Basin Integrated Development Master Plan Project. Phase II Report. Ministry of Water Resources, Addis Ababa, Ethiopia.

Benini, L., Antonellini, M., Laghi, M., & Mollema, P. N. (2016). Assessment of water resources availability and groundwater salinization in future climate and land use change scenarios: a case study from a coastal drainage basin in Italy. *Water Resources Management*, *30*, 731-745.

Berhanu, K. G., & Hatiye, S. D. (2020). Identification of groundwater potential zones using proxy data: case study of Megech Watershed, Ethiopia. *Journal of Hydrology: Regional Studies*, *28*, 100676.

Bessedik, M., Abdelbaki, C., Tiar, S. M., Badraoui, A., Megnounif, A., Goosen, M., Mourad, K. A., Baig, M. B., & Alataway, A. (2023). Strategic decision-making in sustainable water management using demand analysis and the water evaluation and planning model. *Sustainability*, *15*(22), 16083.

Bezerra, M. O., Vollmer, D., Acero, N., Marques, M. C., Restrepo, D., Mendoza, E., Coutinho, B., Encomenderos, I., Zuluaga, L., & Rodríguez, O. (2022). Operationalizing integrated water resource management in Latin America: insights from application of the Freshwater Health Index. *Environmental Management*, *69*(4), 815-834.

Biswas, A. K. (2004). Integrated water resources management: a reassessment.

Boitt, M., Khayasi, P., & Wambua, C. (2023). Assessment of Groundwater Potential and Prediction of the Potential Trend up to 2042 Using GIS-Based Model and Remote Sensing Techniques for Kiambu County. *International Journal of Geosciences*, *14*(10), 1036-1063.

Cai, X., & Rosegrant, M. W. (2002). Global water demand and supply projections: part 1. A modeling approach. *Water International*, *27*(2), 159-169.

Cooper, R. J., & Hiscock, K. M. (2025). Groundwater resources: Challenges & solutions. *Cambridge Prisms: Water*, *3*, e1.

Daniel, H. (2024). Modeling surface water potential using the SWAT model combined with principal component analysis in the ungauged Gelana watershed, Ethiopia. *Journal of Water and Climate Change*, *15*(2), 703-732.

Daniel, H., & Abate, B. (2022). Effect of climate change on streamflow in the Gelana watershed, Rift valley basin, Ethiopia. *Journal of Water and Climate Change*, *13*(5), 2205-2232.

Das, A. (2025). Water quality assessment and geospatial techniques for the delineation of surface water potential zones: A data-driven approach using machine learning models. *Desalination and Water Treatment*, 101461.

Dawana, Y. (2025). Groundwater Potential Zone Mapping In Ajora-Woybo Watershed, OMO Basin, Southern, Ethiopia, Using GIS, RS & AHP Techniques.

Dawit, M., Olika, B. D., Muluneh, F. B., Leta, O. T., & Dinka, M. O. (2020). Assessment of surface irrigation potential of the Dhidhessa River Basin, Ethiopia. *Hydrology*, *7*(3), 68.

Debebe, D., Seyoum, T., Tessema, N., & Ayele, G. T. (2023). Modeling rainfall-runoff estimation and assessing water harvesting zone for irrigation practices in Keleta watershed, Awash river basin, Ethiopia. *Geocarto International*, *38*(1), 2236582.

Dereje, B., & Nedaw, D. (2019). Groundwater recharge estimation using WetSpass modeling in Upper Bilate Catchment, southern Ethiopia. *Momona Ethiopian Journal of Science*, *11*(1), 37-51.

Dessu, S. B., Melesse, A. M., Bhat, M. G., & McClain, M. E. (2014). Assessment of water resources availability and demand in the Mara River Basin. *Catena*, *115*, 104-114.

Dibaba, W. T., Demissie, T. A., & Miegel, K. (2020). Watershed hydrological response to combined land use/land cover and climate change in highland Ethiopia: Finchaa catchment. *Water*, *12*(6), 1801.

Dinar, A. (2024). Challenges to water resource management: The role of economic and modeling approaches. *Water*, *16*(4), 610.

El-Rawy, M., Zlotnik, V. A., Al-Raggad, M., Al-Maktoumi, A., Kacimov, A., & Abdalla, O. (2016). Conjunctive use of groundwater and surface water resources with aquifer recharge by treated wastewater: evaluation of management scenarios in the Zarqa River Basin, Jordan. *Environmental Earth Sciences*, *75*(15). https://doi.org/10.1007/s12665-016-5946-1

Faisal, I. M., Young, R. A., & Warner, J. W. (1997). Integrated economic-hydrologic modelling for groundwater basin management. *International Journal of Water Resources Development*, *13*(1), 21-34.

Farriansyah, A. M., Juwono, P. T., Suhartanto, E., & Dermawan, V. (2018). Water allocation computation model for river and multi-reservoir system with sustainability-efficiency-equity criteria. *Water*, *10*(11), 1537.

Farrokhzadeh, S., Hashemi Monfared, S. A., Azizyan, G., Sardar Shahraki, A., Ertsen, M. W., & Abraham, E. (2020). Sustainable water resources management in an arid area using a coupled optimization-simulation modeling. *Water*, *12*(3), 885.

Fenta, A. A., Kifle, A., Gebreyohannes, T., & Hailu, G. (2015). Spatial analysis of groundwater potential using remote sensing and GIS-based multi-criteria evaluation in Raya Valley, northern Ethiopia. *Hydrogeology Journal*, *23*(1), 195.

Ferdowsi, A., Piadeh, F., Behzadian, K., Mousavi, S.-F., & Ehteram, M. (2024). Urban water infrastructure: A critical review on climate change impacts and adaptation strategies. *Urban Climate*, *58*, 102132.

Gassman, P. W., Sadeghi, A. M., & Srinivasan, R. (2014). Applications of the SWAT model special section: overview and insights. *Journal of Environmental Quality*, *43*(1), 1-8.

Gebreslassie, H., Berhane, G., Gebreyohannes, T., Hagos, M., Hussien, A., & Walraevens, K. (2025). Water Harvesting and Groundwater Recharge: A Comprehensive Review and Synthesis of Current Practices. *Water*, *17*(7), 976.

Gebreyohannes, T., De Smedt, F., Walraevens, K., Gebresilassie, S., Hussien, A., Hagos, M., Amare, K., Deckers, J., & Gebrehiwot, K. (2013). Application of a spatially distributed water balance model for assessing surface water and groundwater resources in the Geba basin, Tigray, Ethiopia. *Journal of Hydrology*, *499*, 110-123.

Gedefaw, M., Wang, H., Yan, D., Qin, T., Wang, K., Girma, A., Batsuren, D., & Abiyu, A. (2019). Water Resources Allocation Systems under Irrigation Expansion and Climate Change Scenario in Awash River Basin of Ethiopia. *Water*, *11*(10). https://doi.org/10.3390/w11101966

Genjebo, M. G., Kemal, A., & Nannawo, A. S. (2023). Assessment of surface water resource and allocation optimization for diverse demands in Ethiopia's upper Bilate Watershed. *Heliyon*, *9*(10).

Gleeson, T., Wada, Y., Bierkens, M. F., & Van Beek, L. P. (2012). Water balance of global aquifers revealed by groundwater footprint. *Nature*, *488*(7410), 197-200.

Golmohammadi, G., Prasher, S., Madani, A., & Rudra, R. (2014). Evaluating three hydrological distributed watershed models: MIKE-SHE, APEX, SWAT. *Hydrology*, *1*(1), 20-39.

Grigg, N. S. (2025). Integrated Water Resources Management After 2030: An Agenda for Educators. *Water*, *17*(2), 189.

GSE, G. S. o. E. (2000). Hydrogeology and Hydrochemisry of Nekemte and Arjo area. Sheet Number: NC37-9 and NC37-13.

GSE, G. S. o. E. (2006). Hydrogeology and Hydrochemisry of Nekemte and Arjo area. Sheet Number: NC37-9 and NC37-13.

Gupta, R., Yan, K., Singh, T., & Mo, D. (2020). Domestic and international drivers of the demand for water resources in the context of water scarcity: A cross-country study. *Journal of risk and financial management*, *13*(11), 255.

Hadri, A., Saidi, M. E. M., El Khalki, E. M., Aachrine, B., Saouabe, T., & Elmaki, A. A. (2022). Integrated water management under climate change through the application of the WEAP model in a Mediterranean arid region. *Journal of Water and Climate Change*, *13*(6), 2414-2442.

Hagereselam, T. A. a. Y. (2005). Engineerin geological and hydrogeological mapping of the Chewaka-Arjo area. Addis Ababa: Geological Survey of Ethiopia.

Hailu, R., Tolossa, D., & Alemu, G. (2018). Integrated Water Resources Management as a System Approach for Water Security: Evidence from the Awash River Basin of Ethiopia. *Ethiopian Journal of the Social Sciences and Humanities*, *14*(1), 53-82.

Hargreaves, G. H., & Samani, Z. A. (1982). Estimating potential evapotranspiration. *Journal of the irrigation and Drainage Division*, *108*(3), 225-230.

Harmancioglu, N. B., Barbaros, F., & Cetinkaya, C. P. (2013). Sustainability issues in water management. *Water Resources Management*, *27*, 1867-1891.

Hussen, B., Mekonnen, A., & Pingale, S. M. (2018). Integrated water resources management under climate change scenarios in the sub-basin of Abaya-Chamo, Ethiopia. *Modeling Earth Systems and Environment*, *4*, 221-240.

Irvine, D. J., Singha, K., Kurylyk, B. L., Briggs, M. A., Sebastian, Y., Tait, D. R., & Helton, A. M. (2024). Groundwater-Surface water interactions research: Past trends and future directions. *Journal of Hydrology*, *644*, 132061.

Jain, S., Ramesh, D., Trivedi, M. C., & Edla, D. R. (2023). Evaluation of metaheuristic optimization algorithms for optimal allocation of surface water and groundwater resources for crop production. *Agricultural Water Management*, *279*, 108181.

Janjić, J., & Tadić, L. (2023). Fields of application of SWAT hydrological model—a review. *Earth*, *4*(2), 331-344.

Jiri Sima, Z. Y. a. A. G. (2018). Hydrogeological and Hydrochemical Maps of Arjo (NC 37-13) map sheet.

Kahsay, G. H. (2008). Groundwater resource assessment through distributed steady-state flow modeling, Aynalem Wellfield, Mekele, Ethiopia.

Kahsay, G. H., Gebreyohannes, T., Gebremedhin, M. A., Gebrekirstos, A., Birhane, E., Gebrewahid, H., & Welegebriel, L. (2019). Spatial groundwater recharge estimation in Raya basin, Northern Ethiopia: an approach using GIS based water balance model. *Sustainable Water Resources Management*, *5*(2), 961-975.

Karlović, I., Marković, T., Vujnović, T., & Larva, O. (2021). Development of a hydrogeological conceptual model of the Varaždin alluvial aquifer. *Hydrology*, *8*(1), 19.

Kazemi, M., Bozorg-Haddad, O., Fallah-Mehdipour, E., & Chu, X. (2021). Optimal water resources allocation in transboundary river basins according to hydropolitical consideration. *Environment, Development and Sustainability*, *24*(1), 1188-1206. https://doi.org/10.1007/s10668-021-01491-0

Kebede, A. B., Tufa, F. G., Kitessa, W. M., Gudeta, B. G., Debela, S. K., Yenehun, A., Feyessa, F. F., Hermans, T., & Walraevens, K. (2025). Estimation of Groundwater Recharge in the Volcanic Aquifers in a Tropical Climate, Southwestern Ethiopia: Insights from Water Table Fluctuation and Chloride Mass Balance Methods. *Water*, *17*(21), 3043.

Kedir, E. G. (2023). Ground water potential assessment and sustainable management. *Environmental monitoring and assessment*, *195*(7), 891.

Kisiki, C. P., Ayenew, T., & Mjemah, I. C. (2023). Estimation of groundwater recharge variability using a GIS-based distributed water balance model in Makutupora basin, Tanzania. *Heliyon*, *9*(4).

Leong, W., & Lai, S. (2017). Application of water evaluation and planning model for integrated water resources management: case study of Langat River Basin, Malaysia. IOP Conference Series: Materials Science and Engineering,

Li, P., & Wu, J. (2023). Water resources and sustainable development. In (Vol. 16, pp. 134): MDPI.

Liu, Y., Zheng, H., & Zhao, J. (2024). Reframing water demand management: a new co-governance framework coupling supply-side and demand-side solutions toward sustainability. *Hydrology and Earth System Sciences*, *28*(10), 2223-2238.

Loukas, A., Mylopoulos, N., & Vasiliades, L. (2006). A Modeling System for the Evaluation of Water Resources Management Strategies in Thessaly, Greece. *Water Resources Management*, *21*(10), 1673-1702. https://doi.org/10.1007/s11269-006-9120-5

Malik, M. I., AL-Shammary, S. H., & AL-Hamzawy, H. M. (2016). Morphometric analysis of al-Chabab river basin east of Iraq using Remote Sensing and GIS techniques. *International Journal of Scientific Engineering and Research (IJSER), ISSN (Online)*, 2347-3878.

Mekonnen, D. F., Duan, Z., Rientjes, T., & Disse, M. (2018). Analysis of combined and isolated effects of land-use and land-cover changes and climate change on the upper Blue Nile River basin's streamflow. *Hydrology and Earth System Sciences*, *22*(12), 6187-6207.

Mekuria, E. T. (2022). Assessment of Water Balance of Deme Watershed, Omo-Gibe Basin, Ethiopia Using SWAT Model and ARC-GIS for Water Resources Management. *Journal of Water Resources and Ocean Science*, *11*(6), 86-98.

Melese, T., & Belay, T. (2022). Groundwater potential zone mapping using analytical hierarchy process and GIS in Muga Watershed, Abay Basin, Ethiopia. *Global Challenges*, *6*(1), 2100068.

Meresa, E., & Taye, G. (2019). Estimation of groundwater recharge using GIS-based WetSpass model for Birki watershed, the eastern zone of Tigray, Northern Ethiopia. *Sustainable Water Resources Management*, *5*(4), 1555-1566.

Merga, D. D., Adeba, D., Regasa, M. S., & Leta, M. K. (2022). Evaluation of surface water resource availability under the impact of climate change in the Dhidhessa Sub-Basin, Ethiopia. *Atmosphere*, *13*(8), 1296.

Mesene, I. K. M. (2020). Challenges, Experiences and Opportunities of Water Resource Management in Ethiopia.

Mirdashtvan, M., Najafinejad, A., Malekian, A., & Sa'doddin, A. (2021). Sustainable water supply and demand management in semi-arid regions: optimizing water resources allocation based on RCPs scenarios. *Water Resources Management*, *35*, 5307-5324.

Moisa, M. B., Merga, B. B., & Gemeda, D. O. (2022). Land suitability evaluation for surface irrigation using geographic information system: a case study in Didessa River Sub-Basin, Western Ethiopia. *Sustainable Water Resources Management*, *8*(3), 82.

Moriasi, D. N., Arnold, J. G., Van Liew, M. W., Bingner, R. L., Harmel, R. D., & Veith, T. L. (2007). Model evaluation guidelines for systematic quantification of accuracy in watershed simulations. *Transactions of the ASABE*, *50*(3), 885-900.

Mukherjee, A., Jha, M. K., Kim, K.-W., & Pacheco, F. A. (2024). Groundwater resources: challenges and future opportunities. *Scientific Reports*, *14*(1), 28540.

Mukhtyar Singh, D. A. K. (2024). Evaluation and Administration of Water Resources: A Comprehensive Review. *International Journal for Multidisciplinary Research (IJFMR)*.

Mulie Asrade, T. (2024). Application of coupled WetSpass-M and MODFLOW models to estimate spatial–temporal water balance components in the Chemoga watershed, Ethiopia. *Water Practice & Technology*, *19*(9), 3833-3854.

Munyaneza, O., Mukubwa, A., Maskey, S., Uhlenbrook, S., & Wenninger, J. (2014). Assessment of surface water resources availability using catchment modelling and the results of tracer studies in the mesoscale Migina Catchment, Rwanda. *Hydrology and Earth System Sciences*, *18*(12), 5289-5301.

Nancarrow, B., & Syme, G. (2004). Fairness principles in allocating water: integrating views of different agents.

Nannawo, A. S., Lohani, T. K., & Eshete, A. A. (2021). Exemplifying the Effects Using WetSpass Model Depicting the Landscape Modifications on Long-Term Surface and Subsurface Hydrological Water Balance in Bilate Basin, Ethiopia. *Advances in Civil Engineering*, *2021*(1), 7283002.

Nannawo, A. S., Lohani, T. K., Eshete, A. A., & Kaloop, M. (2021). Exemplifying the Effects Using WetSpass Model Depicting the Landscape Modifications on Long-Term Surface and Subsurface Hydrological Water Balance in Bilate Basin, Ethiopia. *Advances in Civil Engineering*, *2021*, 1-20. https://doi.org/10.1155/2021/7283002

Nauges, C., & Whittington, D. (2010). Estimation of water demand in developing countries: An overview. *The World Bank Research Observer*, *25*(2), 263-294.

Ndayizeye, A. (2022). *Application of WEAP model for assessment of current and future water resources availability and demands of Mukungwa catchment, Rwanda* University of Rwanda (College of science and Technology)].

Ndubuisi, O. G., & FNisafetyE, F. (2025). Integrated Water Resource Management in a Changing Climate: Assessing Adaptive Strategies, Technologies, and Policies for Resilient Water System.

Ojha, R., Ramadas, M., & Govindaraju, R. S. (2015). Current and future challenges in groundwater. I: Modeling and management of resources. *Journal of Hydrologic Engineering*, *20*(1), A4014007.

Pengxiao, Z., Zhang, Q., Zhang, F., & Li, Z. (2025). Sustainable Water Resource Management: Challenges and Opportunities. *Environments*, *12*(8), 268.

Qian, Y. (2016). Sustainable management of water resources. *Engineering*, *2*(1), 23-25.

Rahaman, M. M., & Varis, O. (2005). Integrated water resources management: evolution, prospects and future challenges. *Sustainability: Science, Practice, & Policy*, *1*(1).

Rahi, K. A., Al-Madhhachi, A.-S. T., & Al-Hussaini, S. N. (2019). Assessment of surface water resources of eastern Iraq. *Hydrology*, *6*(3), 57.

Regasa, M. S., & Nones, M. (2023). SWAT model-based quantification of the impact of land use land cover change on sediment yield in the Fincha watershed, Ethiopia. *Frontiers in Environmental Science*, *11*, 1146346.

Robert G., B. P. G. (2014). TOTAL ESTIMATED RECOVERABLE STORAGE FOR THE LEONA GRAVEL IN MEDINA COUNTY FOR GROUNDWATER MANAGEMENT AREAS 1 0 AND 13. *Texas Water Development Board Groundwater Resources Division*, (512) 936-0870.

Rosegrant, M. W., & Cai, X. (2002). Global water demand and supply projections: part 2. Results and prospects to 2025. *Water International*, *27*(2), 170-182.

Ruidas, D., Pal, S. C., Islam, A. R. M. T., & Saha, A. (2021). Characterization of groundwater potential zones in water-scarce hardrock regions using data driven model. *Environmental Earth Sciences*, *80*(24). https://doi.org/10.1007/s12665-021-10116-8

Sajil Kumar, P. J., Schneider, M., & Elango, L. (2021). The state-of-the-art estimation of groundwater recharge and water balance with a special emphasis on India: A critical review. *Sustainability*, *14*(1), 340.

Santhi, C., Arnold, J. G., Williams, J. R., Dugas, W. A., Srinivasan, R., & Hauck, L. M. (2001). Validation of the swat model on a large rwer basin with point and nonpoint sources 1. *JAWRA Journal of the American Water Resources Association*, *37*(5), 1169-1188.

sekar, A., Valliammai, A., Nagarajan, M., Sivakumar, S., Baskar, M., & Sujitha, E. (2024). Conjunctive use in water resource management: current trends and future directions. *Water Supply*, *24*(11), 3881-3904.

Setegn, S. G., Srinivasan, R., & Dargahi, B. (2008). Hydrological modelling in the Lake Tana Basin, Ethiopia using SWAT model. *The open hydrology Journal*, *2*(1), 49-62.

Shabani, M., Masoumi, Z., & Rezaei, A. (2022). Assessment of groundwater potential using multi-criteria decision analysis and geoelectrical surveying. *Geo-Spatial Information Science*, *25*(4), 600-618.

Shiva Dwivedi, M. K., Pradeep Kumar Singh, Brij Gopal. (2024). SWAT model applications in hydrology: A systematic review. *International Journal of Advanced Biochemistry Researc*, 603-607.

Sieber, J., & Purkey, D. (2009). WEAP21–A Demand-, Priority-, and Preference-Driven Water Planning Model: Part 2, Aiding Freshwater Ecosystem Service Evaluation.

Sieber, J., & Purkey, D. (2015). Water evaluation and planning system user guide. *Stockholm Environment Institute, US Center*, *11*.

Sileshi, M. (2006). Groundwater Resource evaluation and aquifer productivity classification in volcanic terrains of Ethiopia. Addis Ababa: Geological Survey of Ethiopia.

Speed, R., Yuanyuan, L., Zhiwei, Z., Le Quesne, T., & Pegram, G. (2013). *Basin water allocation planning: Principles, procedures and approaches for basin allocation planning*. Asian Development Bank, GIWP, UNESCO, and WWF-UK.

Tefera, G. W., Dile, Y. T., Srinivasan, R., Baker, T., & Ray, R. L. (2023). Hydrological modeling and scenario analysis for water supply and water demand assessment of Addis Ababa city, Ethiopia. *Journal of Hydrology: Regional Studies*, *46*, 101341.

Todd, D. K., & Mays, L. W. (2004). *Groundwater hydrology*. John Wiley & Sons.

Tofu, D. A. (2025). Prediction of future climate variability and its implications for rainfed agriculture in the Guder watershed, Ethiopia. *Scientific African*, *27*, e02531.

Tolche, A. D. (2021). Groundwater potential mapping using geospatial techniques: a case study of Dhungeta-Ramis sub-basin, Ethiopia. *Geology, Ecology, and Landscapes*, *5*(1), 65-80.

Touseef, M., Chen, L., & Yang, W. (2021). Assessment of surface water availability under climate change using coupled SWAT-WEAP in Hongshui River Basin, China. *ISPRS International Journal of Geo-Information*, *10*(5), 298.

Tramblay, Y., Jarlan, L., Hanich, L., & Somot, S. (2018). Future scenarios of surface water resources availability in North African dams. *Water Resources Management*, *32*, 1291-1306.

Vazquez-Amábile, G., & Engel, B. (2005). Use of SWAT to compute groundwater table depth and streamflow in the Muscatatuck River watershed. *Transactions of the ASAE*, *48*(3), 991-1003.

Wang, G., Kumar, S., Huang, Z., & Liu, R. (2024). Water resource management and policy evaluation in Middle Eastern countries: Achieving sustainable development goal 6. *Desalination and Water Treatment*, *320*, 100829.

Wang, J., Hou, B., Jiang, D., Xiao, W., Wu, Y., Zhao, Y., Zhou, Y., Guo, C., & Wang, G. (2016). Optimal Allocation of Water Resources Based on Water Supply Security. *Water*, *8*(6). https://doi.org/10.3390/w8060237

Wang, J. F., Cheng, G. D., Gao, Y. G., Long, A. H., Xu, Z. M., Li, X., Chen, H., & Barker, T. (2008). Optimal water resource allocation in arid and semi-arid areas. *Water Resources Management*, *22*, 239-258.

Wang, Z., Yang, J., Deng, X., & Lan, X. (2015). Optimal Water Resources Allocation under the Constraint of Land Use in the Heihe River Basin of China. *Sustainability*, *7*(2), 1558-1575. https://doi.org/10.3390/su7021558

Wicaksono, A. A., Suprapti, A., Sunarti, S., & Ariyanti, V. (2024). Implementing IWRM approaches with climate-change adaptation on riverside slum upgrading, Indonesia. *Journal of Water and Climate Change*, *15*(7), 3056-3073.

Wikipedia, c. (2022). Climate of Ethiopia. *Wikipedia*.

Woldu, T. T., Ayenew, T., Baychken, B., & Birhanu, B. (2024). Spatiotemporal recharge estimation in the upper Awash sub-basin, central Ethiopia. *Hydrology Research*, *55*(7), 711-727.

Wurbs, R. A. (2005). Texas water availability modeling system. *Journal of Water Resources Planning and Management*, *131*(4), 270-279.

Yang, D., Yang, Y., & Xia, J. (2021). Hydrological cycle and water resources in a changing world: A review. *Geography and Sustainability*, *2*(2), 115-122.

Yang, Z., Wang, Z., Yao, Z., & Bao, X. (2024). Optimal allocation planning of regional water resources with multiple objectives using improved firefly algorithm. *AQUA—Water Infrastructure, Ecosystems and Society*, *73*(4), 746-770.

Yao, A. B., Mangoua, O. M. J., Georges, E. S., Kane, A., & Goula, B. T. A. (2021). Using "Water Evaluation and Planning"(WEAP) model to simulate water demand in Lobo watershed (Central-Western Cote d'Ivoire). *Journal of Water Resource and Protection*, *13*(03), 216.

Yates, D., Sieber, J., Purkey, D., & Huber-Lee, A. (2005a). WEAP21—A Demand-, Priority-, and Preference-Driven Water Planning Model. *Water International*, *30*(4), 487-500. https://doi.org/10.1080/02508060508691893

Yates, D., Sieber, J., Purkey, D., & Huber-Lee, A. (2005b). WEAP21—A demand-, priority-, and preference-driven water planning model: part 1: model characteristics. *Water International*, *30*(4), 487-500.

Yenehun, A., Dessie, M., Nigate, F., Belay, A. S., Azeze, M., Van Camp, M., Taye, D. F., Kidane, D., Adgo, E., & Nyssen, J. (2022). Spatial and temporal simulation of groundwater recharge and cross-validation with point estimations in volcanic aquifers with variable topography. *Journal of Hydrology: Regional Studies*, *42*, 101142.

Zarei, M., Ghazavi, R., Vali, A., & Abdollahi, K. (2016). Estimating groundwater recharge, evapotranspiration and surface runoff using land-use data: a case study in northeast Iran. Biol. Forum Int. J,

Zhang, D., Xie, X., Wang, T., Wang, B., & Pei, S. (2022). Research on water resources allocation system based on rational utilization of brackish water. *Water*, *14*(6), 948.

Zhang, F., Wu, Z., Di, D., & Wang, H. (2023a). Water resources allocation based on water resources supply-demand forecast and comprehensive values of water resources. *Journal of Hydrology: Regional Studies*, *47*. https://doi.org/10.1016/j.ejrh.2023.101421

Zhang, F., Wu, Z., Di, D., & Wang, H. (2023b). Water resources allocation based on water resources supply-demand forecast and comprehensive values of water resources. *Journal of Hydrology: Regional Studies*, *47*, 101421.

Zhang, S., Fang, G., Zhang, D., Ju, M., & Zhong, H. (2023). Water resources optimal allocation model for coordinating regional multi-level water resources managers' interests. *Frontiers in Environmental Science*, *11*, 1152296.