AFRICA CENTER OF EXCELLENCE FOR WATE MANAGEMENT

ADDIS ABABA UNIVRSITY

Numerical Groundwater Flow modelling of Gur Catchment, Central Ethiopia

By:

Urgessa Hirpa

A thesis submitted to the Africa Center of Excellence for Water Management, Addis Ababa University in partial fulfillment of the requirements for the Degree of Master of Science in Water Management (Hydrology and Water Resources)

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Addis Ababa, Ethiopia

Africa Center of Excellence for Water Management

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Declaration

I, Urgessa Hirpa (Id No: GSR/0945/14), hereby declare that this MSc Thesis titled "Groundwater Resource Assessment Using Numerical Modeling in Gur Catchment, Central Ethiopia" has been developed by me and has not been submitted to any other institution for award of any academic qualification. The content of the thesis has not been plagiarized, and where works of other researchers have been used, they have been appropriately cited.

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Urgessa Hirpa	____________	**29/9/2023**

AFRICA CENTER OF EXCELLENCE FOR WATER MANAGEMENT
ADDIS ABABA UNIVERSITY

GROUNDWATER RESOURCE ASSESSMENT USING NUMERICAL MODELING IN GUR CATCHMENT, CENTRAL ETHIOPIA

By:
Urgessa Hirpa

A MASTER'S THESIS SUBMITTED
TO
AFRICA CENTER OF EXCELLENCE FOR WATER MANAGEMENT
ADDIS ABABA UNIVERSITY

APPROVED BY BOARD OF EXAMINERS

This is to certify that we have read this MSc Thesis and that in our opinion; it is fully adequate, in scope and quality, as a Master's thesis for The Degree of Master of Science in Water Management (Hydrology and water Resources)

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ABSTRACT

This study focuses on the numerical modeling of groundwater system in the Gur catchment, located in central Ethiopia. The catchment covers an area of 530 km^2 and exhibits diverse topographic features, including gorges, flatlands, and ridges, with elevations ranging from 1402 to 3341 m. The climatic classification of the catchment falls on Dega (Alpine vegetated zones), Woina Dega (temperate zone), and Kola (hot zone) climatic zones, with mean annual rainfall ranging from 1029 to 1198 mm and average temperatures ranging from 14.4 to 16.5 °C. Land cover analysis reveals that approximately 83% of the study area is covered by cropland. The geological formations in the study area comprise Mesozoic sedimentary rock units, Tertiary volcanic rock units, and Quaternary superficial sediments. The hydrogeological units identified in the catchment include moderately productive porous aquifers, moderately productive fissured aquifers, and aquicludes consisting of gypsum and mudstone. Two methods, namely the Chloride Mass Balance and WetSpass Model, were employed to derive groundwater recharge estimates, yielding an average value of 104.5 mm/year. Groundwater recharge estimation using the WetSpass Model indicates that the catchment receives an annual runoff of 426 mm (39% of precipitation), evapotranspiration of 561 mm (51% of precipitation), and groundwater recharge of 106 mm (10% of precipitation). The numerical groundwater flow model developed for the Gur catchment demonstrates satisfactory calibration results, with simulated hydraulic heads closely matching observed values. The model predicts a total inflow water balance of 246974 m^3/day and an outflow of 246972.7 m^3/day, with a small discrepancy of 1.3 m^3/day. Scenario analysis reveals that increased groundwater extraction leads to a decline in water levels, while reduced recharge results in a significant decrease in hydraulic heads. Combining decreased recharge and increased groundwater abstraction intensifies the decline in water levels. These findings provide valuable insights into the hydrogeological dynamics of the Gur catchment and contribute to sustainable groundwater management in the region.

Keywords: Gur Catchment, Groundwater recharge, Numerical groundwater flow model, Central Ethiopia

TABLE OF CONTENTS

LIST OF FIGURES

LIST OF TABLES

LIST OF ACRONYMS

ASCII	American Standard Code for Information Interchange
ASTER	Advanced Spaceborne Thermal Emission and Reflection
CMB	Chloride Mass Balance
DEM	Digital Elevation Model
DMC	Double Mass Curve
EARS	East African Rift System
ECO	Engineering Corporation of Oromia
ESA	European Space Agency
GHB	General Head Boundary
GIS	Geographic Information System
GPS	Global Positioning System
GSE	Geological Survey of Ethiopia
IDW	Inverse Distance Weight
KRCC	Korea Rural Community Cooperation
M a.m.s.l	Meter above mean sea level
MAE	Mean Absolute Error
ME	Mean Error
MODFLOW	Modular 3 dimensional finite difference groundwater flow models
NASA	National Aeronautics and Space Administration
NMA	National Meteorological Agency
NMA	National Meteorological Agency
NW	North-West
PCG2	preconditioned conjugate gradient 2
PET	Potential evapotranspiration
RMS	Root Mean Squared Error
SE	South-East
SRTM	Shuttle Radar Topography Mission
UTM	Universal transverse Mercator
WetSpass	Water and Energy Transfer between Soil, Plant, and Atmosphere at Quesi-steady State

1. INTRODUCTION

1.1 Background

Groundwater refers to the water that exists beneath the water table, within the saturated soils and geological formations of the subsurface. It is the portion of water that fills the spaces in the soil and rock layers, creating a fully saturated condition (Allafta & Opp, 2021; Ayehu et al., 2018; Dhara & Vekariya, 2020; Melesse et al., 2020). Groundwater is a vital natural resource that holds significant importance worldwide (Dhara & Vekariya, 2020). Groundwater serves as a crucial water source for numerous cities and towns across the globe. Its widespread utilization is primarily attributed to its abundant availability, consistent quality, and cost-effectiveness in terms of extraction and usage (Ansari et al., 2016; Mengistu et al., 2021; Swain et al., 2022). The utilization of groundwater plays a fundamental role in addressing the escalating water demands of rapidly growing urban, industrial, and agricultural sectors, particularly in arid regions where surface water resources are limited and seasonal (Mihiret, 2022).

The complete awareness and effective use of groundwater resources have a significant impact on the long-term growth of social and economic activities (Saadatpour et al., 2022). Making a quantitative estimate of the groundwater resources in terms of the total amount of water stored in aquifers or long-term average recharge is a key goal of the majority of groundwater studies (Hamid, 2019). The absence of adequate understanding regarding groundwater flow patterns and resource availability has hindered the development of appropriate groundwater management strategies (Moumtaz; et al., 2020). Without comprehensive knowledge in these areas, it becomes challenging to formulate effective plans and policies to sustainably manage and utilize groundwater resources. Consequently, it becomes imperative to simulate groundwater behaviour in order to gain a deeper understanding of aquifer conditions. By employing simulation models, we can simulate and analyse the complex dynamics of groundwater flow, enabling us to assess aquifer characteristics, predict water availability, and make informed decisions regarding groundwater management and sustainable utilization (Izady et al., 2014).

Accurately simulating the behaviour of groundwater, considering the diverse parameters and properties specific to an aquifer, can only be achieved through the use of modeling techniques. Models provide a systematic and quantitative approach to understand and predict groundwater flow, level fluctuations, and contaminant transport within an aquifer system (Adane, 2014; Ayehu et al., 2018; Evans, 2016; Hamid, 2019; Ketemaw et al., 2021; Mihiret, 2022; Moumtaz et al., 2020; Rejani et al., 20018; Yang et al., 2016; Yenehun et al., 2022). The utilization of groundwater modeling as a tool for addressing optimal water management inquiries has become increasingly prevalent. This approach facilitates a deeper comprehension of the behaviour of real groundwater systems and enables predictions regarding their future dynamics. Through simulations and projections, groundwater modeling contributes to a more comprehensive understanding of the system's behaviour and assists in forecasting its future responses and outcomes (Ketemaw et al., 2021). Employing numerical groundwater flow models is a reliable approach for regional hydrogeological investigations, as it facilitates general groundwater resource management and assessment of spatial variations in crucial aquifer parameters (Anderson & Woessner, 2015). Having proper knowledge and understanding of the functioning of the groundwater system is essential before engaging in modeling activities (Gurwin & Lubczynski, 2005; Lubczynski & Gurwin, 2005; Tarhouni & Leduc, 2012).

The application of numerical modeling, particularly using MODFLOW, allows for testing and refining conceptual models, estimating hydraulic parameters, and, of utmost importance for water-resource management, predicting the response of the aquifer to variations in pumping and climate conditions (Moumtaz; et al., 2020; Shishaye et al., 2019). MODFLOW has effectively addressed a significant aspect of groundwater assessment, namely the interaction between streams and aquifers (Lubczynski & Gurwin, 2018). The ease of use, simple structure, and capability to handle separate packages for addressing specific hydrogeological challenges make MODFLOW a favourable choice as a computational program. It offers comparative advantages in predicting groundwater levels under diverse constraints (Chakraborty et al., 2020; Varalakshmi et al., 2014).

In many developing countries, including Ethiopia, the scarcity and poor quality of data pose a significant challenge to the application of groundwater models (Moumtaz; et al., 2020). This lack of data leads to uncertainties in groundwater flow modeling. Excessive groundwater extraction, surpassing the average recharge rate, further exacerbates this issue by depleting aquifer storage and causing a decline in the groundwater table (Mengistu et al., 2021). Despite being considered a primary water source for both rural and urban communities (Ketemaw et al., 2021; Mengistu et al., 2021), Ethiopia faces water scarcity, particularly during the dry season (Kassa, 2007; MacDonald et al., 2021). With an estimated reserve potential of 40 billion cubic meters (Haile et al., 2019), groundwater in Ethiopia holds significant promise. However, the necessary skills to effectively explore, develop, and manage this valuable resource are lacking. As a result, there exists insufficient knowledge regarding the viability and strategic importance of groundwater in the country (Awulachew et al., 2016; Kidanewold et al., 2014). In Ethiopia ambitious development plans, urbanization, and rapid population growth have resulted in excessive pumping of the groundwater resource (Kahsay, 2018). This has led to a significant increase in the demand for groundwater exploitation, primarily for domestic water supply and, to a lesser extent, for agricultural purposes (Haile et al., 2019).

The study area in this research is located in central Ethiopia, specifically encompassing the vicinity of Addis Ababa, which falls within the North Shewa zone of the Oromia regional state. In this study, the groundwater resource and effects of different stresses on the groundwater system in the Gur Catchment are assessed. To accomplish this, the analysis employs numerical groundwater flow modeling to examine the impacts of varying recharges and abstraction rates under steady-state conditions. This analysis is facilitated through the integration of spatial data within a Geographic Information System (GIS) and the utilization of MODFLOW software. The study endeavours to estimate groundwater recharge, construct steady-state numerical groundwater flow models to gain a deep understanding of the aquifer's characteristics, and determine the direction of groundwater flow. By doing so, it aims to enhance the knowledge and comprehension of the groundwater systems in the study area, thereby providing valuable insights for the sustainable management and optimal utilization of groundwater resources.

1.2 Statement of Problem

The management and development of groundwater resources in many regions are hindered by insufficient information about the groundwater system (Condon et al., 2021; Dhara & Vekariya, 2020). Groundwater mapping is challenging due to its hidden nature, making it difficult to locate and assess. To effectively utilize available water resources and meet community demands, it is crucial to have knowledge of groundwater potential and conduct thorough assessments (Allafta & Opp, 2021).

In the Gur catchment, despite the recognized moderate quantity and good quality of groundwater potential (Tigistu et al., 2014), there is a lack of comprehensive understanding regarding the aquifer's response to future stresses, and the distribution of groundwater heads under different scenarios. This knowledge gap hinders effective management and sustainable utilization of the catchment's water resources. Furthermore, while previous unpublished MSc and PhD thesis studies and reports (Azagegn et al., 2015; Mulatu, 2017; Tigistu et al., 2014) have highlighted the Gur catchment's groundwater potential, there is a need to perform groundwater modeling to assess the impact of pumping and variations in recharge on the water table, as well as on the discharge from springs and wells. The absence of such modeling restricts the ability to accurately forecast the long-term sustainability of the catchment's water resources under various conditions and stresses. Therefore, this study aims to address these knowledge gaps and fill the need for a comprehensive groundwater model that can provide insights into the mechanisms of groundwater flow, predict future groundwater heads, and evaluate the catchment's response to changing pumping rates and recharge patterns. By conducting a thorough groundwater modeling analysis, this research will support informed decision-making and facilitate the development of sustainable water resource management strategies in the Gur catchment.

1.3 Objectives

1.3.1 Main Objective

The main goal of this research is to assess the groundwater flow dynamics and effects of different stresses on the groundwater system in the Gur Catchment using numerical groundwater flow modeling.

1.3.2 Specific Objective

In a brief sense, the project research holds several particular aims but can be studied under the same scheme. Thus, the specific rationales of this work are:

- To estimate groundwater recharge of the study area
- To develop the conceptual setup and design a numerical model of the study area
- To assess the potential impacts of increased abstraction and recharge variability on the groundwater head using steady-state numerical modeling

1.4 Research Questions

a) What is the amount and spatial distribution of groundwater recharge within the Gur catchment?

b) How well do the simulated hydraulic heads correspond to the observed heads?

c) Under various well operation scenarios, how does the groundwater head of the Gur catchment react to variations in groundwater recharge and the rate of groundwater abstraction?

1.5 Significance of the Research

The study carried significant scientific importance as it aims to provide a comprehensive understanding of the groundwater behaviour within the Gur catchment. It investigated the flow system and its response to potential future stresses in a changing environment, contributing to the advancement of knowledge in the field. One important aspect of the study is to identify the optimal utilization of the aquifer in the study area while ensuring their sustainability. It examines groundwater dynamics and offers valuable insights and guidelines for future groundwater resource development and effective management practices. This information is vital for ensuring the long-term availability of groundwater for various purposes without compromising the health and integrity of the aquifers. Furthermore, the study serves as a reference framework for students, government organizations, and non-governmental organizations interested in further investigations and development related to groundwater resources. The comprehensive understanding of the groundwater system and the insights gained from this research provide a solid foundation for future studies, and sustainable development initiatives in the region. Overall, this research has the potential to generate valuable knowledge, practical guidelines, and a reference point for stakeholders involved in groundwater management, thereby contributing to the sustainable utilization and preservation of this vital natural resource.

1.6 Scope of the Study

The scope of the study in the Gur catchment encompassed several key tasks aimed at understanding and analysing the groundwater system. These tasks included collecting both secondary and primary data, estimating groundwater recharge, and developing both conceptual and numerical groundwater flow models. To begin, relevant secondary data were collected from existing sources, such as meteorological, hydrogeological, and geological records, along with primary data gathered through field surveys.

Different methods were employed to estimate recharge rates, taking into account factors such as precipitation, land cover, soil properties, and geological characteristics. The conceptual model involved constructing a simplified representation of the groundwater system based on the collected data and geological understanding. Furthermore, a mathematical groundwater flow model was constructed to simulate and analyse the movement of groundwater within the catchment. The model was calibrated using the available data to ensure its accuracy and reliability. Various scenarios were then analysed using the calibrated model to assess the response of the groundwater system under different conditions, such as changes in recharge rates and pumping rates. The combination of data collection, recharge estimation, and the development of conceptual and mathematical models facilitated a holistic analysis of the system and enabled the evaluation of different scenarios.

2. LITERATURE REVIEW

2.1 Groundwater Recharge

Groundwater recharge plays a vital role in evaluating groundwater availability, making it a critical model input parameter that requires careful examination and meaningful implementation. It refers to the process through which water infiltrates the soil and reaches the water table, replenishing the aquifer with water from the land surface (Ketabchi, 2022). Proper management and protection of limited groundwater resources require a thorough understanding of recharge processes and their quantification (Dalechca, 2018; Ketabchi, 2022; Mondal & Ajaykumar, 2021).

Recharge estimation can be accomplished through various methods, such as the chloride ion mass balance method, empirical methods, water balance methods, water budget model methods, or by calculating the product of water-level fluctuations in wells with the specific yield of the aquifer material (Arefaine et al., 2012). It is important to note that recharge processes can vary significantly from one area to another (Teerapunyapong et al., 2020a). Therefore, there is no guarantee that a particular recharge estimation method proven effective in one locality will yield reasonable results when applied to a different area. The complex interactions between climate, geology, soil properties, and land use practices make it necessary to carefully consider the specific characteristics of each location when selecting an appropriate recharge estimation method. Local hydrogeological conditions and data availability should be taken into account to ensure accurate and reliable results (Mathenge et al., 2020).

An accurate assessment of groundwater resources in an area may require quantification of recharge amounts at both large spatial and temporal scales. While small-scale assessments can provide valuable insights into local groundwater dynamics, larger-scale flow and contaminant modeling often necessitates a broader understanding of recharge processes (Tilahun et al., 2009; Yenehun et al., 2021) emphasize that a key factor in effectively selecting among different recharge estimation techniques is a thorough understanding and identification of the recharging mechanisms of aquifers, as well as the underlying assumptions of each estimation method.

Different methods are available for estimating recharge in fractured aquifers, each with its own strengths and limitations. Water balance models, as highlighted by (Zhu et al., 2020), are commonly used to estimate diffuse recharge, which refers to the relatively uniform distribution of recharge over a larger area. These models consider various factors such as precipitation, evapotranspiration, and soil properties to estimate the overall recharge flux.

However, when it comes to estimating focused recharge in fractured aquifers, water point measuring-based methods are often preferred. One such method is water table fluctuation, as mentioned by (Scanlon et al., 2002). This approach involves monitoring the water level fluctuations in wells over time and relating them to the recharge processes. By analyzing the patterns and magnitudes of water level changes, it is possible to identify and quantify the focused recharge occurring through preferential flow pathways.

Despite the advantages of water point measuring-based methods for focused recharge estimation, one challenge is their limitation in providing spatially distributed estimates. As noted by (Yenehun et al., 2021), these methods typically provide point-specific recharge values and may not capture the spatial variability of recharge across the aquifer. This limitation can make it challenging to assess the overall recharge dynamics in a fractured aquifer and may require additional techniques or approaches to address the spatial variability. Conventional point recharge estimation techniques should not be used to extrapolate or regionalize results due to the significant spatial variability of recharge. This variability is influenced by factors such as geology, topography, soil texture, land use, and meteorological variables. Therefore, it is not advisable to generalize recharge estimates beyond the specific locations where these point-based techniques are applied (Tilahun et al., 2009).

Therefore, in this study, the WetSpass model, a physically-based water balance model, is utilized to simulate recharge in a spatially and temporally distributed manner. Unlike conventional point-based techniques, WetSpass considers various factors and processes, allowing for a more comprehensive understanding and estimation of recharge patterns across the study area. By incorporating these spatial and temporal dynamics, the WetSpass model provides a more accurate representation of recharge processes, enhancing the reliability of the results obtained in the study. The WetSpass model, which stands for Water and Energy Transfer in Soil, Plants, and Atmosphere in quasi Steady State, was initially developed by Batelaan and De Smedt in 2001 (Batelaan & Smedt, 2001). This model provides a comprehensive framework for simulating the transfer of water and energy across different components of the hydrological cycle, including soil, plants, and the atmosphere. It operates under the assumption of a quasi-steady state, where the system is assumed to be in a relatively stable condition over time. Since its initial creation, the WetSpass model has undergone modifications by Batelaan and De Smedt in 2007 (Batelaan & Smedt, 2007). These modifications likely involved refining and improving certain aspects of the model to enhance its performance and accuracy in simulating water and energy transfer processes.

According to the findings of (Armanuos et al., 2016), the WetSpass model utilizes long-term average climatic data, along with topographical information, land cover data, and soil mapping, to estimate the average spatial patterns of surface runoff, actual evapotranspiration, and groundwater recharge. By incorporating these inputs, the model can simulate the distribution of these hydrological variables across the study area (Batelaan & Smedt, 2007).

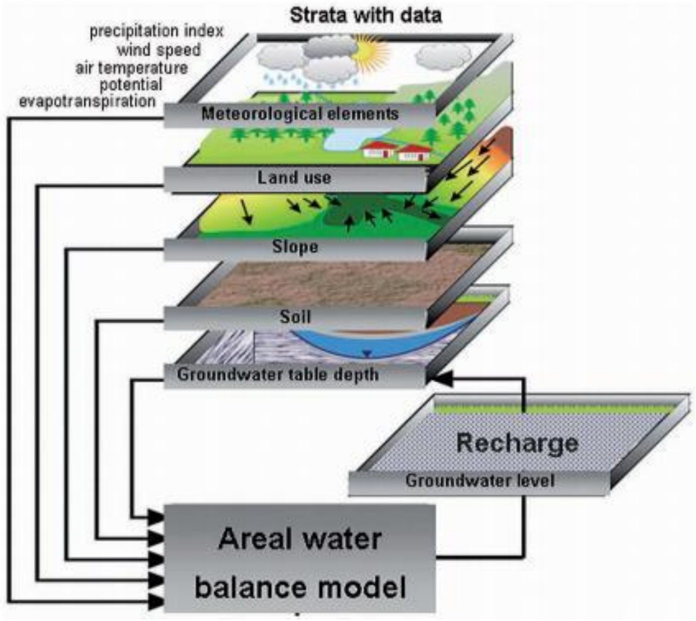

Figure 2.1 Schematization and integration of data for a hypothetical raster cell in the WetSpass water balance model (Batelaan & Smedt, 2001).

The WetSpass model is a mathematical model specifically designed to simulate the spatial distribution of hydrological parameters and processes at the basin scale, considering long-term averages and operating in a quasi-steady state. This implies that the model primarily captures the average behaviour of hydrological processes and allows for seasonal or monthly temporal fluctuations. In the context of the Gur catchment, the WetSpass model was employed as a physically-based water balance model to estimate groundwater recharge resulting from rainfall. By incorporating various inputs such as precipitation data, land cover information, soil properties, and topographical data, the model can simulate the movement of water through the hydrological system, including the estimation of groundwater recharge. The application of WetSpass in the Gur catchment enable the estimation of spatially distributed groundwater recharge, providing insights into the replenishment of the groundwater resources in the area.

2.2 Groundwater Modeling

Model is simplified representation of the actual phenomena to understand the real world system. A groundwater model is a simplified representation of a groundwater system (Kumar, 2019; Pétré et al., 2019). Groundwater modeling studies have been conducted in various parts of the world to better understand and manage groundwater resources (e.g., (Ansari et al., 2016; Chakraborty et al., 2020; Gaur et al., 2011; Ghodoosipour, 2013; Ghosh & Sharma, 2006; Kahsay, 2008; Lubczynski & Gurwin, 2005, 2018; Moumtaz et al., 2020; Tarhouni & Leduc, 2012; Varalakshmi et al., 2014)). In many studies, including those conducted by (Chakraborty et al., 2020; Ghosh & Sharma, 2006; Varalakshmi et al., 2014; Kumar, 2013), models are often defined as conceptual descriptions or approximations that use mathematical equations to represent physical systems or processes. It is important to note that models are not exact replicas or representations of the real-world systems; rather, they are simplified representations that aim to capture the essential aspects of the system being studied.

Models provide a quantitative representation of the relationships among entities or processes in a hydrogeological system. By mathematically simplifying the system, models allow for the prediction, testing, and comparison of alternative scenarios. According to (Ghosh & Sharma, 2006), a groundwater model is a simplified representation of a groundwater system designed to approximate the relevant cause-and-effect relationships within the system. The model aims to simulate and replicate the essential dynamics of the groundwater system, providing an approximation of its behavior and responses to different inputs and conditions.

The primary significance of numerical modeling lies in its ability to deliver fast, accurate results and reliable calculations (Anderson & Woessner, 2015). Numerical modeling serves as a management tool for assessing resource potential and predicting future impacts under various circumstances. The predictive capacity of a model makes it an invaluable tool for planning, designing, implementing, and managing groundwater resources effectively. According to (Ghodoosipour, 2013), groundwater models play a crucial role in investigating the response of groundwater systems to external natural and anthropogenic changes. They help in understanding the characteristics of hydrogeological systems and their interrelationship with groundwater. Groundwater modeling has emerged as a valuable tool for gathering diverse databases related to aquifers. Consequently, through groundwater modeling studies, researchers have been able to enhance their understanding of aquifer dynamics and address water demands for industrial, agricultural, and domestic purposes, which are constantly evolving (Pande, 2016).

According to (Evans, 2016), groundwater models find their primary applications in the fields of water quantity and water quality assessment. In quantitative groundwater modeling, the focus is on modeling the flow and movement of water within the aquifer (Kahsay, 2018). This involves applying model algorithms based on Darcy's law (the equation of motion) and the continuity of mass equation. By combining these equations, the groundwater flow equation is derived.

In the past, groundwater flow behaviour was simulated using scale models, analogue models, and analytical models. However, in recent decades, computer codes have become common, allowing for the design and development of sophisticated mathematical models. This shift to computer-based modeling has facilitated the creation of complex model approaches for simulating groundwater flow behaviour (Kahsay, 2018). Various techniques have been developed to solve the partial differential equations that describe the behaviour of groundwater flow systems. Among these techniques, the most commonly used numerical solution methods are Finite Difference, Finite Element, and Analytical Element methods. The Finite Difference method was the earliest method employed for systematic numerical solutions of partial differential equations. As (Anderson & Woessner, 2015) discuss, many numerical models of groundwater flow utilize finite difference methods to discretize and solve the governing partial differential flow equation. In this approach, the aquifer system is represented by a discretized domain comprising an array of nodes and associated finite difference blocks or cells (Condon et al., 2021; Kahsay, 2018; Pande, 2016).

MODFLOW, developed by the U.S. Geological Survey (USGS), is considered one of the most widely used numerical groundwater flow models. It is a three-dimensional model that provides a comprehensive framework for simulating and analysing groundwater flow in aquifer systems. MODFLOW incorporates the finite difference method to discretize the aquifer domain into a grid of cells, allowing for the spatial representation of the groundwater system. It considers various factors such as hydraulic conductivity, boundary conditions, and recharge rates to simulate the movement and distribution of groundwater within the aquifer. MODFLOW offers a range of capabilities and features that allow for the simulation of complex hydrogeological scenarios. It can handle steady-state and transient flow conditions, as well as incorporate solute transport simulations to assess groundwater quality (Michael G. McDonald, Arlen W. Harbaugh, 1988). MODFLOW, a widely-used groundwater flow model, offers several advantages including data preparation facilities, standard data exchange, extensive worldwide experience, continuous development, availability of source code, and relative affordability. These features contribute to its popularity and make it a valuable tool for studying and managing groundwater resources (Kumar, 2014). MODFLOW has limitations when it comes to certain aspects of groundwater modeling. Notably, it does not explicitly account for surface runoff and unsaturated flow processes. As a result, for transient problems where the flux at the groundwater table depends on the calculated head and the function is unknown in advance, MODFLOW may not be suitable or applicable. It is important to consider these limitations and explore alternative modeling approaches when dealing with such scenarios (Kumar, 2013).

2.3 Previous Works

Several types of research have been done both by governmental offices and individuals on the study of groundwater in the Middle Abay basin and central Ethiopia. But most of the research did not model the groundwater of this area in their studies. Even though the concept of groundwater modeling has been used to evaluate the groundwater resource and in the study of groundwater hydrology in different parts of the world including Ethiopia, such a practice is rarely exercised in Gur catchment. But, Groundwater modeling is increasingly recognized as a powerful quantitative tool available to hydrogeologists for evaluating groundwater systems (Varalakshmi et al., 2014). Recent studies by (Azagegn et al., 2015; Baye, 2009; Melesse et al., 2020; Mulatu, 2017; Tilahun, 2014; Yonas, 2009) and unpublished report (Tigistu et al., 2014) have applied groundwater modeling in their studies.

According to (Ashenafi, 2018) The geological structure and regional fault system from NW-SE trending horst beneath volcanic rock unit and ridges control the aquifer distribution in the catchment. The volcanic aquifer unit which is fractured basalt and scoraceous as well as trap series columnar basalts have moderate to high moderate hydraulic conductivity. As (Ashenafi, 2018) concluded, The volcanic rock unit have high productive in which fracture and joint act as conduit through which ground water flow. Project by (Tigistu et al., 2014) identified that recharge of the Debretsigie area varies between 100 mm and 300 mm per year. Water level fluctuation in four drilled wells under this project has been measured over a period of one year at monthly time step. The water level changes recorded was less than a maximum of one meter-implying high yielding aquifers.

In central Ethiopia, litho-structural setup of the three sub-basins of the southern flank of the Middle Blue Nile basin (Guder, Muger and Jema) and the adjacent Upper Awash River basin had been investigated by (Azagegn et al., 2015) to develop conceptual groundwater flow model and to characterize the groundwater hydrodynamic relationship between the aquifer systems of the two basins. The development of conceptual groundwater flow model was based on interpretation of Digital Elevation Model (DEM) from SRTM and Landsat images together with field geological observation, integrated with existing boreholes lithologic logs and pumping test data. (Azagegn et al., 2015) also identified as the NW–SE trending horsts beneath the volcanic successions and the overlying volcanic ridges control aquifer distribution in the Guder, Muger, and Jema groundwater sub-basins. In the South-Jema catchment, which is situated at the eastern border of the Gur catchment in central Ethiopia, an MSc thesis study was conducted by (Zekarias Ashine, 2020). This study focused on recharge and hydrochemistry within the catchment and aimed to provide insights into groundwater dynamics in the area. The study findings, although unpublished, revealed important information about the recharge and groundwater flow patterns in the South-Jema catchment. The average long-term recharge in the catchment was determined to be 122 mm. This value represents the amount of water that infiltrates into the groundwater system over an extended period. Additionally, the study investigated the groundwater flow direction within the catchment. It was observed that the groundwater movement follows the topographic setup, indicating that the flow direction is towards the north in the South-Jema catchment.

3. METHODOLOGY

3.1 Description of the study area

3.1.1 Location

The present study is conducted in the Gur catchment, located in Central Ethiopia, within the middle Abay basin, specifically in the Oromia regional state of Ethiopia. Geographically, it is bounded between coordinates 1050000mN to 1095000mN and 460000mE to 500000mE, using the UTM coordinate system with the Adindan datum and Z-37 zone. The total surface area of the catchment is 530 Km^2, and the elevation within the area ranges from 1402 to 3341 m above sea level (m.a.s.l.). Access to the study area is primarily facilitated by the Addis Ababa —Muka Turi—Debretsige—Fiche asphalt road, which provides a main transportation route. This well-established road links the capital city, Addis Ababa, with various towns and settlements within the region. Additionally, there are several interconnected gravel and dry soil roads within the area, allowing for further access to different parts of the study area and connecting with the main asphalt roads.

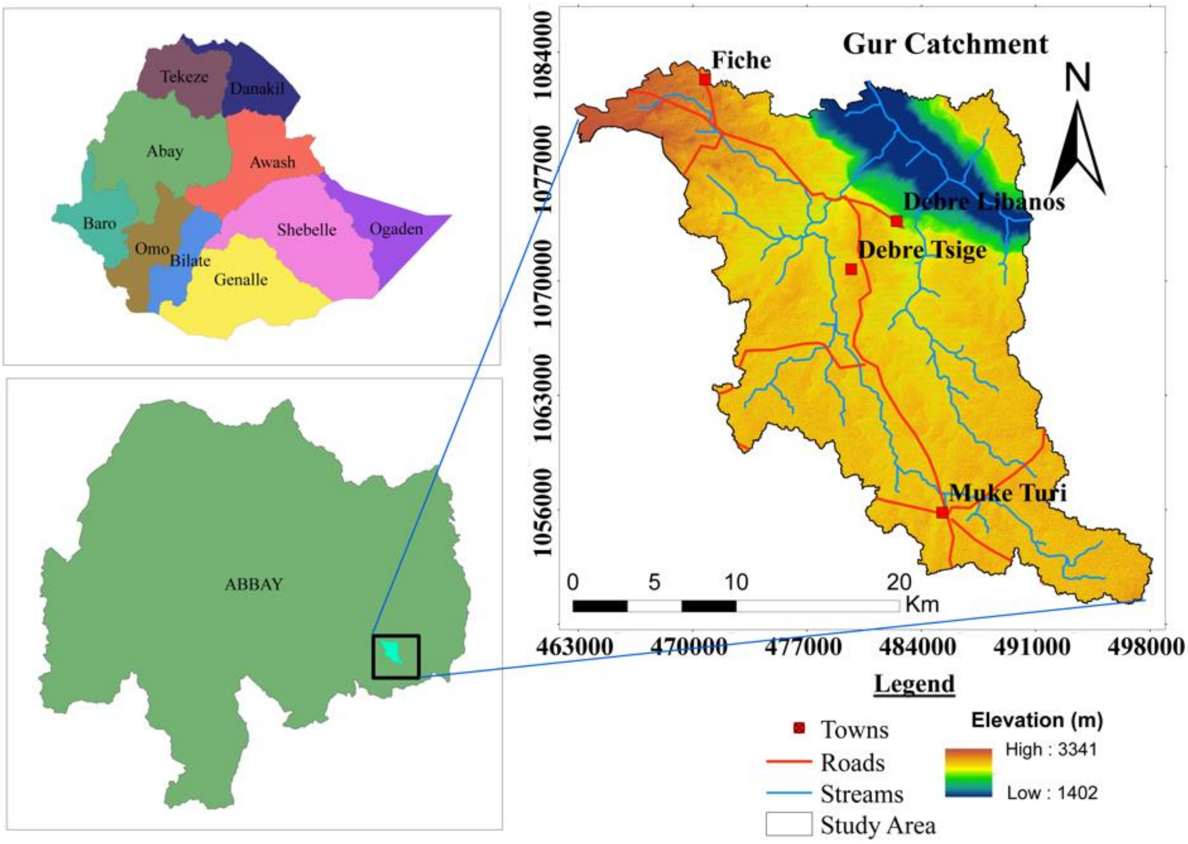

Figure 3.1 Location Map of the Study Area

3.1.2 Physiography and Drainage pattern

The Gur catchment exhibits diverse topographic features resulting from tectonic activities and subsequent erosion processes. Situated on the south eastern margin of the Blue Nile (Abay) basin, the study area is characterized by deep-cut gorges, sharp escarpments, flat-top hills, and gently sloping terrain. To analyse and visualize the topography of the study area, a digital elevation model (DEM) was generated. The DEM was obtained by clipping the ASTER DEM dataset, which has a resolution of 30 meters, using ArcGIS 10.4 software. The resulting DEM, as depicted in the accompanying figure 3.2, provides a comprehensive representation of the landforms within the study area. The unenhanced DEM, as shown in the figure, depicts the presence of cliffs, plateaus, gorges, and other distinctive landforms, with elevation ranging from 1402 to 3341 m.

The Gur River catchments drain into the Jema River, which is one of the largest tributaries, flowing in a north western direction. Eventually, the Jema River joins the Blue Nile River, which flows in an east-west direction, forming a nearly perpendicular junction. The river catchments predominantly exhibit a dendritic and parallel pattern, with the general flow direction being from south to north. The majority of the rivers and streams in the region are influenced by faults, resulting in the formation of deep, steep valleys. This combination of fault-controlled waterways and the incised valleys contributes to the unique characteristics of the river and stream network in the study area. The easily traceable paths, incised channels, and the influence of faults highlight the significant role played by both the topography and geology in shaping the drainage patterns and landforms within the region.

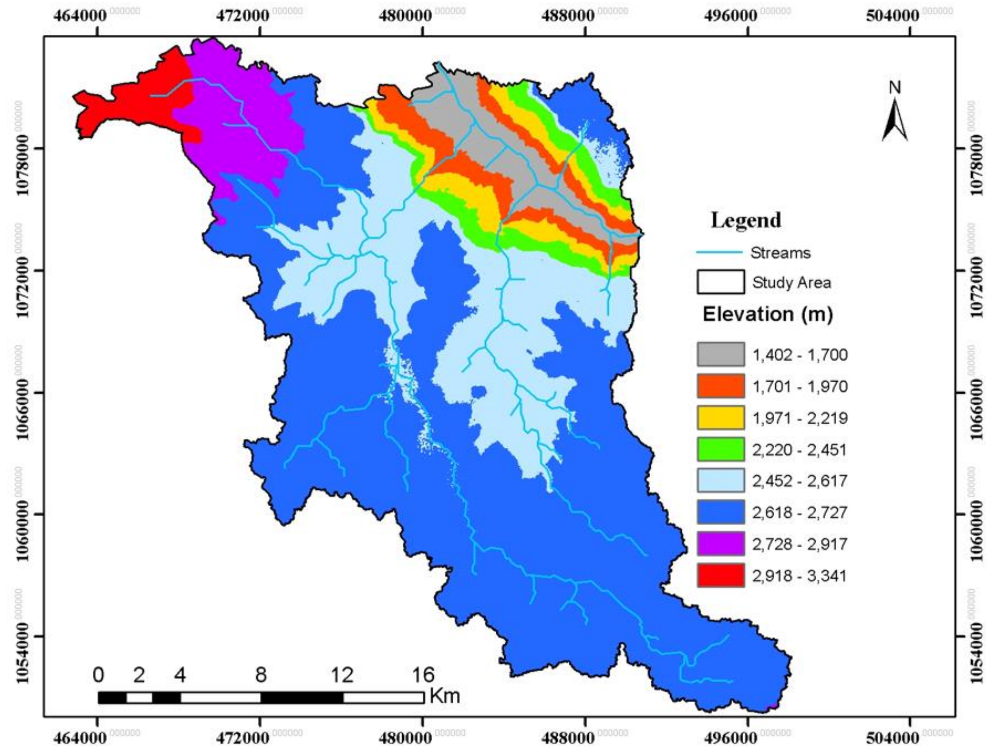

Figure 3.2 Topography and drainage map of Gur catchment

3.1.3 Climate

According to (Belay, 2015), the climate of Ethiopia can be classified in various ways, such as traditional, Thornthwaite's, rainfall regimes, and agro-climatic zone classification systems. The traditional and agro-ecological zone systems are the most commonly used. The traditional classification system categorizes Ethiopia into five climatic zones based primarily on altitude and temperature. These zones are: Wurch (This zone represents a cold climate found at altitudes above 3000 meters), Dega (It is a temperate climate found in the highlands with altitudes ranging from 2500 to 3000 meters), Woina Dega (This zone exhibits a warm climate and is located at altitudes between 1500 and 2500 meters), Kola (It is a hot and arid climate found at altitudes below 1500 meters), and Berha (This zone represents a hot and hyper-arid climate) (NMA et al., 2001). Rainfall regimes can be classified into three main patterns: monomial, bimodal, and diffused. Monomial regimes exhibit a single peak in precipitation during a specific period, while bimodal regimes have two distinct peaks corresponding to two wet seasons. Diffused regimes lack clear peaks and are characterized by a relatively even distribution of rainfall throughout the year.

In the downstream region, Gur catchment experiences a hot and arid climate, while in the upstream part, it falls within the Wurch climatic zone. This means that the climate conditions in the catchment vary from hot and arid to a different climate type as we move upstream. The major rainy season in the Gur Catchment occurs from June to September, representing a monomial rainfall pattern. Additionally, a shorter rainy period occurs from March to May. Farmers in the area typically commence cultivation in March, coinciding with this shorter rainy period.

3.1.4 Soil Texture

The most governing factor affecting the water holding capacity, infiltration and runoff characteristics of soils is texture. The ability of soil to store and transport water is controlled by soil texture, soil structure and soil moisture content. The soil map of the Gur catchment area was derived from a comprehensive study conducted by the Engineering Corporation of Oromia (ECO) in the Abay basin. According to the soil classification derived from the ECO study, the dominant soil type in the Gur catchment is clay, covering approximately 362.4 Km^2, which accounts for 67.9% of the area. Other significant soil types include Loam, covers an area of 108.1 Km^2, accounting for 20.3% of the catchment. Clay loam occupies an area of 26.0 Km^2, representing 4.9% of the catchment and Silty clay covers 16.8 Km^2, comprising 3.2% of the catchment. Furthermore, there are smaller areas within the Gur catchment that are characterized by different soil types. Silty loam covers an area of 12.9 Km^2, accounting for 2.4% of the catchment. Sandy loam occupies a smaller area of 0.3 Km^2, representing 0.1% of the catchment. Additionally, there are areas covered by silt which spans 6.8 Km^2, making up approximately 1.3% of the catchment.

Table 3.1 a summary of the proportion of each soil texture type

Soil texture	Areal coverage (Km^2)	Percent (%)
Clay	362.4	67.9
Silty loam	12.9	2.4
Clay loam	26.0	4.9
Loam	108.1	20.3
Silty clay	16.8	3.2
Sandy loam	0.3	0.1
Silt	6.8	1.3

3.1.5 Land Use Land Cover

In many resource management, planning, and monitoring projects, accurate and current land use and land cover information is important. The European Space Agency (ESA) published a global land cover product for 2020 in October 2021. It offers openly available data with a 10-meter resolution using information from the Sentinel-1 and Sentinel-2 satellites. The ESA's global land cover map was modified to produce the land use and land cover map for the Gur catchment. Field observations made in the research area were used to judge the accuracy of this adapted map. The results of the field observations showed that the amended map and the real ground conditions had a high degree of agreement, proving its accuracy and dependability. The research area contains a variety of land cover types. The key land cover components include shrubs, trees, grassland, built-up, cropland, and vegetation areas. The primary land-use of the catchment is agriculture, which makes up 83% of the study area's land cover and is dispersed throughout the catchment. Grassland and shrubland each make up 6% of the total area. A total of 5% of the land is used for built-up and other minor land use types.

Table 3.2 Land use/Land cover type of Gur catchment

LULC Type	Area (sq Km)	Percent (%)
Tree cover	6.320	1.204
Shrubland	32.461	6.185
Grassland	32.337	6.161
Cropland	439.075	82.706
Built-up	9.464	1.803
Mixed forest	10.135	1.931
Permanent water bodies	0.006	0.001
Herbaceous wetland	0.044	0.008
Total	530	100

3.2 Geological setting

3.2.1 Geology

Ethiopia's geological history is characterized by a complex series of events, including the formation and breakup of the Gondwana supercontinent during the Late Carboniferous to late Cretaceous periods. This period was marked by intracontinental rifting and separation. Furthermore, during the Tertiary period, there was extensive volcanic activity in the form of continental flood basalts, resulting in plateau uplift and the formation of the East African Rift System (EARS) (Dawit, 2010).

In central Ethiopia, the geology is predominantly composed of various geological formations. These include the Precambrian crystalline basement, sedimentary layers from the Palaeozoic and Mesozoic eras, and the Tertiary continental flood basalts also known as the Trap series (Bereket et al., 2011). The geology of the Gur catchment area specifically consists of a sequence of Mesozoic sedimentary rocks, Tertiary volcanic rocks, and Quaternary superficial sediments.

Lithostratigraphy

Based on technical hydrogeological report of Addis Ababa (Bereket et al., 2011), different borehole data reported by different drilling company, and other literatures (Azagegn et al., 2015; Tigistu et al., 2014; Tilahun, 2014), two distinct sedimentary rock units, lower to upper tertiary volcanic rock units and Quaternary superficial sediments are exposed in the study area.

Sedimentary rock units

The Gur catchment area is characterized by the presence of Mesozoic sedimentary rocks, specifically the Muger Mudstone and the Upper Coarse Grained Sandstone, which is also referred to as Debre Libanos Sandstone. The term "Muger Mudstone" was adopted after a designated section was established along the Muger River bank (N 09°37'/E 38°24) in the eastern region of the Blue Nile canyon (Dawit, 2010). The Muger Mudstone is exposed in the downstream parts of the study area along the Zega Wedem river beds. It covers an approximate area of 18.1 km2 within the Gur catchment, with observed maximum thickness reaching around 320 meters in the Zega Wedem river gorge. Typically, the Muger Mudstone forms gentle slopes in lower topographic areas and is conformably overlain by a sandstone unit with a gradual transition. The primary rock types within this formation include mudstone, gypsum, siltstone, and shale. Gypsum exhibits a fresh white colour, mudstone appears red, shale ranges from light green to grey, and siltstone varies from yellow to white. The Muger Mudstone formation shows a high degree of weathering, and its main structural features include laminations, cross laminations, ripple marks, and bedding.

The Upper Sandstone is prominently exposed in the Jemma, Zega Wedem, and Mugger river gorges (Bereket et al., 2011). It appears in the form of cliffs and has a maximum measured thickness of approximately 328 m. The areal coverage within the study area is estimated to be around 25 km^2. The Upper Sandstone unit is characterized by a sharp and unconformable contact with the overlying basalt, indicating a distinct boundary between the two rock formations. In contrast, the contact with the underlying unit shows a more gradual transition. The sandstone unit exhibits a wide range of compositional variations. Towards the top, it appears as well-sorted, medium-grained sandstone with a yellow colour. In the middle section, it transforms into conglomeratic, cross-bedded sandstone with a red colour. The bottom part of the unit is dominated by jointed, fine-grained white sandstone. In terms of weathering, the Upper Sandstone unit displays slight weathering at the top, while the bottom section exhibits a higher degree of weathering. Overall, the unit demonstrates a coarsening upward sequence, with the grain size becoming progressively larger from the bottom to the top.

Tertiary Volcanic Rock Units

The Ethiopian plateau is primarily composed of Tertiary volcanic rocks (Bereket et al., 2011; Dawit, 2010; Tigistu et al., 2014). They exhibit a wide range of compositions, ranging from fluid basaltic rocks to highly viscous acidic rhyolite, representing both central and fissure-type volcanism. In terms of traditional classification, the Ethiopian flood basalts can be categorized into four stratigraphic units, which are diachronous, meaning they occurred at different times. These units, from bottom to top, include Ashangie (Eocene), Aiba (32-25 Ma), Alaji (32-15 Ma), and Termaber (30-13 Ma) (Mohr, 1983; Mohr & Zanettin, 1988).

In the study area, the underlying geological formations consist of columnar, weathered vesicular, and scoraceous basalt plateau, which correspond to the trap series basalt. Among these formations, the Ashangie basalt is the lowest and oldest in the volcanic stratigraphic sequence. Field observations indicate that the Ashangie basalt is characterized by thinner lava flows, a smooth surface, high degree of weathering, dark to brownish color, tectonic disturbances with numerous joints and small-scale faults, and brittle nature.

The basalts found in the Gur catchment, specifically the Upper basalt or Lemi-Debre Libanos-Fitche basalt, correspond to the Termaber basalt (Assiged Getahun, 2007). This particular basalt formation covers an area of approximately 416 km^2 and is exposed in various parts of the study area along river beds, road cuts, and quarry sites. Fresh outcrops of the Termaber basalt exhibit a dark grey color. However, upon weathering, the basalt takes on a dark-brown, grey, and reddish-brown hue. The lower portion of this basalt unit consists of columnar jointed, cliff-forming, and relatively fresh aphanitic basalt. These columnar joints are characterized by well-developed hexagonal faces.

Quaternary Volcanic and Sedimentary Rock Units

Quaternary plateau basalts typically appear as boulder outcrops, and the vesicles within them are often filled with secondary minerals. These basalts predominantly form ridges, with a maximum thickness of approximately 50 meters in central Ethiopia, as noted by (Assiged Getahun, 2007). In the northwestern part of the study area, specifically at Degem, these basalts form topographically high domes and stains. Within this unit, a sheeted and layered flow structure is observable at the top of the dome, oriented in an east-west direction with a shallow dip angle.

The Quaternary superficial deposits unit primarily consists of eluvial soil with a small proportion of alluvial soil. The eluvial soil is predominantly found in the southwestern and central parts of the area. It exhibits colors ranging from dark grey to dark brown and black. The thickness of the eluvial soil layer varies between 1 and 5 meters, as reported by (Meten et al., 2015). On the other hand, the alluvial sediments are deposited within the Zega Wedem river valleys. These sediments exhibit varying textures, ranging from sandy to silty in size. The presence of basalt, limestone, and quartz grain fragments in the alluvial sediments suggests that they were likely derived from these parent rocks, as indicated by (Assiged Getahun, 2006).

3.2.2 Geological Structures

Geological structures can be grouped as primary or secondary based on their formation in relation to the rock formation. These structures have a significant influence on the mechanical behaviour of rocks and play a crucial role in controlling groundwater dynamics. In the Gur catchment, secondary geological structures are commonly observed, including small and large-scale faults, joints, and lineaments, which were identified during fieldwork. The orientation of these geological structures varies, with major lineaments trending in the NE-SW, NW-SE, N-S, and E-W directions. These lineaments are observed across all geological units. Most of the lineaments follow the alignment of ridges, mountains, river valleys, and streams (Matebie Meten et al., 2021).

The observed faults in the area trend NE and dip towards Nw. Joints are widely observed in both sedimentary and volcanic units and are influenced by NW-SE, NE-SW, and N-S trending joints. The spacing and aperture of the joints vary among different outcrops. Some of the major fault systems have been identified from previous geological and hydrogeological studies and are presented in the geological map (Figure 3.6). The presence of faults, joints, and lineaments highlights the complexity of the groundwater system in the catchment(Azagegn et al., 2015; Bereket et al., 2011; Dawit, 2010).

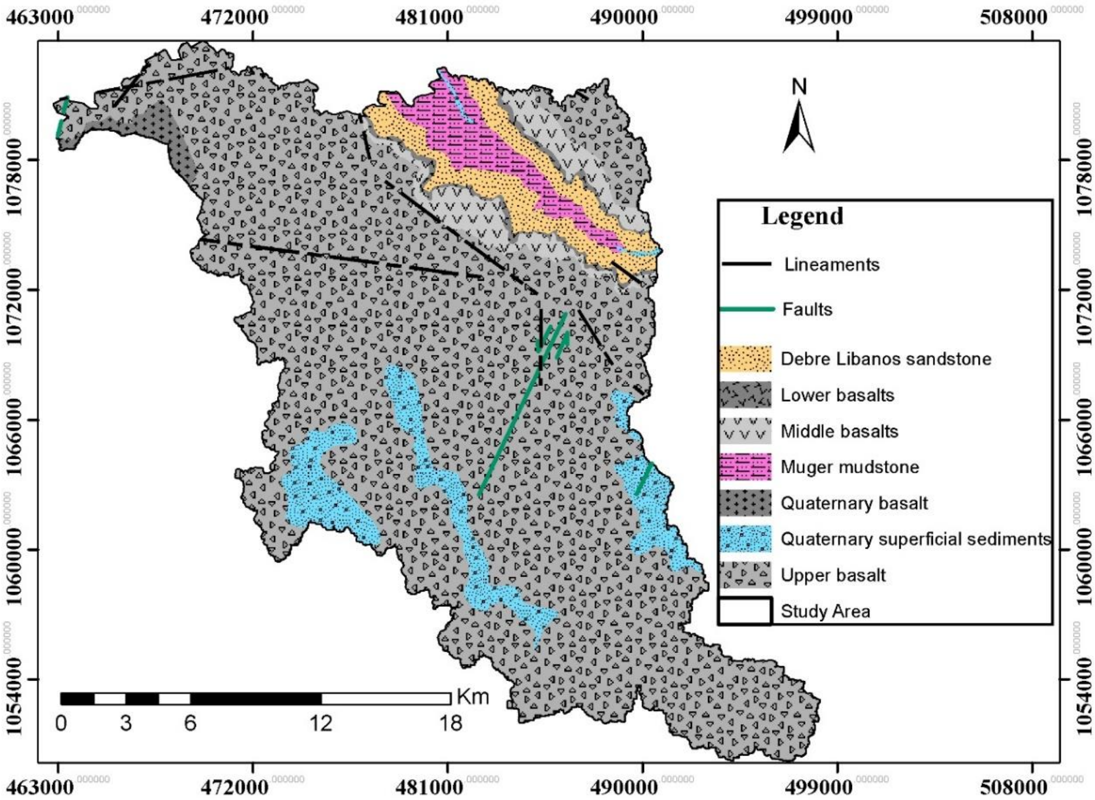

Figure 3.3 Geological map of the Gur catchment (adopted from GSE, 2011)

3.3 Data Collection

To ensure the effective and reliable simulation of groundwater systems, a diverse range of data was required. This included geological data such as lithology maps and stratigraphic descriptions, hydrogeological data, including information on hydrogeological units, Hydraulic properties and an inventory of wells. Additionally, topographic data, such as topographic maps and Digital Elevation Models (DEMs), were considered. Meteorological data, hydrological data such as precipitation, soil properties, and land use/land cover information, were also incorporated into the groundwater models. Numerical models of groundwater requires extensive and accurate data sets that cover the entire region of interest. However, with the advancement of GIS approaches and complex statistical methods, it became possible to model the area of interest even with limited data. The following details and data need to be ready in order to construct a groundwater model:

(a) Complete layer discretization and slice elevations: This involves dividing the area of interest into layers and determining the elevation of each slice within the layers.

(b) Aquifer parameters: These parameters describe the characteristics of the aquifer, such as hydraulic conductivity, porosity, and transmissivity.

(c) Boundary conditions: It define the inputs and outputs of the groundwater system, including recharge rates, hydraulic head values, and flow boundaries.

In the study mentioned, a significant amount of data was used from multiple sources to develop a groundwater flow model. The literature on groundwater modeling concepts, recharge estimation techniques, and prior studies in the field were reviewed. Specific data sources mentioned in the study include:

- Digital elevation model (DEM): The DEM with a resolution of 30 m for the Gur River catchment was downloaded from the Open Topography website (https://portal.opentopography.org/datasets).
- Soil data: Information on soil properties was collected from the Engineering Corporation of Oromia (ECO).
- Land use and land cover: These were gained from the European Space Agency (ESA) dataset released in October 2021, available at (https://worldcover2021.esa.int/).
- Meteorological data: Meteorological parameters were collected from four stations within the catchment area. Three of these stations, namely Muka Turi, Debre Tsige, and Fiche, obtained their data from the National Meteorological Agency. Additionally, one station utilized data obtained from the NASA Prediction of Worldwide Energy Resource (NASA POWER) satellite, accessible at the provided URL (https://power.larc.nasa.gov/data-access-viewer/).It provides hourly, daily, monthly, and annual time scales information on near-surface air temperature, relative humidity, rainfall, solar radiation, and wind speed and direction. These datasets are generated through simulations using numerical weather prediction models based on a collection of meteorological observations (Chandler et al., 2013). Several studies, including those conducted by (Bai et al., 2010; Rodrigues, 2021; J. W. White et al., 2008), have assessed the accuracy of NASA POWER data. They have concluded that there is a strong correlation between NASA POWER and observed data, with a maximum root mean square error (RMSE) of 4.0°C. These findings indicate that NASA POWER data aligns well with measurements obtained from ground weather stations. This high level of agreement with observed values on the ground is the primary reason for utilizing NASA POWER data in this thesis.

  It is important to note that among the four stations, only Fiche and the satellite station provide comprehensive climate data, encompassing all the required meteorological parameters.

- Geological and hydrogeological information: A geological and hydrogeological map, well completion report, data from pumping tests, well logs, and information about groundwater levels were gathered from different organizations such as the Ethiopian Construction Design and Supervision Works Corporation, Engineering Corporation of Oromia, and Geological Institute of Ethiopia
- Field observations: Readings of borehole locations and elevations, rainfall data, and ground truth observations, including geological descriptions, stratigraphy, geomorphologic setting, and discharge locations were collected through fieldwork. A topographic map was utilized to locate the observation stations, and portable Garmin GPS device was employed to record the exact locations.

After the collection of primary and secondary data, data compilation, processing, and analysis were performed to meet the input requirements of the groundwater model. The raw data were checked for continuity and consistency before being used in the modeling process.

3.3.1 Estimation of Missed Climate Data

Data was checked if there is missed data. Long time series data may be missed due to construction of new building, fence, changing of gauge location, planting of trees or cutting of forest nearby or another from a recording gauge. Missing records of the rainfall data was estimated by using normal ratio method which is recommended to estimate missing data in the catchment where annual rainfall among stations differ by more than 10% (Dingman, 2002). For this study the missing percentage is 13%. This approach enables an estimation of missing rainfall data by weighting the observation at N gauges by their respective annual average rainfall values as expressed by equation below.

$$P_x = \frac{1}{N}\left(\sum \frac{p_x}{p_i} * p_g\right)$$ Where:

P_X = missing data, p_x = the annual average precipitation at the gauge with the missing data, p_i = annual average values of neighbouring stations, p_g = monthly rain fall data in station for the same month of missing station, and N = the total number of gages under consideration.

Additionally, the widely used interpolation tool called Inverse Distance Weighting (IDW) within the ArcGIS spatial analyst module was selected to predict the spatial distribution and generate various raster maps for further analysis. IDW is a commonly used interpolation method that estimates values at unmeasured locations based on the values at neighboring measured locations. This technique is easier and quicker to implement even in limited number of data than others. The way IDW works is that it requires everything being related to everything else, but near things are more related than distant things. To predict a value for any unmeasured location, IDW uses measured values surrounding the prediction location and assumes that each measured point has a local influence that diminishes with distance (Gebru et al., 2019). Inverse distance weighting is a deterministic method that uses a weighted average of nearby locations with the closer point to the center of the cell being estimated as described in the following (Zeiler M, 2010).

$$Z(X_0) = \frac{\sum_{i=1}^{n} Z(Xi) d_{ij}^{-r}}{\sum_{i=1}^{n} d_{ij}^{-r}}$$

Where x_0 is the estimation point and x_i are the data points within a chosen neighborhood. The weights (r) are related to distance by d_{ij}, which is the distance between the estimation point and the data points. Interpolated maps were verified using randomly selected measured values.

3.3.2 Data Consistency Analysis

To assess the consistency of records at a particular station, a Double Mass Curve (DMC) technique was employed. This technique involves plotting the cumulative annual (or seasonal) precipitation data from the station against the concurrent cumulative values of mean annual (or seasonal) precipitation from a group of base stations (Zemadim, 2010). The purpose of this plot is to compare the cumulative precipitation collected at the gauge of interest, where measurement conditions may have significantly changed, with the average cumulative precipitation collected at several gauges in the same region. The underlying principle of the DMC technique is that if the recorded data comes from the same base station, they should exhibit consistency. Therefore, the double-mass curve is a graphical representation of the cumulative catch at the gauge of interest in relation to the cumulative catch from one or more gauges in the region that have experienced similar hydro-meteorological events and are known to be consistent. If the rainfall record accurately reflects the hydro-meteorological occurrences over the entire recording period, the double-mass curve will exhibit a constant slope. A consistent record refers to a record where its characteristics have remained unchanged over time. On the other hand, if there is a change in the slope of the double mass curve, it indicates that an external factor has influenced the properties of the measured values. In such cases, adjustments are required for the record, either by modifying the early or later period of the recorded data.

A set of four base stations located in the vicinity of the station was selected for analysis. The data from these stations were arranged in reverse order, with the most recent record listed first and the oldest record listed last. The objective of this arrangement was to examine the proportionality between the measurements at the suspect station and those obtained from the surrounding region. Any change in this proportionality would be reflected in a change in the slope of the trend observed in the plotted points. If the Double Mass Curve analysis reveals a significant change in slope that can be attributed to altered measurement conditions at the suspect station, it is necessary to adjust the values of the earlier period in the record to ensure consistency with the later period records. This adjustment is crucial before computing areal averages. To achieve this adjustment, a correction factor denoted as K is applied to the records preceding the slope change. The relationship for calculating this correction factor is as follows.

$$K = \frac{\text{Slope for period after slope change}}{\text{Slope for period before slope change}}$$

Cumulative data is plotted on the graph. Accumulated precipitation data of singular station is on Y axis and average accumulated precipitation data of neighboring stations is on X axis. Locate where the graph deviates and then the slope of the good data is found. The slope of the data want to be adjusted is founded again. Multiply this data by the factor founded before and then the new cumulative data is calculated. Finally the new data was plotted.

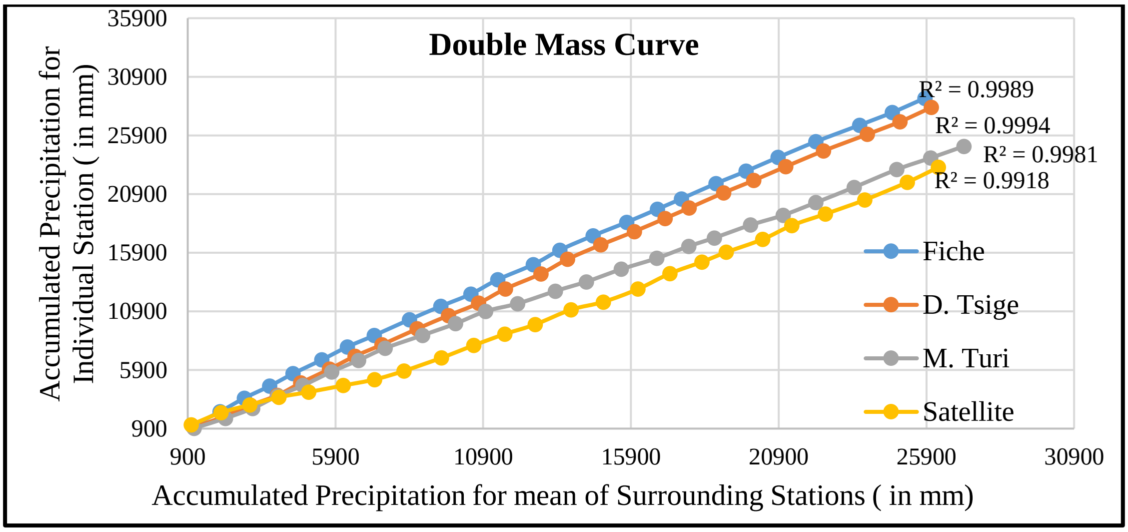

Figure 3.4 Cumulative of Each station vs Cumulative of Group station double mass curve

3.4 Conceptual Framework of the Study

The conceptual framework diagram shown in figure 3.5 is designed to create Schematic view of the overall techniques followed in the research work. And the route followed from the beginning of data collection to the succeeding of the study objectives is presented.

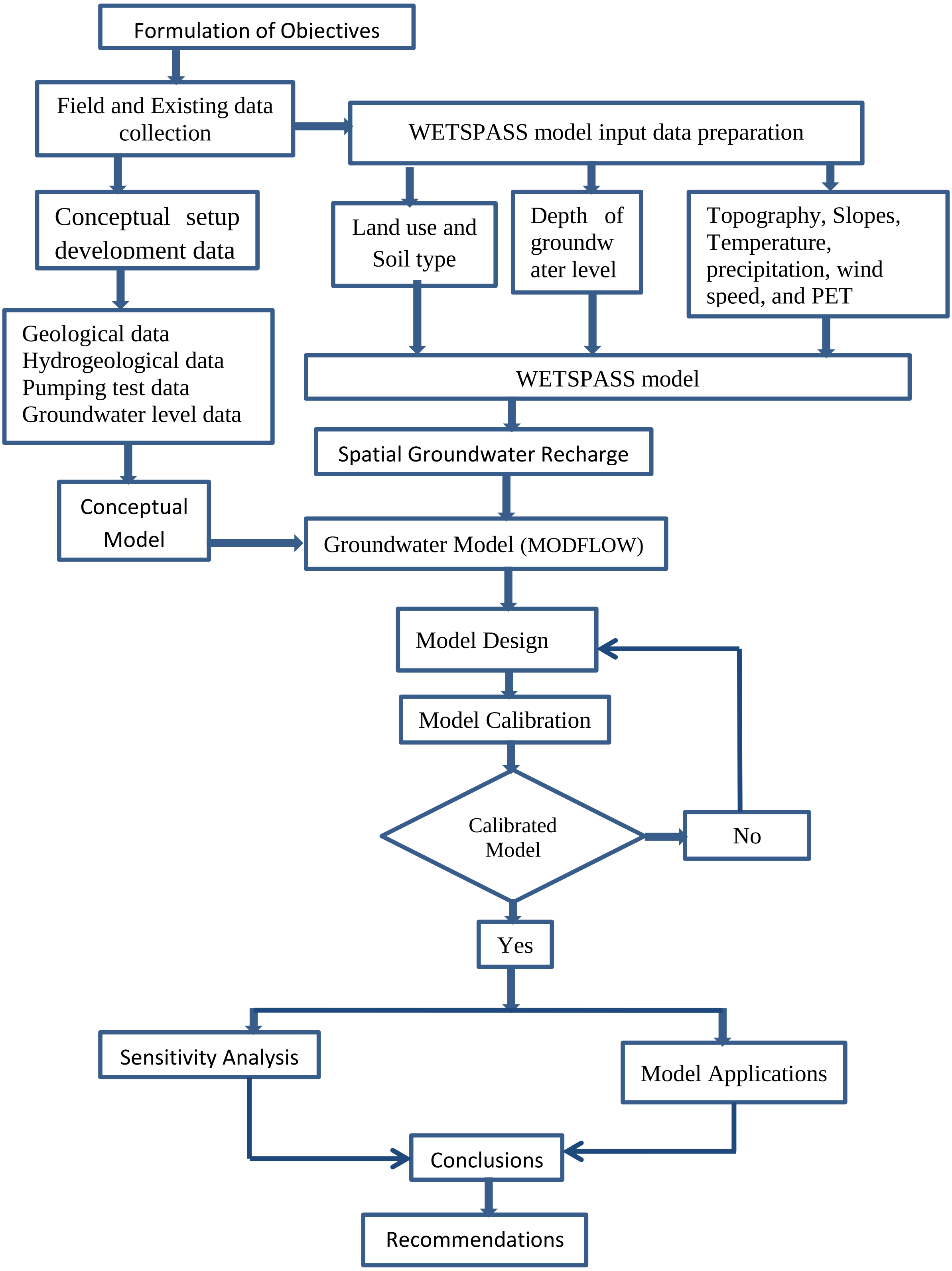

Figure 3.5 Conceptual framework diagram

4. PRELIMINARY ANALYSIS

4.1 Meteorological Data Analysis

4.1.1 Precipitation

The analysis of rainfall distribution and its temporal variability in the study area was conducted using rainfall data. The results revealed a unimodal (single peak) rainfall pattern, with the main rainy months occurring in June, July, August, and September, which are considered the wet season. The rainfall analysis of the catchment is a crucial component of the study as it directly influences the recharge of the study area. Data from three meteorological stations and one satellite data was collected and presented in table 4.1. The mean annual rainfall varied between 1029 and 1198 mm across the stations from 1990 to 2022 G.C. During the dry season, the average monthly rainfall was recorded at 33 mm, while the summer season (spanning from June to September) exhibited an average monthly rainfall of 207 mm. The highest mean monthly maximum rainfall of 369 mm was observed in July at the Fiche station.

Table 4.1 Mean monthly rainfall distribution (mm) / 1990 – 2022/

Name of Stations	Jan	Feb	Mar	Apr	May	Jun	Jul	Aug	Sep	Oct	Nov	Dec	Total
Fiche	17	25	53	64	61	95	369	351	118	19	13	13	1198
Debre Tsige	25	26	59	59	48	83	299	277	111	38	18	16	1059
Muke Turi	19	20	59	50	54	98	306	316	116	26	10	8	1081
Satellite	11	25	45	67	57	111	269	267	124	27	13	12	1029
Average	18	24	54	60	55	97	311	303	117	27	14	13	1092

At all stations, the highest amount of rainfall consistently occurs in August and July. These months represent the primary rainy season, which coincides with the wet season. This period of intense rainfall is vital for replenishing freshwater reservoirs, strengthening springs, and facilitating the presence of groundwater. Additionally, there is a secondary rainy season that occurs from the end of February to May. While this season's rainfall is relatively less significant, it still plays a role in supporting small-scale agriculture, providing grazing grass for livestock, and sustaining the local flora and fauna in the area.

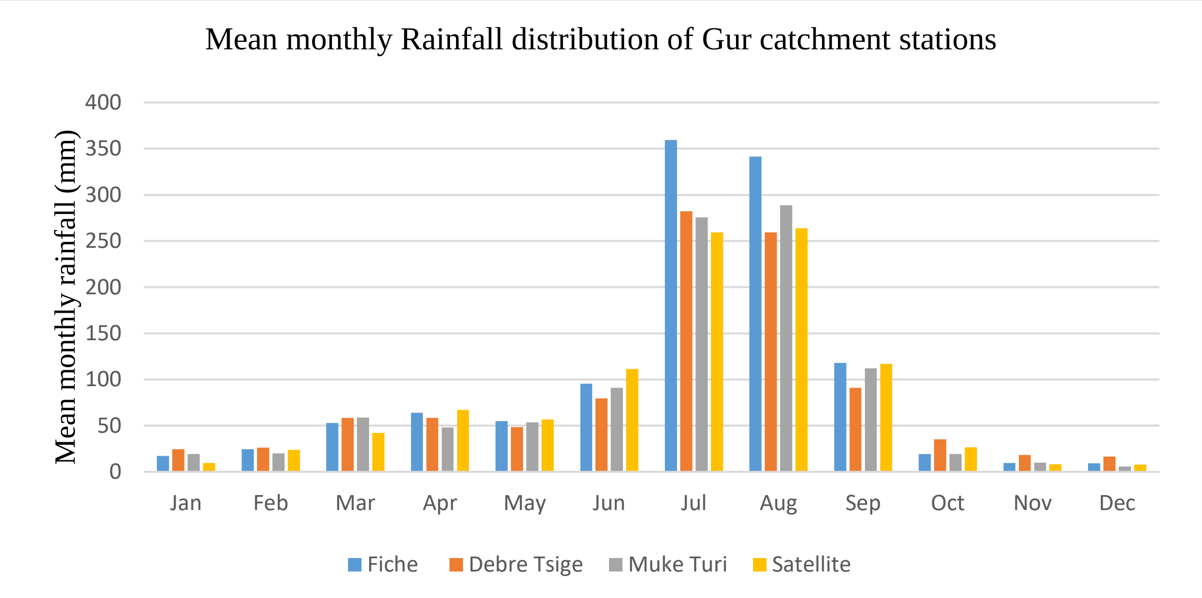

Figure 4.1 Mean monthly rainfall distribution for the periods of 1990─2022

(Source: Ethiopian Meteorological Agency and NASA)

Rainfall distribution in space

The precipitation of Gur catchment was assessed by analysing data from the four stations located within the area. The mean areal depth of precipitation over the catchment was determined using the Thiesen polygon method, which involved constructing a Thiesen polygon incorporating all four stations. Based on this analysis, the catchment was found to receive an average annual precipitation of 1085 mm.

Table 4.2 Areal mean depth of Rainfall using Thiesen polygon

Name of Stations	Rainfall (Pi)	Area (Ai)	Ai*Pi
Muke Turi	1081	118	127087
Satellite	1029	127	130701
Debre Tsige	1059	176	186529
Fiche	1198	109	130741
Total		530	575058

$$\overline{P} = \frac{1}{A}\sum_{i=1}^{N} AiPi = \frac{547259}{530} = 1085 \text{ mm}$$

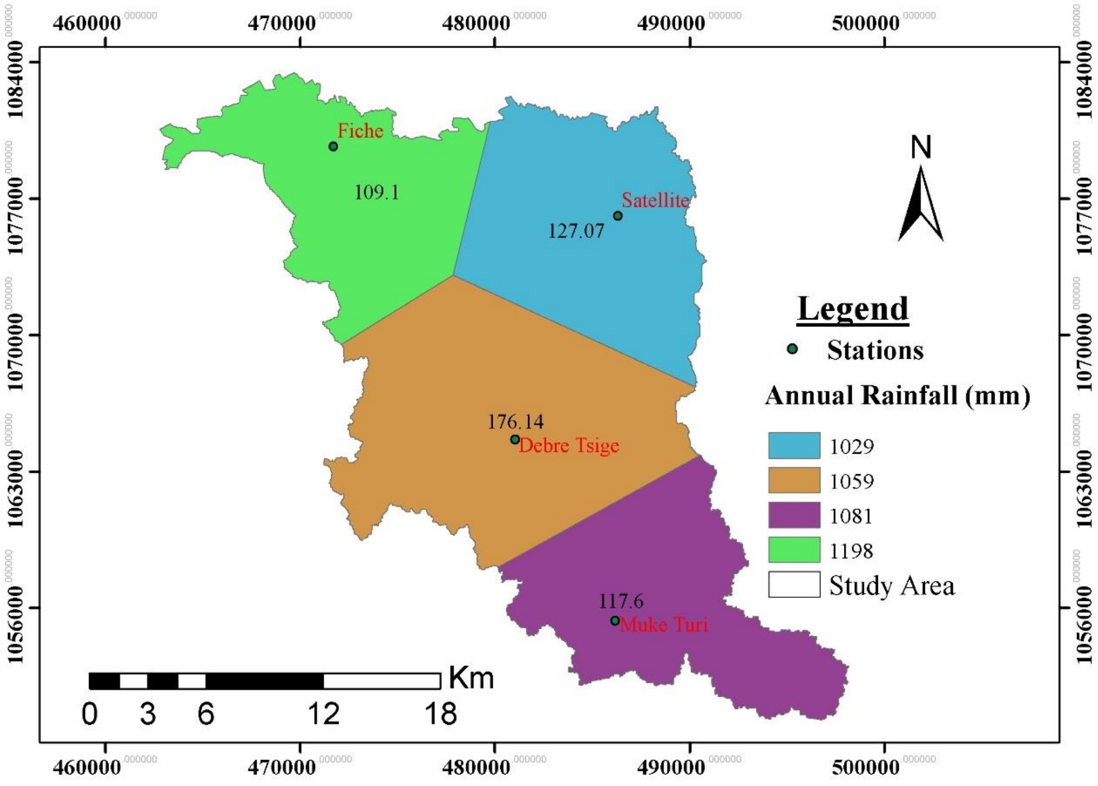

Figure 4.2 Constructed Thiessen polygon for each station

4.1.2 Temperature

The mean monthly temperature in the Gur catchment varies between different stations. At the Fiche and Satellite stations, the maximum mean monthly temperature ranges from 21.8°C during the wet season to 24.4°C during the dry season. The minimum mean monthly temperature ranges from 4.6°C to 10°C, as indicated in table 4.3 and figure 4.3. Unlike precipitation, the temperature in the study area generally decreases with increasing elevations, as shown in figure 4.3. The mean monthly temperature in the catchment ranges from the lowest value of 14.5°C in December to the highest value of 18.1°C in May. The mean annual temperature for the catchment is 15.4°C, as stated in table 4.3

Table 4.3 maximum and minimum average Temperature of Gur catchment

Stations	Temp	Jan	Feb	Mar	Apr	May	Jun	Jul	Aug	Sep	Oct	Nov	Dec
Fiche	TMPMAX	20.3	21.7	22.2	22.4	22.8	22.2	18.2	17.8	18.7	19.4	19.7	19.8
	TMPMIN	7.0	8.2	9.2	9.7	9.9	9.7	9.5	9.4	9.0	6.7	6.1	6.1
	Average	13.7	14.9	15.7	16.0	16.4	15.9	13.8	13.6	13.9	13.1	12.9	12.9
Satellite	TMPMAX	26.0	26.1	26.3	26.2	26.0	26.0	25.8	25.7	25.7	25.7	25.8	25.9
	TMPMIN	4.2	5.8	7.2	8.5	9.5	10.2	9.5	9.5	8.3	4.6	3.3	3.2
	Average	15.1	15.9	16.7	17.4	18.1	17.4	17.6	17.6	17.0	15.2	14.6	14.5

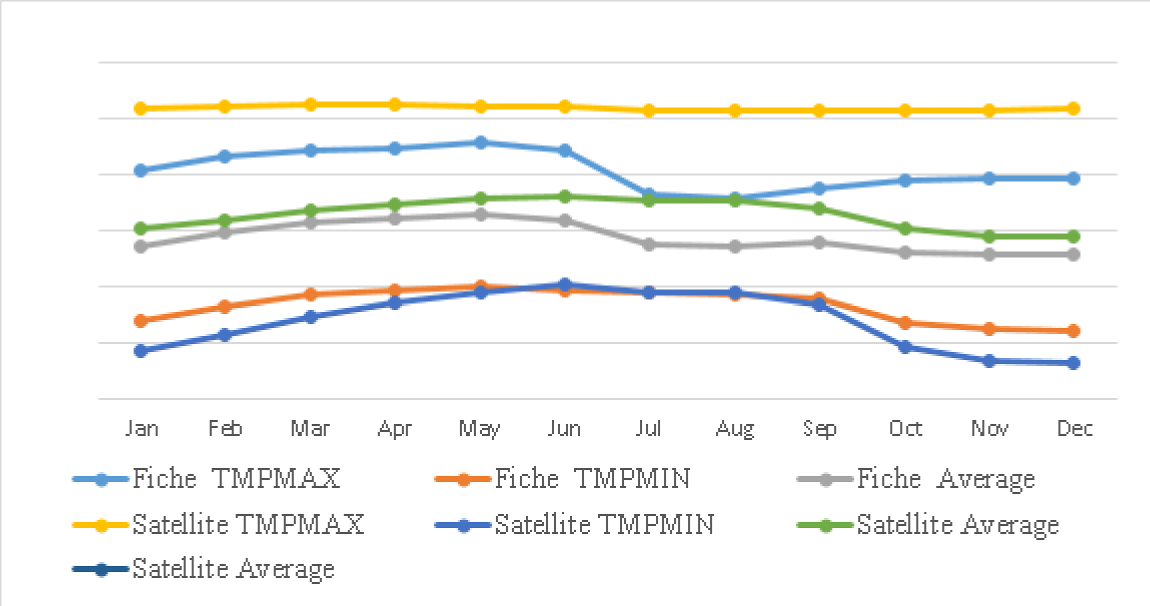

Figure 4.3 The Gur catchment's average lowest and maximum monthly temperatures from 1990 to 2022.

4.1.3 Relative humidity, Wind speed, and sunshine hours

The mean monthly wind speed in the catchment is 2.0 m/s, accompanied by an average of 7.6 sunshine hours per day. The decrease in temperature from month to month is influenced by factors such as low sunshine hours, high wind speed, and relative humidity. The area is characterized by a mean monthly relative humidity of 64.7%. The relative humidity ranges from 53.7% in December and January to 83.7% in August. Notably, the relative humidity shows high values from mid-July to mid-September. These variations in relative humidity contribute to the overall moisture content and climatic conditions in the catchment.

Table 4.4 Average monthly Wind speed, Sunshine hours and Relative humidity of Gur catchment

	Jan	Feb	Mar	Apr	May	Jun	Jul	Aug	Sep	Oct	Nov	Dec
Wind Speed	1.4	1.5	1.6	1.7	1.8	1.4	1.2	1.1	1.2	1.5	1.4	1.3
Relative Humidity	55.0	53.3	56.4	60.8	60.5	64.7	81.9	83.4	78.6	68.3	63.6	56.9
Sunshine Hours	8.8	8.4	7.7	7.6	8.5	7.3	4.6	5.0	7.0	8.9	8.8	8.9

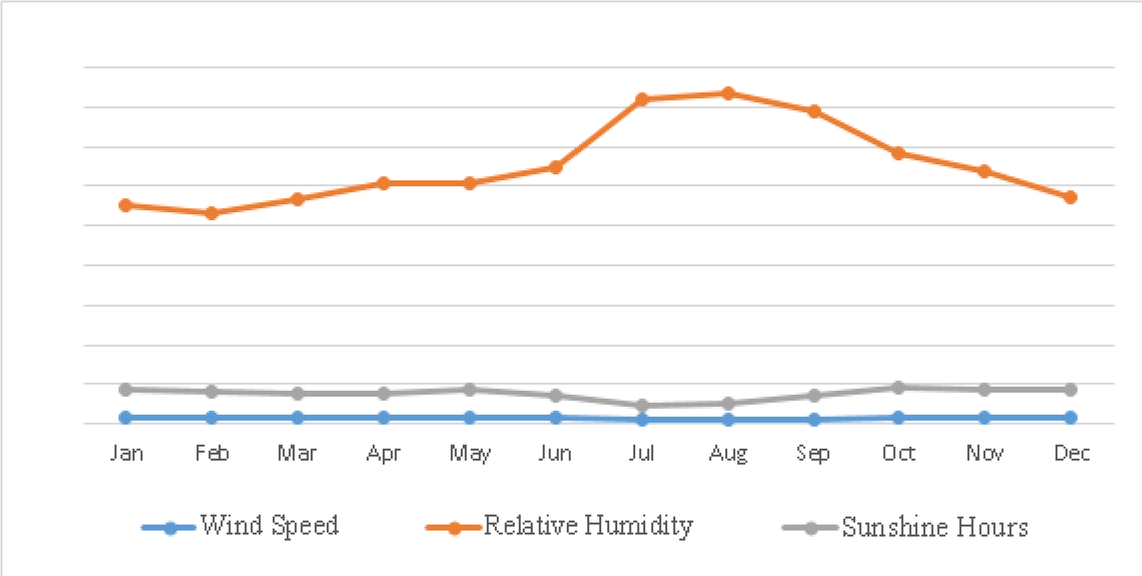

Figure 4.4 Average monthly wind speed, sunshine hours and Relative humidity of the study area

4.2 Groundwater recharge estimation

Groundwater recharge refers to the mechanism through which water infiltrates into the soil and eventually reaches the underground aquifer system (Freeze & Cherry, 1979). This replenishes the groundwater reservoir with water sourced from the land surface, occurring naturally or through artificial means (Arefaine et al., 2012). It serves as the fundamental basis for the hydrologic processes within the subsurface water system, as it plays a vital role in replenishing water within the aquifer system (Teerapunyapong et al., 2020b). Gaining a comprehensive understanding of the spatial and temporal distributions of water balance components, with a specific focus on groundwater recharge, is of utmost importance for effective water resource management and accurate modeling of subsurface fluid and contaminant transport (Arefaine et al., 2012). Estimating groundwater recharge is a task that presents challenges and complexities due to the dependence on various parameters. Factors such as topography, soil texture, and land use/land cover (LULC), groundwater depth, meteorological conditions, and other hydrological characteristics all contribute to the intricate nature of groundwater recharge estimation (BGS, 2016). Multiple methods exist for estimating groundwater recharge, encompassing various approaches. These include Base Flow (BF) separation, chloride mass balance (CMB), statistical techniques like water table fluctuation (WTF), and numerical methods such as water balance simulation. Each method offers a distinct approach to estimating groundwater recharge, allowing for flexibility and adaptation based on available data and specific study objectives (Acharya et al., 2018).

4.2.1 WetSpass model Method

Numerous factors play a role in influencing the process of groundwater recharge. Some of the key factors include: the characteristics of the land surface and underlying geological formations; the amount, intensity, duration, and spatial distribution of rainfall; the presence of runoff and the formation of ponds or temporary water bodies; irrigation practices; the interaction between rivers and aquifers; and soil characteristics (Rwebugisa, 2008).

In the context of this study, the WetSpass model has been chosen to be employed as a physically based methodology for estimating the long-term average of various water balance components. These components include surface runoff, actual evapotranspiration, and groundwater recharge. The WetSpass model, developed by (Batelaan & Smedt, 2001), is specifically designed to estimate the spatially varying patterns of these water balance components over extended periods. The name "WetSpass" itself reflects the purpose of the model, which is to analyze the transfer of water and energy between the soil, plants, and the atmosphere under quasi-steady state conditions. The model builds upon the fundamental principles of a time-dependent spatially distributed water balance model (Batelaan & Smedt, 2007).

The WetSpass model is primarily concerned with simulating hydrological processes and parameters on a basin scale, focusing on long-term average spatial distributions. It operates under the assumption of a quasi-steady state, which means that it considers only seasonal or monthly temporal fluctuations while disregarding shorter-term variations. This approach allows the model to provide valuable insights into the spatial distribution of water balance components over a long-term average. In practice, the WetSpass model divides precipitation into three main components: surface runoff, actual evapotranspiration, and groundwater recharge. By analyzing these components, the model can generate maps that depict their long-term seasonal values across different spatial locations within the study area. It is worth noting that, within the context of this research, the term "runoff" specifically refers to the surface component of river flow (Yenehun et al., 2022).

$$P = S + ET + R \quad (1)$$

Equation (1) represents the overall water balance equation, where precipitation (P) is equal to the sum of surface runoff (S), actual evapotranspiration (ET), and groundwater recharge (R).

$$S = f_1 * P_n \quad (2)$$

Equation (2) describes the calculation of surface runoff (S), which is determined by the runoff factor (f1) influenced by land use and vegetation characteristics, soil texture, and slope. Net precipitation (Pn) refers to the precipitation reaching the ground surface after subtracting the amount intercepted by the plant canopy.

$$ET = f_2 * EP \qquad (3)$$

Equation (3) represents the calculation of actual evapotranspiration (ET), which is determined by the evapotranspiration factor (f2) influenced by land use, vegetation characteristics, soil texture, and the potential evaporation of open water (EP).

Groundwater recharge is determined as the balancing term in equation (1). The WetSpass model calculates each hydrological component at the pixel scale by dividing each pixel into categories such as open water, impervious surface, bare soil, and vegetated areas. The model assigns percentage values to these categories based on land use classes specified in the parameter table, with some adjustments made by local experts. The study area is divided into a grid of equally sized columns and rows. WetSpass requires parameter tables as inputs in addition to grid maps. While certain land-use parameters and the number of rainy days may be adjusted based on measured data specific to the local context, default values for soil-related parameters are retained. For instance, the root depth for forest areas may be modified based on the prevalent tree species in the region.

4.2.1.1 WetSpass Model Input Data Preparation

Topography

The study utilized a Digital Elevation Model (DEM) obtained from the United States Geological Survey (USGS) SRTM data sets. The catchment's lowest elevation point, located downstream, was recorded at 1305 m, while the highest point in the upper stream area reached 3454 m. The average elevation of the catchment, calculated from the DEM, was determined to be 2438 m. figure 3.2 provides a visual representation of these elevation characteristics within the catchment.

Slope

The catchment exhibits a range of slope variations, ranging from level landforms to extremely steep-sided cliffs. The steepest slopes are primarily located in the sides of river gorges, particularly in the northeastern part of the study area where Mesozoic sedimentary rocks are present. The slope gradient of the study area is categorized into six classes: 0- 4, 4-10, 10-19, 19-30, 30- 44, and >44 degrees, representing areas with nearly horizontal to very steep slopes. Based on the slope classification map (figure 4.5), it is observed that a significant portion of the catchment falls within the 0- 4 degree slope range. The slope of an area plays a key role in determining various factors, such as the amount of runoff, percolation, soil thickness, vegetation cover, and watershed density. These factors, in turn, influence the percentage of recharge from the total precipitation in the catchment.

Land use land cover

In hydrological and groundwater studies, land use plays a significant role as one of the major controlling factors for various hydrological processes within a catchment. These processes include recharge (the replenishment of groundwater), evapotranspiration (the combined loss of water through evaporation from soil and transpiration from plants), and runoff (the movement of water over the land surface) (Pan et al., 2011). The LULC map provides important data about land cover types, allowing the WetSpass model to simulate processes such as surface runoff, groundwater recharge, and evapotranspiration.

Soil map

The soil map of the Gur catchment area was obtained from the detailed study map conducted by the Engineering Corporation of Oromia (ECO) region, focusing on the Abay basin. The primary soil classification system used in WetSpass, based on soil texture, was developed by ECO. According to the soil classification derived from the ECO study, the dominant soil type in the Gur catchment is clay, loam, clay loam, and silty clay (figure 4.5). The soil map of the study area was converted raster and then ASCII format.

Groundwater depth

The groundwater level map plays a critical role in accurately estimating groundwater recharge using the WetSpass model, as it provides essential insights into the depth and distribution of groundwater throughout the catchment. In this particular study, the groundwater depth grid map was created by utilizing data from 84 boreholes located within and in close proximity to the catchment area. By subtracting the measured static water level from the surface elevation, the groundwater depth was determined. To visualize this information, a raster map was generated using ArcGIS and the IDW interpolation method. The resulting groundwater elevation values depicted in the map range from 2946 meters to 2408 meters, with an average elevation of 2623 meters. Within the Gur catchment, the static water level varies from 1 meter to 106 meters below the surface, with the maximum depth reaching 492 meters. Additionally, the escarpment region of the study area contains both seasonal and perennial springs, further contributing to the groundwater dynamics.

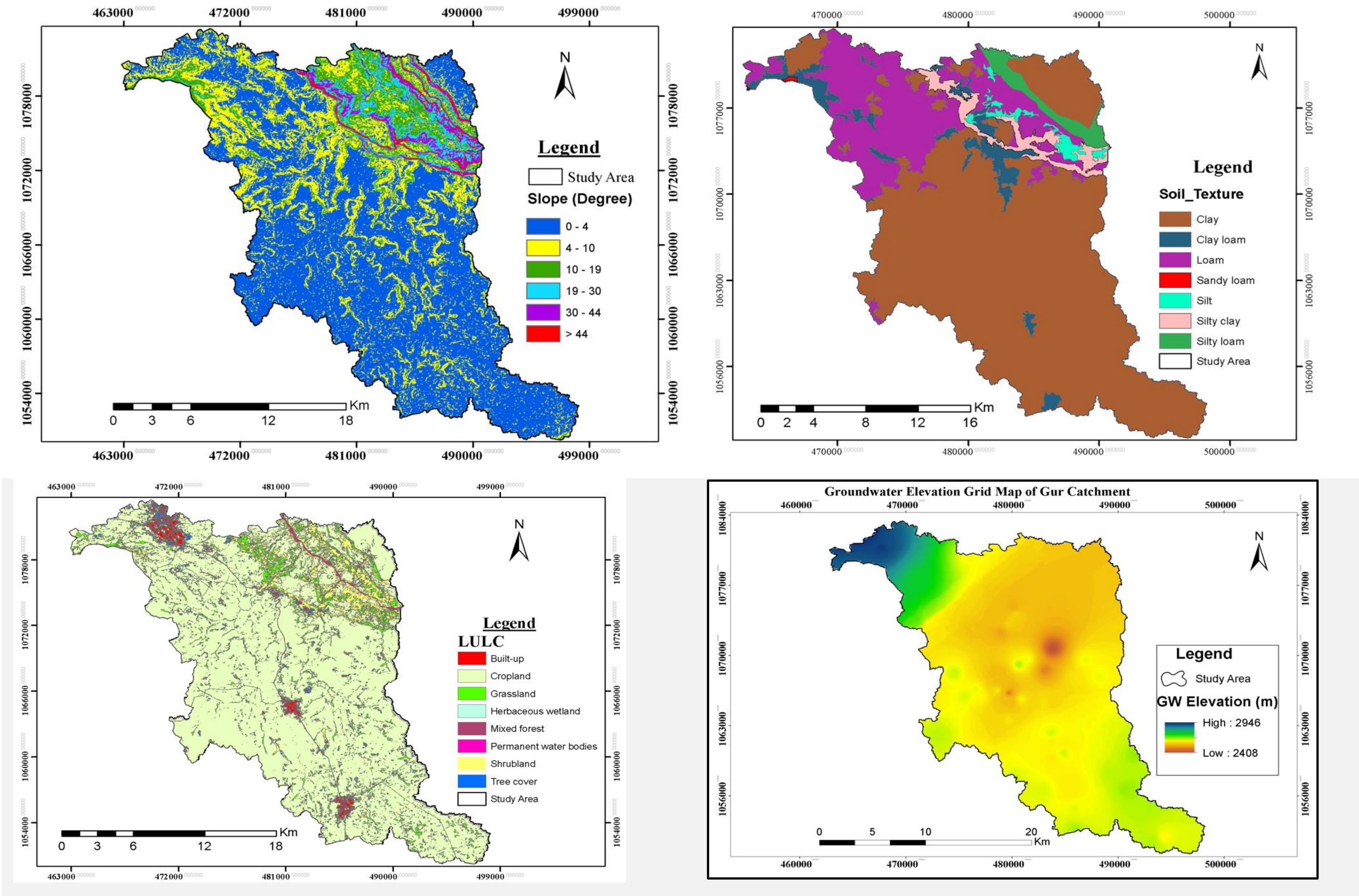

Figure 4.5 Spatial distribution Maps of Slope, Land use land cover, Soil texture, and Groundwater Elevation of Gur Catchment

Precipitation

To generate the distributed rainfall map, point rainfall data from three meteorological stations and one satellite data source are used as input. These stations are strategically located within the catchment to capture rainfall measurements from different areas. The satellite data provides additional spatial coverage, enhancing the accuracy and coverage of the rainfall information.

The annual mean rainfall value for the catchment is calculated to be 1092 mm. This value represents the average rainfall amount received in the catchment over a year. It serves as a representative measure of the typical or central rainfall amount experienced within the catchment. The grid map used in the catchment simulation model is shown in the figure below. This grid map represents the spatial distribution of rainfall across the catchment. Each grid cell in the map corresponds to a specific area within the catchment, and the rainfall values assigned to these cells are derived from the interpolation analysis.

Temperature

The temperature data collected from the Fiche meteorological station and satellite data from NASA POWER (https://power.larc.nasa.gov/data-access-viewer/) were combined to create a comprehensive dataset for analysing temperature variations in the study area. The Fiche meteorological station is a ground-based station that provides local temperature measurements, while satellite data offers a broader perspective by capturing temperature information from a larger spatial extent. These two data collected were utilized to generate a temperature variation map. This map visually represents how temperatures change from the plain area to the escarpment. By analyzing this map, researchers and meteorologists can gain insights into the spatial distribution of temperature and identify any patterns or gradients that exist within the study area.

The minimum temperature recorded annually is 7.7°C, indicating the coldest temperature experienced in the region. On the other hand, the maximum recorded temperature is 23.2°C, representing the highest temperature observed. These values provide an understanding of the temperature range in the study area. The mean temperature, which is the average temperature across the entire dataset, is calculated to be 15.4°C. This value gives an indication of the central tendency of the temperature distribution in the study area. Additionally, the standard deviation of 1.2°C represents the variability or spread of the temperature data around the mean. A lower standard deviation suggests less variability, while a higher standard deviation indicates greater variability in the temperature values.

Furthermore, the mean temperature values for the dry and wet seasons are reported as 15.2°C and 16°C, respectively. This information highlights the distinction between temperature conditions during these two distinct seasons. It provides insights into the temperature differences that can be expected between the dry and wet periods, which can be useful for various applications such as agriculture, tourism, and climate studies.

Potential evapotranspiration

Potential evapotranspiration (PET) is the maximum amount of water that can be evaporated or transpired from the Earth's surface under conditions of abundant soil moisture. In the case of the Gur catchment, PET was determined using data from Fiche meteorological station and a satellite data that measured minimum and maximum temperatures.(Thornthwaite, 1948) developed an empirical formula for calculating PET based on average monthly temperature and day length. The most significant methods have been used in estimation potential Evapotranspiration (PE) based on the monthly average temperature. Thornthwaite method is the empirical formula, although it entirely depends on the air temperature and latitude of the site, it was widely accepted, mainly due to its ease of use by means of tables and monographs (Al-sudani, 2019; Res et al., 2005). This formula assumes an exponential relationship between mean monthly temperature and consumptive water use. The formula proposed by Thornthwaite is as follows:

$ET = 1.6c\ [10Ta/I]^{a}$, where ET represents the monthly potential evapotranspiration in centimeters per month, Ta is the mean monthly air temperature in degrees Celsius, I is the annual heat index calculated as the sum of $(Tai/5)^{1.514}$, and c is a latitude correction factor. The mean monthly air temperature is used to estimate PET. To spatially represent PET across the Gur catchment, the calculated PET values were converted into grid maps using interpolation techniques. These grid maps, along with other input data, were then used in the WetSpass model to estimate groundwater recharge, surface runoff, and actual evapotranspiration.

The PET values in the Gur catchment exhibit variation throughout the year, ranging from 47 to 72 mm/month. This indicates that evapotranspiration rates are higher during the warmer months when solar radiation and temperatures are elevated. The average annual PET for the Gur catchment, based on the collected data, is calculated to be 716 mm/year. This value provides an overall estimation of the evaporative demand in the catchment throughout the entire year. As indicated in figure 4.6, analyzing the average PET values for individual months, there is a gradual increase from January to May, with a peak reached in June. From June onwards, PET values gradually decrease until November, followed by a slight increase in

December. Understanding the seasonal patterns and variations in PET is crucial for water resource management, irrigation planning, and assessing the water balance in the Gur catchment.

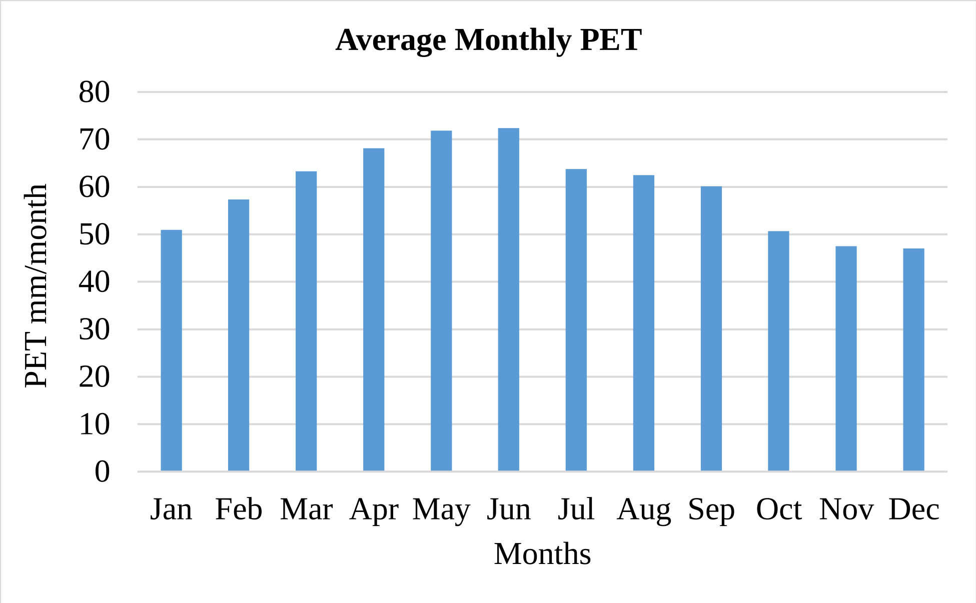

Figure 4.6 Average monthly Potential evapotranspiration

Wind speed

Wind speeds exhibit seasonal variation throughout the year within the Gur catchment. The average monthly wind speed, measured at a height of two meters above the ground, ranges from 1.2 to 3.1 m/s. The average annual wind speed for the Gur catchment is approximately 2.1 m/s. During the summer months of July and August, wind speeds generally tend to be lower, averaging around 1.1 to 1.2 m/s. Conversely, wind speeds are typically higher during the spring and autumn months, specifically from April to June and September to November, with values ranging from 1.4 to 1.8 m/s.

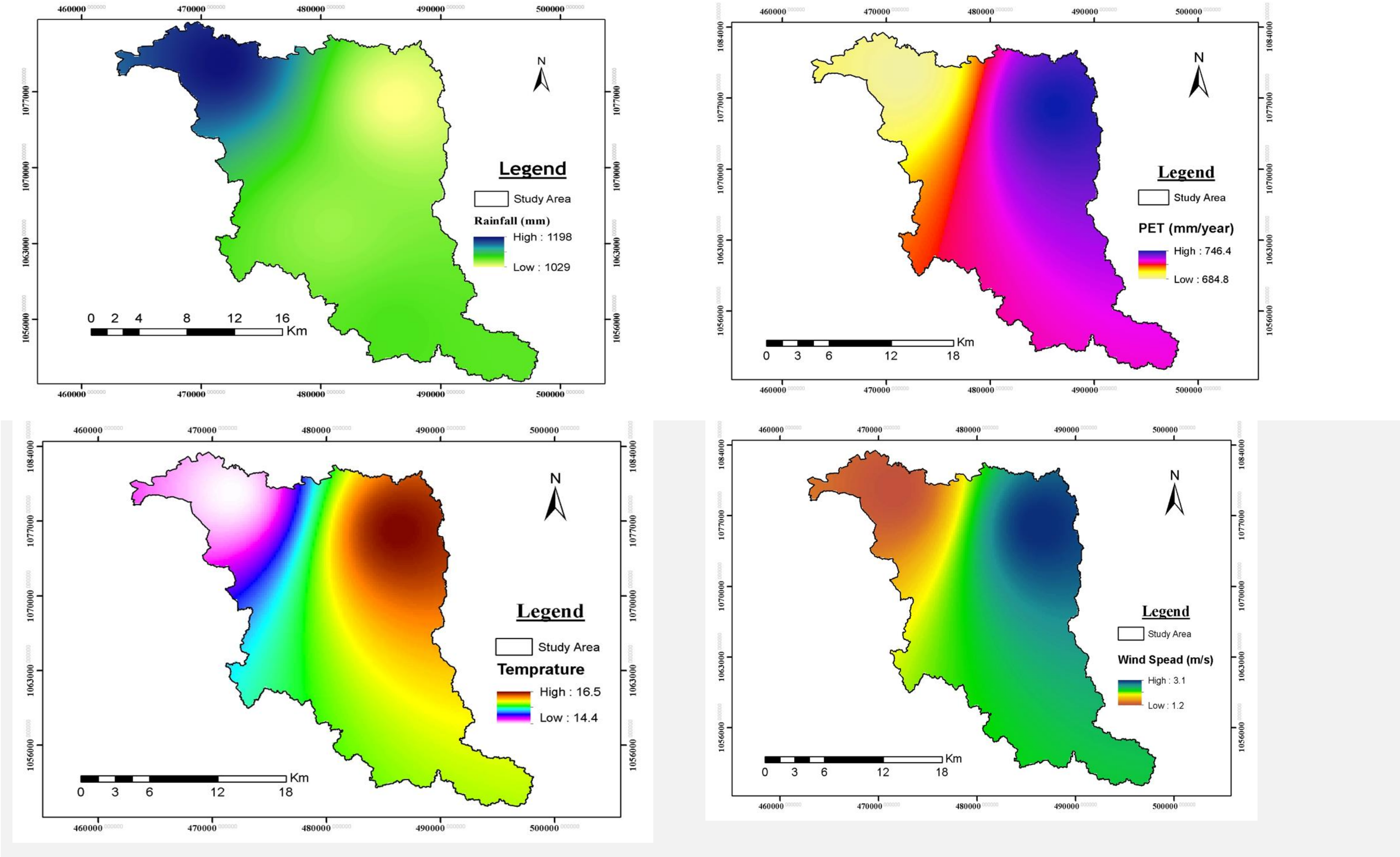

Figure 4.7 Spatial distribution Maps of Average annual Rainfall, Temperature (in °C), Potential evapotranspiration and wind speed of Gur Catchment.

1

Parameter tables

Parameter tables play a crucial role in hydrological and environmental modeling, particularly when simulating the behavior of catchment. These tables are used to link the specific characteristics of land use/land cover and soil types to the corresponding grid cells or spatial units within the simulation model (Olabode & Comte, 2022).

Land use/land cover parameters in the table describe the characteristics and properties of different land cover types, such as forests, agriculture, urban areas, or water bodies. These parameters can include factors like surface roughness, infiltration rates, vegetation density, and evapotranspiration rates. By associating these parameters with the grid cells or spatial units, the model can accurately represent the hydrological processes and interactions within the catchment. Similarly, the soil parameters in the table provide information about the properties and behavior of different soil types present in the catchment. These parameters include soil texture characteristics. By linking these soil parameters to the corresponding grid cells or spatial units, the model can simulate water movement, infiltration, runoff generation, and other soil-related processes.

During the simulation, the model refers to the parameter tables as lookup tables. When a computation or analysis is performed at a specific grid cell or spatial unit, the model retrieves the corresponding land use/land cover and soil parameters from the tables. This approach enables the model to incorporate the appropriate characteristics and properties for each location, enhancing the accuracy of the simulation results.

4.2.1.2 WetSpass Results

The WetSpass model result comprises seasonal, Annual and monthly hydrologic outputs. This model generated the outputs of Groundwater recharge, Annual Actual Evapotranspiration and Surface Runoff of the study area. The results are provided in the form of grid maps of 200 m resolution. In these maps, every pixel represents the magnitude of the water budget component (in mm). The annual groundwater recharge ranges from 0 mm to 318 mm and has a mean value of 106 mm/year. From this, about 80 mm is recharged in the wet season and 26 mm in the dry season. The estimated annual recharge is about 10% of the total mean catchment precipitation. The estimated annual runoff for the whole catchment is about 426 mm/year, accounting for about 39% of the average precipitation. About 95% of the runoff is taking place during the wet season, while the remaining is taking place during the long dry season. Relatively higher runoff is observed in the north eastern, and lower runoff has been noted in the central and southern part of the catchments. The total estimated annual Actual evapotranspiration over the catchment is 561 mm/year, which is 51% of the mean catchment precipitation.

Table 4.5 Monthly, annual, and seasonal WetSpass simulated components of Gur catchment

Period	Precipitation (mm)	Recharge (mm)	Evapotranspiration (mm)	Runoff (mm)
Monthly Range	13-311	1-27	11-86	0-173
Monthly Average	91	9	47	36
Monthly Std.dev.	106	9	30	63
Dry Season	265	26	230	20
Wet Season	828	80	331	406
Annual	1093	106	561	426

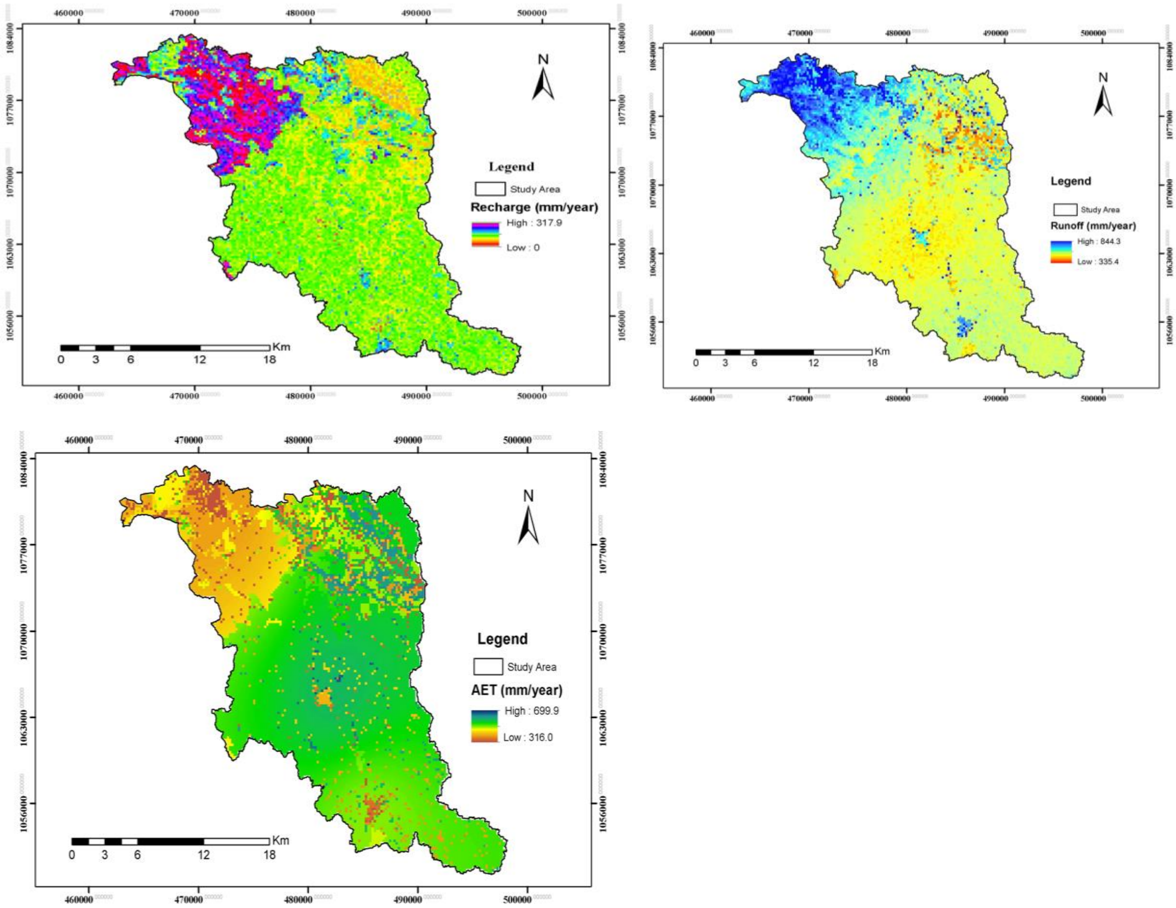

Figure 4.8 Spatial distribution of simulated mean annual water balance component

One of the limitations encountered in this study is the absence of WetSpass model calibration. This limitation arises due to the inherent characteristics of the WetSpass model, which operates based on monthly or annual average water balance computations rather than continuous time series analysis. Consequently, it is not feasible to calibrate the model against continuous river discharge data, as such data is not compatible with the model's computation approach. This limitation is not unique to the present study but is observed in previous studies conducted in Ethiopia and other regions as well. Given the nature of the WetSpass model and its reliance on monthly or annual averages, calibration of the model has not been a common practice in the literature (Al-badry & Shamkhi, 2021; Al Kuisi & El-Naqa, 2013; Arefaine et al., 2012; Bitsiet & Dessie, 2018; Meresa & Taye, 2019; Zdon et al., 2019). This limitation is acknowledged and considered in the analysis. To address this limitation, the simulated results were verified using alternative methods such as the Chloride Mass Balance method and previous studies conducted by other researchers. These approaches provide additional means of assessing the accuracy and reliability of the simulated results, helping to validate the model outputs.

4.2.2 Chloride mass balance Method

To validate and enhance the reliability of the WetSpass model's recharge estimations, a comparison was made with the recharge values obtained through the Chloride Mass Balance (CMB) method. The CMB method, developed by (Eriksson & Khunakasem, 1969), has been widely used by researchers in various aquifers to estimate recharge rates (Ferede et al., 2020; Lorentz et al., 2003; Rwebugisa, 2008).

The CMB method was specifically chosen for estimating recharge because of its conservative nature and its prevalence in precipitation data (Kisiki et al., 2022). The chloride ion, which is the basis of the CMB method, remains unchanged and does not interact with sediment particles or undergo chemical reactions (Cooper et al., 2013; Ferede et al., 2020). This makes it suitable for studying chemical recharge. The CMB method can be applied in both unsaturated and saturated zones to estimate groundwater recharge, and it is recognized as a primary environmental tracer for estimating recharge rates in different climatic, geological, and soil conditions (Scanlon et al., 2002).

The CMB method involves analyzing the chloride ion concentration in both precipitation and groundwater. However, it's important to note that there are limitations and advantages associated with using the CMB method for recharge estimation. Some limitations include the presence of other chloride sources in the soil (Ferede et al., 2020), uncertainties in determining chloride from atmospheric deposition, and errors in chloride determination due to sea salt particles on vegetation (Naranjo et al., 2015).

On the other hand, the advantages of the CMB method include its low cost and the requirement for knowledge of annual precipitation and chloride concentrations in rainfall and groundwater (Rwebugisa, 2008) (Ali Rahmani et al., 2016). The technique relies on the ratio between chloride concentrations in rainfall and groundwater samples.

The CMB technique is based on several key assumptions to ensure accurate estimations. These assumptions include considering precipitation as the only source of chloride in groundwater, excluding contributions from recycling or dissolution of chloride-bearing minerals. The method assumes that chloride is not affected by adsorption or accelerated by anion exclusion and that it remains a constant mass flux over time. Additionally, the application rate of chloride is assumed to be constant and known, sampling sites are assumed to have negligible chloride runoff or run-on, and steady-state conditions are assumed to prevail.

In this study, average annual rainfall values from the years 1990 to 2022 were calculated using monthly rainfall data from three meteorological stations and one NASA satellite station in Ethiopia. Samples of precipitation from three stations (Muka Turi, Debre Tsige, and Fiche) were collected and tested its chloride concentration at Ethiopian Construction Design and Supervision Works Corporation. The average chloride concentration in these samples was found to be 1.90 mg/l. Groundwater chloride concentration data were obtained from well completion reports conducted by different companies in the study area. Four data points found to be well distributed in the study area were collected, and the average chloride concentration in groundwater from these boreholes was determined to be 20 mg/l.

Table 4.6 Chloride concentration value in both groundwater and precipitation of Gur catchment

Chloride concentration in Groundwater			**Chloride concentration in precipitation**	
Well Locations		Concentration value in mg/l	Towns from samples were collected	Concentration value in mg/l
X	Y			
479102	1067490	23.66	Fiche	1.9
479297	1067111	19.88	Debre Tsige	1.9
478875	1066550	20.93	Muka Turi	1.9
480142	1074817	16.47		
Average concentration		20		1.9

As stated by (Bear & Verruijt, 1987), the fundamental equation that can be used for the determination of recharge using the chloride mass balance approach is: $R = P * [Cl^{-}_{p}] / [Cl^{-}_{GW}]$. Here, R represents mean groundwater recharge in mm/year, P represents mean annual precipitation depth in mm, $[Cl^{-}_{GW}]$ represents the average concentration of chloride in groundwater in mg/l, and $[Cl^{-}_{p}]$ represents the concentration of chloride in precipitation in mg/l. In this specific case, the values used were: P = 1092 mm/yr, Cl^{-}_{P} = 1.9 mg/l, $[Cl^{-}_{GW}]$ = 20 mg/l, and R = 103 mm/yr.

The recharge value obtained using this method was found to be almost similar to the value obtained using the WetSpass model method, with only a slight reduction of 3 mm/year. This suggests that the chloride-based estimation approach provides a reasonably accurate estimate of recharge in comparison to the more complex WetSpass model.

However, it is important to acknowledge the limitations of this method, which include:

- The study relied on only three rainfall samples collected in mid-August. To capture the temporal variation of chloride concentration more comprehensively, it would be beneficial to collect rainfall data throughout the year.
- The accuracy of the results is contingent on the sensitivity and precision of the laboratory analysis for chloride concentration. Even a slight error or limitation in the detection capabilities of the laboratory could lead to potentially erroneous results.

Furthermore, the estimated groundwater recharge derived from the WetSpass model was compared to values determined by different researchers in both the study catchment and neighbouring catchments. This comparative analysis served to provide further insights into the reliability of the estimated recharge values and their consistency with previous studies conducted in similar hydrological contexts. The comparison of groundwater recharge estimates obtained from the WetSpass model with those determined by various authors within and neighbouring catchments is summarized in table 4.7.

Table 4.7 comparing the estimated recharge values from the WetSpass model with those derived by previous researchers

No	Researchers	Year	Estimated recharge(mm/year)	Applied methods	Study area
1	Zekarias Ashine	2020	122 mm/ year	WetSpass	South-Jema
2	Tilahun Azagegn	2014	86 mm/ year	Base flow	Jema-Sub Basin
		2014	122 mm/ year	CMB	Jema-Sub Basin
		2014	148 mm/ year	CMB	Muger-Sub Basin
3	Yonas Mulugeta	2009	150 mm/year	Base flow	Cacaha Catchment

5. CONCEPTUAL HYDROGEOLOGICAL MODEL

Before constructing a numerical groundwater flow model, it is crucial to develop a conceptual model (Moumtaz et al., 2020). A conceptual model represents the simplified understanding of the hydrogeological system based on available data, field observations, and scientific knowledge (Joodavi, 2021). It provides a conceptual framework that describes the key components, boundaries, hydrogeologic units, and relationships within the system. The conceptual model serves as a blueprint for developing the numerical model and guides the selection of appropriate model parameters, boundary conditions, and simulation approaches. (Chakraborty et al., 2020; Ghosh & Sharma, 2006; Joodavi, 2021; Ketemaw et al., 2021; Lubczynski & Gurwin, 2018; Mihiret, 2022; Moumtaz; et al., 2020; Moumtaz et al., 2020; Yang et al., 2019). The conceptual model serves as the fundamental understanding of how a system or process operates, laying the groundwork for the subsequent development of a detailed model. (Karlovi & Markovi, 2021).

Conceptualization involves creating a simplified representation of the groundwater system, often depicted as a block diagram or cross section. The goal is to develop a conceptual view that closely approximates the real-world conditions, as this leads to more accurate results in groundwater modeling (Yang et al., 2019). The conceptualization of a groundwater system typically begins by identifying hydrostratigraphic units within the study area that share similar hydrogeologic properties. These units are then classified as aquifers or aquitards based on their capacity to transmit water. The resulting conceptual representation views the groundwater system as a series of layers consisting of aquifers or aquitards, each characterized by its unique aquifer properties and water boundary conditions. Aquifer properties, such as hydraulic conductivity, porosity, and specific yield, are examples of characteristics that describe the geological medium through which groundwater flows. They provide important insights into the ability of the aquifers to transmit water and the amount of water they can store.

Water boundary conditions encompass factors that influence the movement of water between aquifer layers and interact with surface characteristics. For instance, they may include parameters like the frequency of well pumping, which affects the extraction of groundwater, and the rate of groundwater recharge, which signifies how quickly water replenishes the aquifer system. By considering these aquifer properties and water boundary conditions, the conceptual view of the groundwater system provides a simplified yet informative representation. It helps in understanding the behavior of groundwater flow and supports the development of accurate groundwater models (Yang et al., 2016).

In this study, the conceptual model was constructed by establishing boundary conditions, hydrostratigraphic units, and the flow system. The determination of layer composition, dimensions, aquifer type, thickness, and assumptions regarding groundwater flow direction (horizontal or vertical) were predefined. Site-specific information regarding stratigraphy and hydraulic conductivity data was utilized to define hydrostratigraphic units. The groundwater flow system was characterized using hydrological information, including precipitation, recharge, water level head, base flow, and subsurface outflow. Water level measurements were employed to estimate flow direction and illustrate connections between aquifers and surface waters.

5.1 Groundwater Point Inventory

The main objectives of the water point inventory are to accurately locate and gather data on specific water points, including dug wells, springs, swampy areas, and drilled shallow and deep wells. This involves conducting field measurements and collecting information from various sources such as drilling companies, water works construction enterprises, and well owners. Prior to the field work, a comprehensive review of relevant literature and previous studies is carried out.

Data on boreholes are collected from drilling companies, and a thorough desk work is performed. Subsequently, field work is conducted to inventory water points, which includes measurements of water levels, sampling, and descriptions of the geological and geomorphological conditions at the sites. In this study, a total of 253 wells and springs were inventoried within and in close proximity to the study area boundary. Data were obtained from organizations such as the Ethiopian Construction Design and Supervision Works Corporation, Oromia Water Works Design & Supervision Enterprise, North Shewa Zone of Oromia Water Resources Bureau, and previous research studies.

After ensuring data quality and consistency, a subset of the collected data was used for the study. Specifically, 74 wells and 65 springs with information on location (UTM coordinates) and static water levels were selected. Among the wells, 38 had information on well yield (Q), while only 11 had pumping test data that provided information on hydraulic properties such as hydraulic conductivity and transmissivity. Out of the mentioned springs, 14 had information on yield (Q) and were located within or in close proximity to the study area. The available well depths within the study area ranged from a minimum of 2 meters to a maximum of 492 meters. The deepest recorded static water level was 106.5 meters.

Springs

The majority of springs in the area are situated along the slopes of deep gorges, ridges, and abrupt changes in elevation on undulating plateaus. However, there are also some springs found in flat areas. The springs in the region are predominantly of the depression and fracture types. Additionally, there are springs that occur at lithological contacts.

The occurrence of springs is closely associated with fault lines and lineaments that generally trend in the northeast-southwest (NE-SW) and north-south (N-S) directions. Springs are present across various lithologic units, exhibiting a significant variation in discharge rates. According to the Hydrogeological Reports of the Addis Ababa map sheet (Bereket et al., 2011), field surveys and reported data indicate that during the dry season, the discharge of springs can vary widely, ranging from 0.01 to 31 liters per second. Most of the springs located on gently sloping plateaus and flat lands, where productive basalt aquifers are present, are developed and utilized for community purposes.

Borehole

The majority of boreholes drilled within the study area encounter water-bearing basalt aquifers. The total depths of most boreholes range from 20 meters to 492 meters. Although shallow wells are predominant in the study area, there are also some promising deep wells that have been drilled. Analysis of collected data and field inventory indicates that the yield of boreholes tends to increase as the depth increases. Overall, the available data reveals that the static water level in the basaltic aquifers within the study area ranges from 1 meter to 106.5 meters below ground level.

Hand dug wells

Hand dug wells are extensively used for water abstraction in the study area. There is a significant presence of approximately 66 hand dug wells within the catchment. Among these, 28 wells have recorded depths ranging from 2 to 20 meters below the ground surface. The hand dug wells are primarily located on flat and gently sloping terrains, often associated with recent deposits, alluvial fans, and highly weathered basalt formations. These wells serve as a source of water supply for small community usage.

5.2 Hydro-stratigraphic Units

Identifying hydrostratigraphic units is important for understanding the groundwater flow dynamics within the aquifer system. In hydrogeological investigations, geological layers or formations are often classified into hydrostratigraphic units, which consist of geological units with similar hydrogeological properties. Hydrogeological units play a fundamental role in determining the spatial distribution and occurrence of groundwater. To transform the lithostratigraphic units into hydrogeological units, various hydrogeological properties are considered, such as the infiltration capacity of surficial materials, permeability of the exposed rocks in the catchment, degree of weathering and fracturing, topographic and morphological characteristics, and hydrologic features. Field observations, borehole lithological logs, and pumping test results are utilized to characterize the hydrogeological units.

In the Gur catchment, the main lithologic units include volcanic rocks (particularly Aiba, Ashangi, and Tarmaber basalts) and sedimentary rocks such as upper sandstone, Muger mudstone, and eluvium/alluvial sediments. The basalts display uniform topography with flat-topped surfaces, often showing columnar jointing. Drilling logs reveal the presence of paleosol layers and gravel beds. Groundwater is found in joints, fractures, and porous layers within the basalts. Pumping test analysis and well logs indicate that the aquifer system in the Gur catchment can be classified as a fractured aquifer. Boreholes drilled in the area demonstrate moderate to high groundwater potential in the Aiba and Tarmaber basaltic aquifer, attributed to the secondary permeability of the lithological units. The hydrogeological systems in the study area have been classified using both qualitative and quantitative methods, as reported in the hydrogeological map of the Addis Ababa map sub-sheet (Bereket et al., 2011). The qualitative classification considers dominant primary porosity, secondary fissured permeability, and impermeable rock units. The quantitative classification utilizes data from field water point inventories and pumping tests, either measured directly in the boreholes or obtained from regional offices (Bereket et al., 2011).

Quantitative classification of aquifer system within the study area

Based on the report from the Ethiopian Institute of Geological Survey regarding the hydrogeological map of the study area, the hydrostratigraphic units have been classified into different classes using field-based water point inventory data and borehole pumping test results (Bereket et al., 2011).

1) Extensive and moderately productive porous aquifers

The porous aquifers in the catchment cover a total area of 37.2 km^2, equivalent to 7% of the catchment area. These aquifers consist of Quaternary sediments, including alluvial, colluvial, and elluvial deposits. The transmissivity of these aquifers ranges from 1.1 to 10 m^2/day, with discharge rates varying between 0.011 and 1 l/s.m. Wells and springs tapping into these aquifers can yield between 0.5 and 5 l/s.

These porous permeable deposits are primarily distributed in a gentle undulating plateau and along rivers within the study area. The thickness of these deposits varies across different locations. Alluvial sediments predominantly comprise porous sandy gravels to silty sand, which are suitable for extraction through shallow dug wells. Meanwhile, the elluvial sediments found in the plateau area consist of silty to clayey soil. The aquifers in the alluvial and elluvial sediments receive direct recharge through rainwater infiltration. Additionally, alluvial sediments can also be recharged by rivers during periods of high discharge and by groundwater flow from aquifers intersected by the river. Groundwater in these aquifers is drained by small springs and rivers. The safe yield, which represents the sustainable extraction rate without depleting the aquifer beyond its natural recharge capacity, is estimated to be around 0.5 l/s for wells drilled into the Quaternary deposits.

2) Extensive and moderately productive fissured aquifers

The study area contains moderately productive fissured aquifers, which are characterized by their fissured permeability. Groundwater primarily accumulates and flows through the weathered rock, specifically through fissures and joints developed in volcanic and sedimentary rocks. These aquifers comprise basalts, mixed units of various Tertiary rocks (such as ignimbrites, basalts, and pyroclastic materials intercalated with sediments), and Mesozoic sandstones. They exhibit a transmissivity ranging from 1.1 to 10 m^2/day, a discharge rate of 0.011 to 1 l/s.m, and a yield of 0.5 to 5 l/s. Within the Gur catchment, the volcanic rocks (including basalts) and Debre Libanos sandstone represent the principal aquifers, covering an area larger than 474.7 km^2.

The volcanic rock aquifers in the study area consist of basalts, ignimbrites, tuffs, and ash. Groundwater in these aquifers typically exists under water table conditions. Basaltic lavas tend to form relatively thin and fluid flows, creating significant pore space at the tops and bottoms of the flows. The basalt flows frequently overlap, separated by permeable zones composed of soil or alluvial materials. Columnar joints that develop in the central parts of basalt flows provide pathways for vertical water movement through the basalt. Basaltic rocks are generally the most productive aquifers among the volcanic rock formations. Ignimbrites, on the other hand, create a hydrogeological environment that is non-homogeneous, with groundwater occurrence varying depending on the fracturing system's frequency, intensity, and distribution. The major lineaments and faults within the volcanic rock units exhibit various orientations, including NE-SW, NW-SE, N-S, and E-W directions. Some areas of the basalt formation contain a large proportion of scoraceous lava flows, which have high porosity, facilitating groundwater storage and movement. Springs within this unit are often controlled by fractures, typically emerging at the intersection points of fractures or faults within topographical depressions. The discharge of springs and wells has been measured during field inventories.

3) Aquiclude consisting of gypsum and mudstone

The gorge situated in the northern tip of the study area contains mudstone and gypsum units having about 18 km^2 areal coverage. These rocks possess low permeability characteristics. An exposed Mesozoic mudstone formation within the gorge serves as an aquiclude, effectively obstructing the flow of water. This formation is an extension of the mudstone caped horst originating from the mugger sub-basin (Tilahun Azagegn, 2015).

Although no direct emergence of water points is observed from these units, springs are formed at the contact zones where the mudstone formation intersects with the overlying aquifers. This phenomenon transpires due to the impermeable nature of the mudstone, compelling water to seek alternative pathways and manifest at these contact zones.

5.3 Hydraulic Properties of Aquifers

Pumping tests conducted on boreholes serve the purpose of determining the hydraulic properties of an aquifer. These properties include parameters like hydraulic conductivity, transmissivity, porosity, specific storage, and storage coefficient. The hydrogeology of a catchment area is influenced by various factors such as geology, geological structure, surface morphology, slope, land use, and the interplay between human activities and the natural environment (Fetter. C.W., 2001). As a result, the hydraulic properties of aquifers within a specific region reflect the combined impacts of these controlling factors. The range of conductivity and transmissivity values within the catchment area is quite extensive due to the presence of diverse lithological units and varying degrees of weathering.

In the context of this particular study, it is crucial to understand the lateral distribution and characteristics of the aquifer, as well as its hydraulic properties, in order to develop a conceptual model. Various data sources are utilized to characterize and classify the aquifer system into different hydrogeological groups. These sources include existing pumping test data, geological and hydrogeological maps, soil maps, and borehole logs that provide information on lithology, aquifer thickness, transmissivity, hydraulic conductivity, water table depth, geological structures, and surface water features. However, it is important to acknowledge that due to limited data availability, the spatial distribution and magnitude of the aquifer's hydraulic properties, especially in terms of vertical variability, may not be well-known. Additionally, the distribution of drilled wells across the study area may not be optimal or representative in capturing the complete hydrogeological characteristics.

Table 5.1 Hydraulic characteristic of wells in the study area

X	Y	Elevation	Depth (m)	SWL	Q (l/s)	T (m^2/day)	K (m/day)
471019	1066600	2570	151	15.9	4.07	5.5	0.11
475829	1089995	2622	120.5	4.94	5.6	50.8	1.13
478411	1068253	2610	271	56.35	22	159	1.76
478847	1068289	2618	276	63.4	22	51	0.57
478950	1072305	2584	121	58.58	10	152.9	3.8
479639	1063669	2617	151.23	16.8	20	43.3	0.94
479880	1065305	2620	225.5	63.25	16	29.9	0.39
482901	1047800	2581	197	3.6	2.87	0.6	0.01
483131	1068541	2544	156	54	13	206	5.71
483851	1070714	2514	250	106.5	2.1	26.1	0.17
504315	1055059	2640	135.5	54.65	6.5	19.3	0.39
486419	1054881	2639	180	14	11.5	25	
494345	1051950	2647	492	25.4	16.34	32.9	
493214	1051411	2659	90	5.7	90	34.7	
483784	1059762	2631	96	26.1	20.7	341	
485941	1060899	2636	96	20.58	15.08	32	
484980	1061256	2640	90	28.7	10	26.1	
483642	1061373	2641	99	36.33	20.3	122	
485511	1056545	2632	92	11.95	14.8	203	

Hydraulic conductivity

Hydraulic conductivity is a fundamental property used to characterize the ability of soils or rocks to transmit water. This property plays a key role in understanding and predicting groundwater flow patterns and the movement of contaminants in aquifers. High hydraulic conductivity values indicate the presence of highly permeable materials, which allow water to flow easily through interconnected pore spaces. Conversely, low hydraulic conductivity values suggest the presence of less permeable materials, which impede water flow due to their smaller and less interconnected pore spaces. The hydraulic conductivity of an aquifer system is influenced by various factors, including the type of rock, primary and secondary structures, degree of weathering, and stratigraphic setting.

In the Gur catchment, the aquifer system exhibits a range of hydraulic conductivity values, spanning from 0.01 to 5.7 m/day, with an average value of 1.2 m/day. Highly fractured and weathered basalt formations tend to have the highest hydraulic conductivity, facilitating the movement of water. Conversely, mudstone and gypsum units display lower conductivity values, indicating lower permeability. To delineate horizontal hydraulic conductivity and permeability zones, an analysis of available pumping test data has been conducted, employing linear interpolation (IDW) techniques.

Transmissivity

Transmissivity, a valuable concept in hydrogeological and groundwater studies, refers to the capacity of a subsurface formation to horizontally transmit water. It quantifies the volume of water that can move through a unit width of the aquifer's full saturation thickness under a unit hydraulic gradient (Fetter. C.W., 2001). In the Gur catchment, the transmissivity values of the aquifers exhibit significant variability. To illustrate this variability, a spatially distributed transmissivity map has been generated by interpolating data obtained from boreholes (figure 5.1). Different hydrogeological units within the area possess distinct transmissivity values, influenced by factors such as hydraulic conductivity and aquifer thickness. The transmissivity values in the catchment range from 25.8 to 339 m^2/day, with an average value of 89.53 m^2/day.

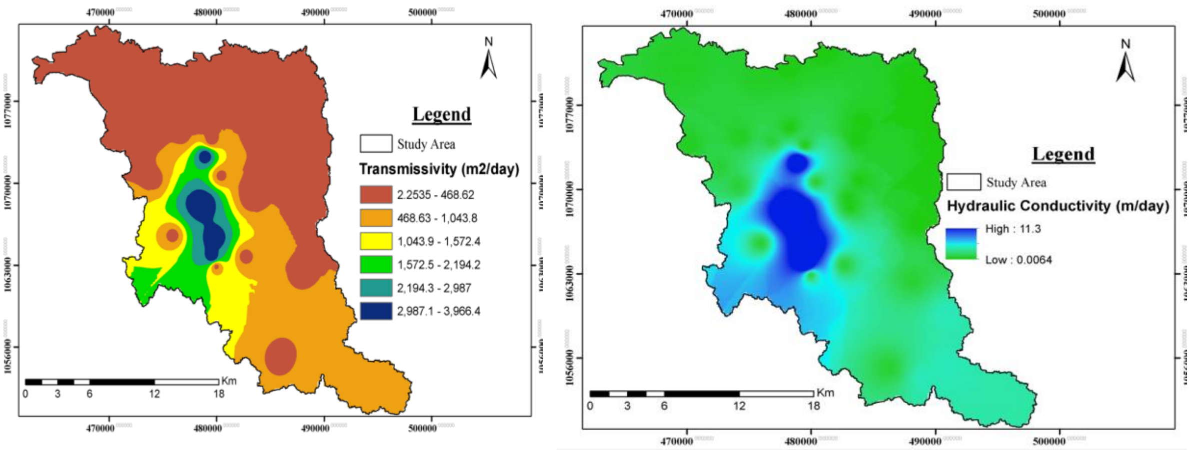

Figure 5.1 Transmissivity (m2/day) and Hydraulic conductivity (m/day) distribution maps of the study area interpolated from point measurements

- The patterns observed in the hydraulic conductivity and transmissivity maps are consistent, indicating that highly fractured and weathered basalt formations exhibit elevated values for both transmissivity and conductivity.

5.4 Groundwater Flow Conceptualization

Groundwater flow is influenced by various factors, including geomorphology, topography, geological structures (such as faults, joints, and lineaments), the presence of impermeable layers, and the hydraulic properties (conductivity, transmissivity, and continuity) of the aquifer system. To delineate groundwater flow directions and identify recharge and discharge areas, several parameters and data are considered. These include slope/gradient and geomorphology, geological structures, groundwater levels, and equipotential contour lines.

In shallow groundwater systems within the catchment, flow is primarily controlled by local topography. Shallow springs that align with the topography serve as valuable indicators of shallow groundwater flow direction. Recharge, which is the water that contributes to groundwater by passing through the unsaturated zone and reaching the static groundwater table, can occur through direct, indirect, or localized mechanisms depending on the water source and the process involved. The amount and nature of recharge are influenced by factors such as land use/land cover, topography, climate, drainage, vegetation, geological structure, soil conditions, and other related factors.

Generally, groundwater flows from higher elevations to lower elevations. However, direct observation of water levels is often not feasible. Therefore, groundwater head data are collected, and an equal potential map is constructed using ArcGIS, depicting points with equal potential. Perpendicular lines are then drawn to these contour lines, indicating the groundwater flow direction of the aquifer system. The primary source of recharge to the regional aquifer is rainfall in the highlands, which infiltrates into the fractured volcanic formations of the catchment. Limited indirect recharge from rivers may occur in both the highlands and lowlands of the catchment. As observed in the figure, groundwater flows from the southern and north western corridors of the catchment towards the central-northern gorge area. Based on this, it can be concluded that the north western and southern catchment regions, along with the fractured highlands, act as recharge areas, while the central-northern lowlands serve as discharge zones within the catchment.

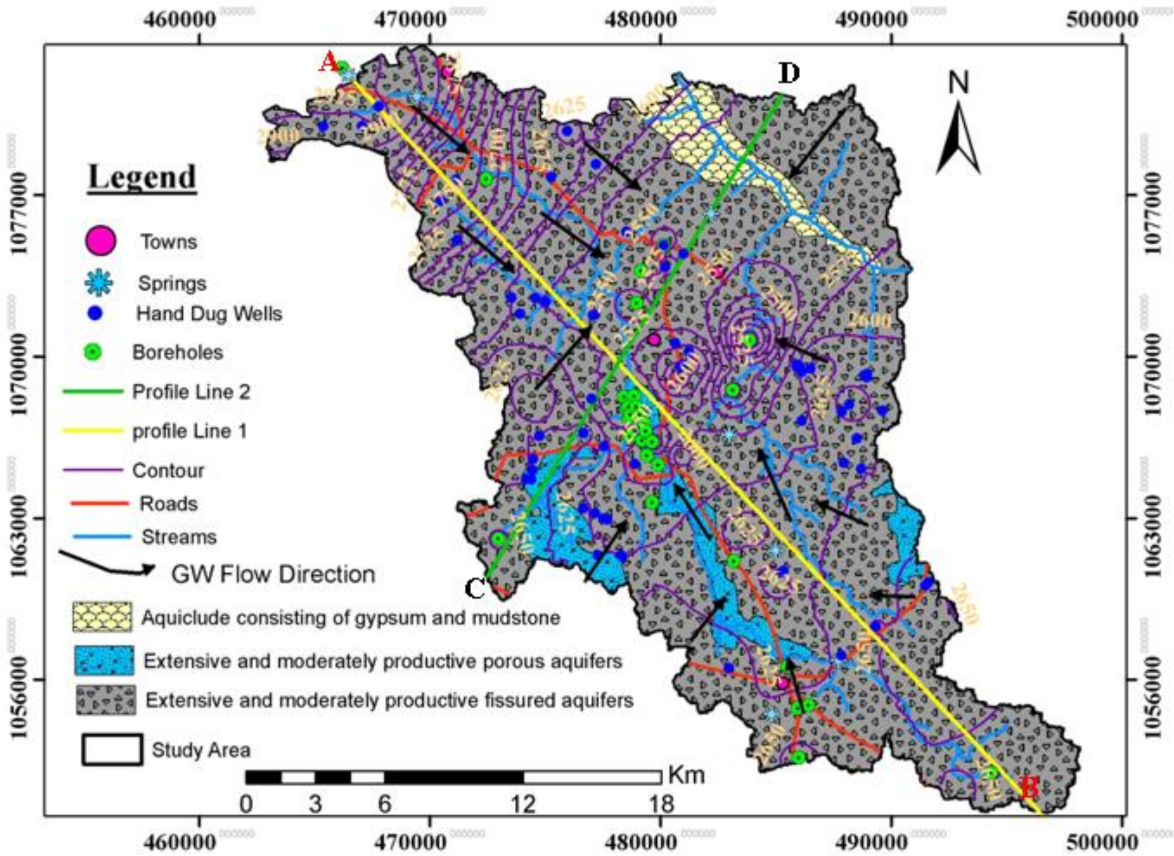

Figure 5.2 Schematic hydrogeological map which shows the Hydro-stratigraphic units, and possible groundwater flow direction of Gur catchment

5.5 System Boundary Conceptualization

The hydrological characteristics at the boundaries of the conceptual model play a vital role in determining the mathematical boundary conditions of a numerical model. These boundary conditions have a significant impact on the calculated flow directions in a steady-state numerical model. Boundaries encompass various hydraulic features such as groundwater divides, as well as physical features like surface water bodies and impermeable rock formations. In a three-dimensional numerical model, the water table typically serves as the upper boundary. Ideally, the lateral and bottom boundaries should align with fixed physical or hydraulic features that remain unchanged as hydrological conditions evolve. The identification of boundaries relies on potentiometric, topographic, and geologic maps of the region and specific site.

Mathematically, boundary conditions can be classified into three types (Anderson et al., 2015):

i) **Specified head boundary (Dirichlet conditions):** In this type, the head along the boundary is set to a known value. The specified head may vary spatially. When all heads along the boundary are set to the same value, it is referred to as a constant head boundary, which is a special case of Type 1 boundary.

ii) **Specified flow boundary (Neumann conditions):** Here, the derivative of head at the boundary is specified, and flow is calculated using Darcy's law. A no flow boundary is a specific instance of a Type 2 boundary, where there is zero flow across the boundary.

iii) **Head-dependent boundary (Cauchy conditions):** This type involves calculating the flow across the boundary using Darcy's law, with the gradient determined as the difference between a specified head outside the boundary and the head computed by the model at the node located on or near the boundary. This boundary condition is sometimes referred to as a mixed boundary condition since it relates a boundary head to a boundary flow.

For the Gur catchment, two types of boundary conditions have been identified based on potentiometric, topographic, geologic, and hydrogeological maps. A General Head Boundary has been assigned to the north eastern and northern boundaries of the aquifer system. A specified flow boundary (no flow boundary) has been designated for all remaining lateral boundaries.

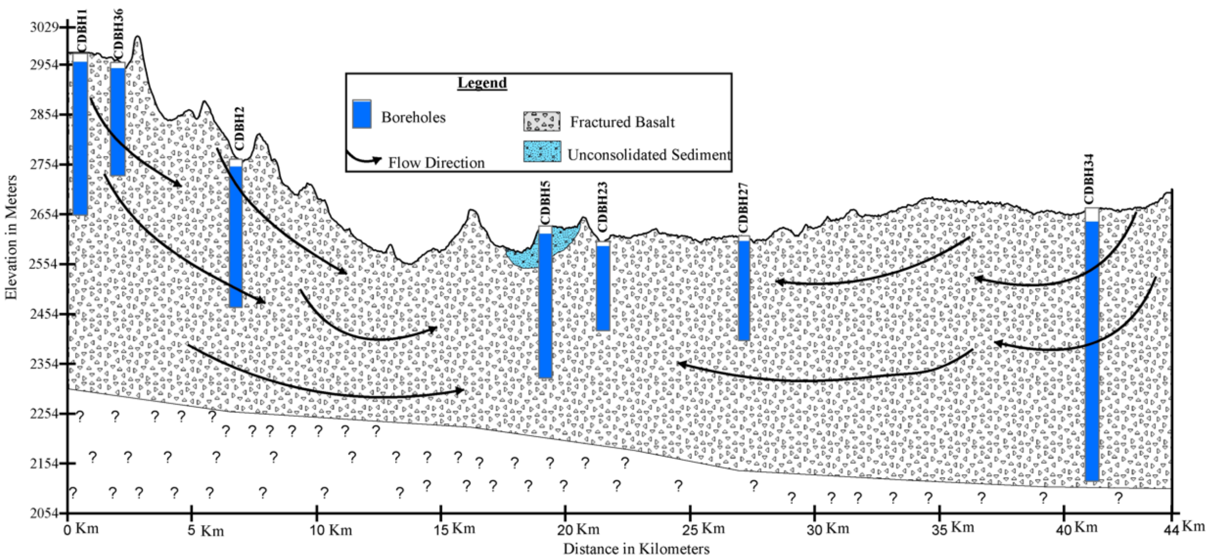

Figure 5.3 Schematic representation of groundwater circulation in the Gur catchment is depicted in a conceptual model (not scaled), utilizing deep borehole well log data to construct the cross-section (A-B).

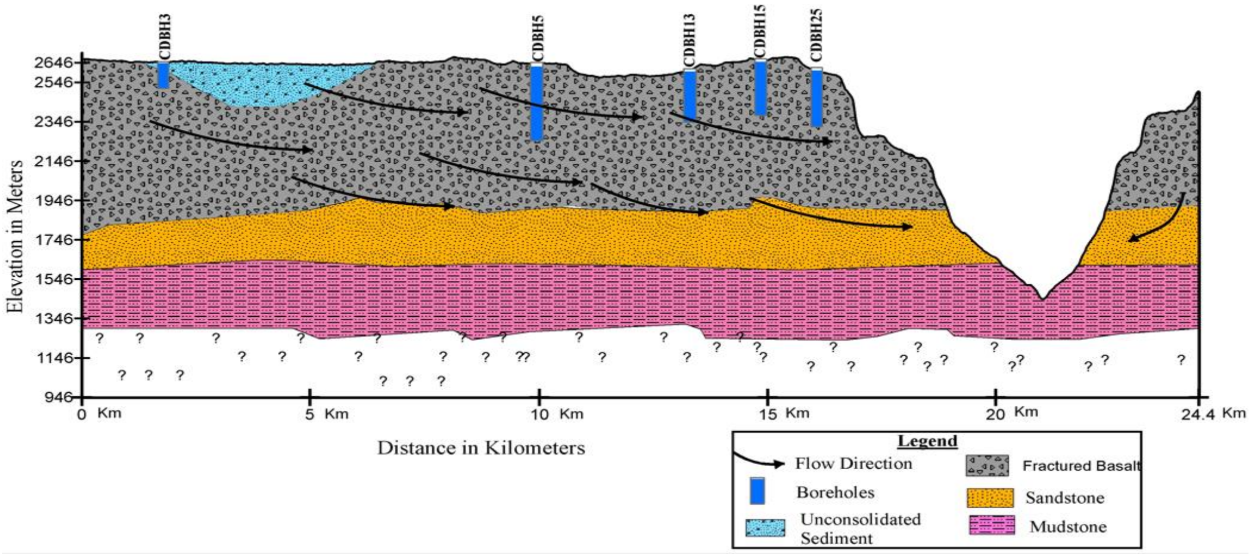

Figure 5.4 Schematic conceptual model of groundwater occurrence and circulation in the Gur catchment which is the cross-section constructed (not scaled) using exploratory well log data (C-D).

6. NUMERICAL GROUNDWATER FLOW MODELING

A numerical groundwater flow model is a mathematical representation of the movement of groundwater within an aquifer system. It simulates the complex interactions between various hydrological factors, such as groundwater recharge, flow velocities, hydraulic conductivity, and water table fluctuations. These models utilize numerical methods and algorithms to solve the equations governing groundwater flow and provide insights into the behavior of groundwater systems. Numerical groundwater flow modeling helps to have a good understanding of the current or to predict the long term tendencies of a hydrogeological system and it allows an analysis of the movement of water through hydrogeologic unit that constitute the groundwater flow system (Kumar, 2013). The numerical modeling is of two type; finite difference model and finite element model. Finite difference (FD) model is a model to replace the continuous aquifer with a set of discrete rectangular network of nodes arranged in a grid pattern at the center of the block. While in finite element model nodes are at edge of the triangular polygon (Anderson & Woessner, 2015; Fetter. C.W., 2001).

The most widely used, open source, legally tested, relatively easy to learn and recent version numerical groundwater flow model which is MODFLOW was applied in this study to represent the groundwater systems and to detect the groundwater balance component in the study area. MODFLOW is a versatile, modular, three dimensional, finite difference, groundwater flow modeling program used to construct numerical flow models of a specific area in all aquifer types under both transient and steady state conditions (Kareem, 2018). It is deterministic model approach which assumes the stage or response of aquifer is predetermined by the help of physical laws governing the groundwater flow (Ayehu et al., 2018). MODFLOW numerically uses block-centred finite differences to solve the flow equations. It consists of a main program and independent subroutines called modules (McDonald & Harbaugh, 1988). The modules are grouped into packages and each package deal with a specific hydrogeologic feature to be simulated. According to (Kahsay, 2018; Moumtaz, et al., 2020) MODFLOW is one of the most widely used groundwater flow code in the field of hydrogeology and is able to simulate steady state and transient flow conditions in one. The model can simulate recharge, flow to wells, flow to drains and flow through riverbeds (Kahsay, 2018). Numerical models describe the entire flow field of interest at the same time providing solutions as many data points as specified by the user, the area of interest is subdivided in to many small areas (usually referred to as cells or elements) and basic groundwater flow equation is selected to solve for each cell. The solution of a numerical model is the distribution of the hydraulic heads at points representing individual cells (Ayehu et al., 2018).

In this thesis, the groundwater flow model of Gur catchment was prepared so as to study the response of the system to different hypothetical scenarios of pumpage, recharge or any other parameter under a steady state condition. To represent the Gur catchment with numerical model, steady state condition, two dimensional flow system and one aquifer layers were considered and the model domain discretized in to regular rectangular grid and finite difference block centered groundwater flow model. The interface applied in this numerical modeling is processing MODFLOW.

This numerical model preparation approach includes the definition of system boundaries, measuring and compilation of wells and springs withdrawal, compilation of water level data, compilation and develop previously estimated recharge, hydraulic conductivities, selection of an appropriate computer code/governing equation for simulation, calibration of calculated heads/fluxes to field observed heads/fluxes and simulation under different scenarios to understand the response of the system.

6.1 The Governing Equation

Combining Darcy's law and the equation of continuity yields the governing equation (Anderson & Woessner, 2015). Applying the idea of an elementary Cartesian fixed control volume and the presumption that fluid properties are uniform in time and space will result in the equation of continuity (R. D. White et al., 2009). The conservation of mass principle states that a change in inflow and outflow should be equal to a change in storage within the control volume. The following governing differential equation is used to model steady-state groundwater flow. It describes the conservation of fluid mass during flow through a porous media and can be represented by the general flow equation in three dimensions for a heterogeneous anisotropic material. (Evans, 2016; Hamid, 2019)

$$\frac{\partial}{\partial x}\left(K_x \frac{\partial h}{\partial x}\right) + \frac{\partial}{\partial y}\left(K_y \frac{\partial h}{\partial y}\right) + \frac{\partial}{\partial z}\left(K_z \frac{\partial h}{\partial z}\right) - Q = S_s \frac{\partial h}{\partial t} \quad \text{.. (1)}$$

Where, Kx, Ky, Kz = hydraulic conductivity along the major axes of hydraulic conductivity, which are considered to be parallel to the x, y, and z axes; h represents Piezometric head; Q represents source/sink terms and is defined as a flux (volume of water per area of aquifer per time); Ss = specific storage coefficient defined as the volume of water released from storage per unit change in head per unit volume of porous material; t is time (T).

Equation (1) describes the distribution of hydraulic head and flow throughout a continuous region (Gannett et al., 2012; Kumar, 2016). Derivations of equation (1) can be found in order to simulate the unconfined aquifer, equation (2) is used which is the Boussinesq Equation.

$$\frac{\partial}{\partial x}\left(K_x h \frac{\partial h}{\partial x}\right) + \frac{\partial}{\partial y}\left(K_y h \frac{\partial h}{\partial y}\right) = S_y \frac{\partial h}{\partial t} - W \quad (2)$$

Assuming the transmissivity as Tx = Kxh and Ty = Kyh

Where; h is the saturated thickness (L); S_y is the specific yield (dimensionless); W represents internal sinks and sources within an element.

If the hydraulic conductivity inside the aquifer layer is assumed to be isotropic, then Kx and Ky are substituted by the single term K to describe horizontal hydraulic conductivity because they are each expected to be equal at any given point. Since the research is in a steady-state condition and the head does not change over time, this portion of equation (1)'s right-hand side becomes zero and it can be re-written as:

$$\frac{\partial}{\partial x}\left(K h \frac{\partial h}{\partial x}\right) + \frac{\partial}{\partial y}\left(K h \frac{\partial h}{\partial y}\right) + W = 0 \quad (3)$$

6.2 Model Design

6.2.1 Model geometry

The model geometry for the study area has a horizontal extent of 33.2 km by 35.4 km. The boundaries of the model domain are defined in UTM/Zone 37/Adindan coordinates, ranging from 462791 to 498155 East and 1050241 to 1083467 north. However, due to the irregular shape of the study area and the locally bounded nature of the aquifers, the actual model domain is reduced to an area of 530 Km^2.

6.2.2 Model discretization

Spatial discretization of the model grid

In numerical models, the continuous natural phenomenon is replaced by a discretized domain which is called grid. Selecting the Grid size depends on hydraulic gradient, degree of aquifer heterogeneity, size of the model area, level of detail required and availability of data (Anderson & Woessner, 2015). Designing the finite grid or finite element mesh is one of the most important and difficult steps in model design. The number of nodes in the grid/mesh affects the accuracy of the solution, the computational time required to solve the model (Anderson & Woessner, 2015). The nodal network forms the computational framework of the numerical model and the nodal spacing determines the resolution of the output as much as groundwater heads are computed at nodes and must be interpolated between nodes.

The Model domain is discretized using nodes and Finite Difference cells/blocks. The cells are rectangular, block centered and have uniform and regularly spaced. This will help to have more computationally accurate result and operationally efficient. The model is horizontally discretized with regular grid spacing of 150m by 150m having 167 rows and 177 columns and contains 1.8377E+11 volume of active cells.

Time discretization of simulation

The model is designed and simulated for steady-state model simulation. The time unit used for the simulation of this model is in a day.

6.3 Model Input Parameters

6.3.1 Modeling environment

1) Boundary condition in numerical modeling

Boundary conditions define groundwater flow into and out of the model domain. In addition, their correct selection, the location of boundaries and their numerical representation in the model, is critical to the development of an accurate model that can simulate system response correctly under proposed scenario. In mathematical analysis of the ground water flow system, three common mathematical boundary conditions are specified (Anderson and Woessner, 1992).

1. Specified Head boundary (Dirichlet conditions) where head at boundary is already determined from field. Head at lake or reservoir are an example of this condition. Unfortunately, there is no such surface water body in the model area, therefore, no constant head boundary is defined in this model.
2. Specified flow boundary (Neumann conditions) – in this type, flux along the boundary specified. Most surface water divides nearly coincide with groundwater boundaries in the study area. Most of the boundary of the catchment is assumed as no flow boundary (Neumann condition). The area is bounded by volcanic ridges, lava domes, and volcanic shields along which groundwater flow is nearly zero. Pumping wells are considered as specified flux boundaries in the model boundary conditions.
3. Head dependent Boundary condition (Cauchy conditions)-flow across the boundary is calculated depending on the hydraulic gradient using Darcy Law. Genera head boundaries at north and south east, rivers and springs are defined as Cauchy conditions in the model domain.

The catchment perimeter boundary was delineated mainly based on the surface physical characteristic. Most perimeters of these natural physical boundaries are generally recognized as surface water and groundwater divides (boundaries) as ridges and volcanic shields of the area characterized with low permeability geologic barriers. The exception is at North east water inter in to the system as lateral inflow and at north water flows out of the system and hence the boundaries are defined as general head boundary conditions (Cauchy Condition). The top layer is recharge layer through which rainfall percolates to join groundwater system. So top layer is specified flow boundary (Neumann condition).

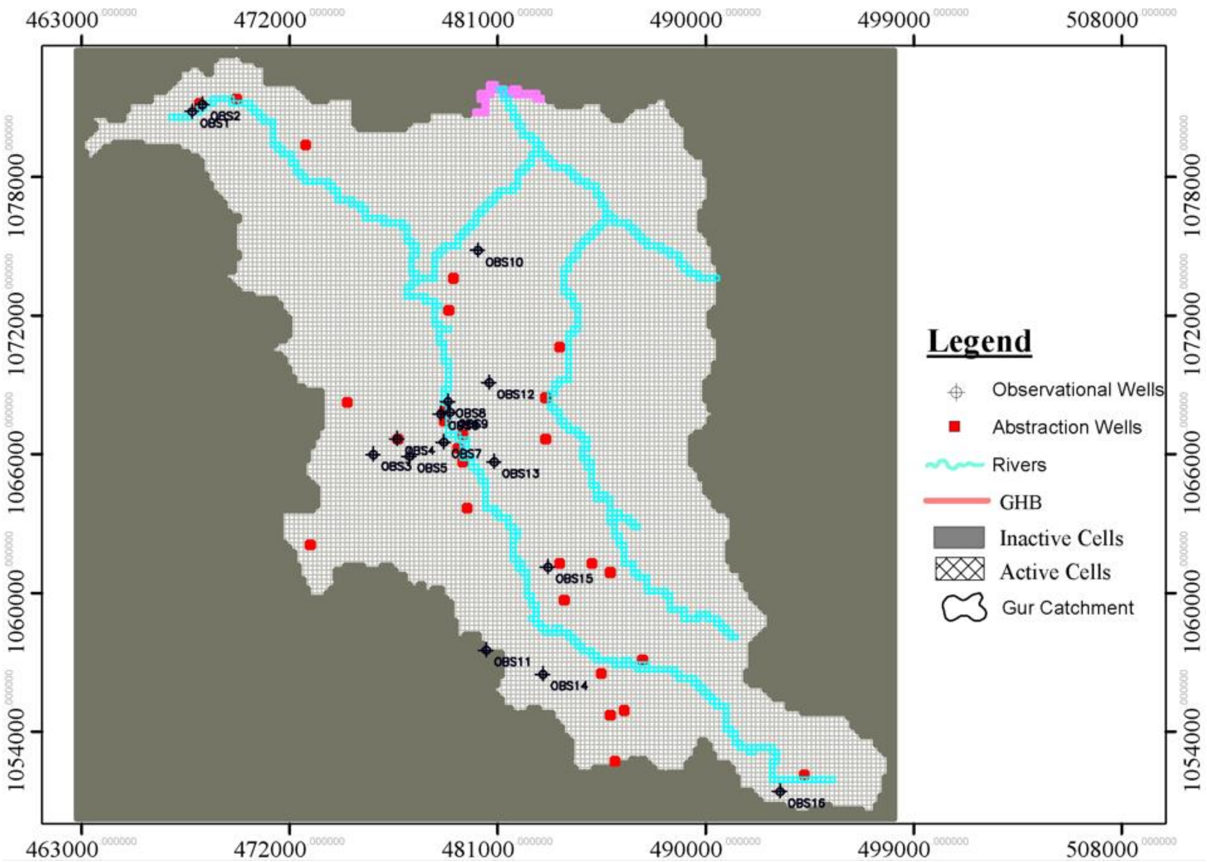

Figure 6.1 Model domain Discretization and Boundary condition of Gur Catchment

2) Top and bottom layers

The proposed model is single layer and unconfined aquifer system. Generally, the model top elevations of the layer were incorporated into the model using 30m by 30 spatial resolution DEM converted into ASCII matrix format. Bottom elevation of the model generated from the top elevation by subtracting the layer thickness which is 350 m from the top layer which makes aquifer to have different thickness rather than constant head throughout the proposed model. Then the software computes the values of the elevations from the input ASCII file.

3) Initial Hydraulic Head

Measured and observed hydraulic head of 74 boreholes were collected, organized and analyzed in ArcGIS. The boreholes have no time series head data. Hydraulic heads data were only one time measurement particularly during drilling and pumping test. Groundwater contour was developed using GIS_IDW interpolation method from representative and reliable groundwater levels at steady state. The interpolated data was resampled into 150 by 150 m model grid size and imported to model environment. Practically, groundwater levels fluctuate from time to time; however, it is assumed that in long term the water levels become nearly constant.

4) Hydraulic Conductivity

Groundwater flow within the model layers was assumed to be horizontal. Hydraulic conductivity and transmissivity are properties that, in conjunction with the horizontal hydraulic gradient, control horizontal flow of groundwater. Hydraulic conductivity for the aquifer system of the study area was estimated from groundwater literatures depending on the geologic and hydrogeologic properties of the aquifer unit and aquifer test data of 12 boreholes drilled in the study area at different times. Accordingly, the aquifer hydraulic conductivity of the Gur catchment ranges from 0.01 m/day to 5.71 m/day.

5) River package

The river package used to simulate the interaction of surface water and groundwater. Surface water bodies such as rivers, streams, lakes and swamps may either contribute water to the groundwater system, or act as groundwater discharge zones, depending on the hydraulic gradient between the surface water body and the groundwater system (Anderson & Woessner 1992). It is assumed that leakage is only through the riverbed sediment but not on side channel wall. As result this package requires hydraulic characteristic of the riverbed sediments (conductance), river stages, river bottom elevations and sediment thicknesses. The hydraulic conductance of river sediments were calculated using the following mathematical equation

Where:

$$C_{riv} = \frac{K_{riv} * L * W}{M}$$

Criv = Hydraulic conductance of the riverbed (L^2/T), Kriv= Hydraulic conductivity of the riverbed sediment ([L/T), L= Length of the river within a cell (L), W= Width of the river within a cell (L), and M= Thickness of the riverbed sediments (L).

But, because of insufficient data to quantify the conductance of the river bed in every cell river network of the modeled area, the thickness and texture of soils or sediments are estimated from well lithologic logs, from previous research works and reports. It is also assumed that, the hydraulic conductivity of the riverbed and the river channel sides is the same as the hydraulic conductivity of the surrounding rocks and sediment in which average conductivity values are assigned.

6.4 Model Stresses

Hydraulic heads in the groundwater flow system respond to stresses on the system, which corresponds to recharge and discharge. As noted earlier, recharge to the groundwater system of the study area is from the infiltration of precipitation and discharge from the system is through groundwater pumpage, springs. Evapotranspiration from the groundwater system can be assumed to be negligible, since there is almost no significant groundwater discharge areas such as marshes, swamps, and/or lakes within the catchment.

1) Groundwater Recharge Package

Annual recharge of Gur catchment was estimated using chloride mass balance and WetSpass model methods as discussed on section 3.6 and the result is applied to top layer as groundwater source. The mean annual groundwater recharge estimated using chloride mass balance and WetSpass model are 103 and 106 mm/year respectively. The spatially distributed recharge value obtained from the WetSpass model was imported into the model. The recharge values resampled by 150 m by 150 m grid size to be accommodated into the model and applied to the most active cells. It is simulated to the groundwater system using recharge packages.

2) Groundwater pumping rate

Due to the irregular rate of pumping and inadequate data documentation, it is challenging to determine the precise amount of water that is being withdrawn from the ground. Approximately 21754005.84 m^3/year of groundwater is currently anticipated to be extracted from the model domain by boreholes and springs.

6.5 Steady state simulation

MODFLOW is a computer code developed to simulate mathematically three dimensional groundwater flow through porous media by using finite difference method (Mc Donald and Harbough, 1988). As a result, to simulate the Gur catchment using a mathematical formulation of steady-state conditions, Processing MODFLOW version 8.0.15 was used. The model was built with a grid size of 150 m by 150 m, a single layer with an average thickness of 350m, and the necessary hydraulic characteristics were encoded. The simulation involved four model packages: the recharge, GHB, river, and well packages. The PCG2 (preconditioned conjugate gradient 2) solver package was chosen to repeatedly and concurrently solve the variable parameters at nodes. The model used the days and the meter as its measuring units. The model is run under steady-state settings, which implies that for a predetermined time period, there is no change in the hydraulic head or storage in the model environment.

6.5.1 Model calibration

The objective of calibration is to minimize the variation between the computed values and observed. The model was calibrated by systematically changing certain model parameters like recharge, hydraulic conductivity and general head boundaries and the model is repeatedly run until the calculated results, in relation to the modeling scale, accurately reflect observable data. The study area's groundwater model is calibrated manually using the history matching method of trial and error. These results were compared with the calibration target (measured value), and if the error in the simulated results is acceptable, the model was considered calibrated. If the level of error is unacceptable, the input parameter values were adjusted within a reasonable range and the model was run again until acceptable results were achieved. In the trial and error calibration there exist good head match between simulated and observed at north western and southern part of model area. At central part like Debre-Thige well field where there are dense wells calculated head significantly vary within hundreds of meters distance. This could be reflection of effect of geological structure or could be error from field measurements and pumping test analysis.

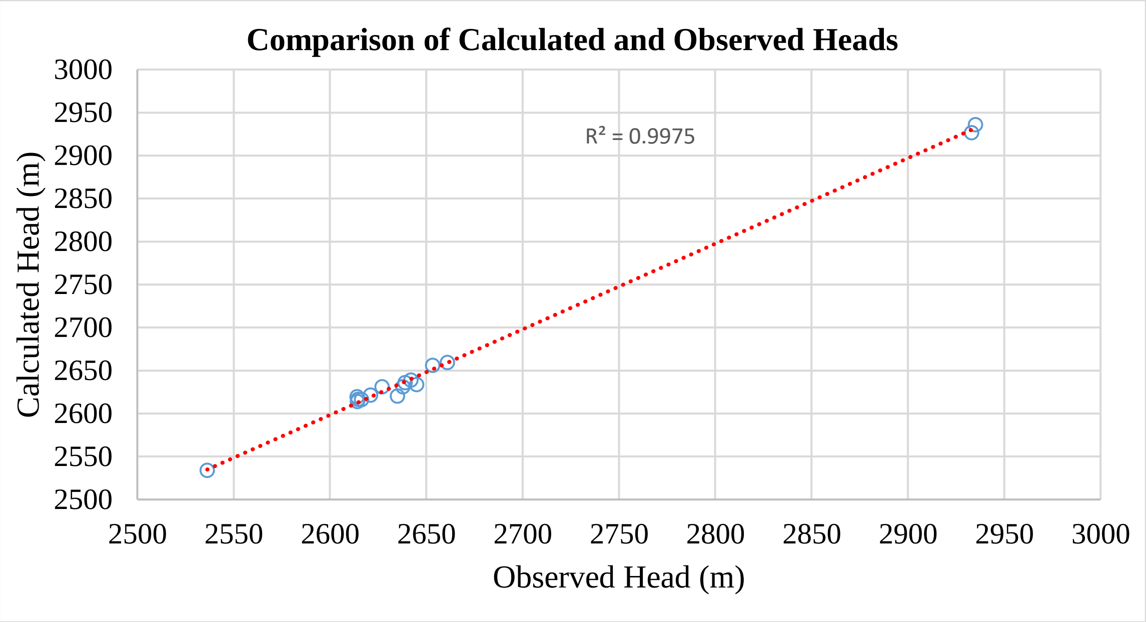

Figure 6.2 Scatter plot of observed against simulated hydraulic heads.

6.5.2 Evaluation of model calibration

The results of the calibration should be evaluated both qualitatively and quantitatively (Anderson & Woessner, 2015). The mean of the observed and simulated heads differences will use to quantify the average error in the calibration process. The three ways of expressing the average difference between simulated heads (hs) and measured heads (hm) are the mean error (ME), the mean absolute error (MAE) and the root mean square error (RMSE) (Adane, 2014). Where mean error (ME) is the mean difference between measured heads and simulated, mean absolute error (MAE) is the mean of the absolute value of the differences in the measured and simulated heads, and the root mean square error (RMSE) is the average of the squared differences in measured and simulated heads. The main target of the calibration is to minimize these error values.

1) The mean error (ME) is the mean difference of the residual errors (measured heads hm minus simulated heads hs): $\mathrm{ME} = \frac{1}{n}\sum_{i=1}^{n}|\mathrm{hm}-\mathrm{hs}|_i$
2) The mean absolute error (MAE) is the mean of the absolute value of the residual.

$\mathrm{MAE} = \frac{1}{n}\sum_{i=1}^{n}|\mathrm{hm}-\mathrm{hs}|_i$

3) The root mean squared error (RMSE) is the average of the squared residuals.

$\mathrm{RMSE}= \left[\frac{1}{n}\sum_{i=1}^{n}(\mathrm{hm}-\mathrm{hs})_i^2\right]^{0.5}$

Table 6.1 Calibration evaluation of mean errors using observed and simulated heads

Well No	calculated value	observed value	ME (AVG (hm-hs))	MAE AVG(|hm − hs|)	RMSE SQRT (AVG (hm-hs) ²)
OBS1	2936.1	2935.0	-1.070	1.1	1.1
OBS2	2926.7	2933.0	6.313	6.3	39.9
OBS3	2638.9	2642.0	3.096	3.1	9.6
OBS4	2631.3	2637.8	6.456	6.5	41.7
OBS5	2631.3	2627.0	-4.273	4.3	18.3
OBS6	2614.1	2614.3	0.202	0.2	0.0
OBS7	2619.8	2614.0	-5.800	5.8	33.6
OBS8	2616.9	2614.6	-2.280	2.3	5.2
OBS9	2616.3	2616.4	0.090	0.1	0.0
OBS10	2534.1	2536.3	2.219	2.2	4.9
OBS11	2633.8	2645.0	11.166	11.2	124.7
OBS12	2659.7	2661.0	1.267	1.3	1.6
OBS13	2621.4	2621.0	-0.435	0.4	0.2
OBS14	2636.1	2639.0	2.940	2.9	8.6
OBS15	2620.5	2635.0	14.5	14.5	208.9
OBS16	2656.3	2653.3	-3.0	3.0	8.8
			ME = 2.0	MAE = 4.1	RMSE = 5.6

7. RESULT AND DISCUSSION

According to what was stated in the objectives section, the annual average recharge received by the Gur catchment was calculated from the analysed data that had been gathered. Subsequently, the catchment's conceptual model was constructed using the flow system, hydrostratigraphic units, and boundary conditions. Additionally, findings from steady-state numerical groundwater modeling were simulated using various data inputs. In general, the outcomes of recharge estimation, aquifer characterization, and steady-state numerical groundwater flow modeling are covered separately in the sections that follow.

7.1 Groundwater Recharge estimation

The selection of recharge methods is influenced by a number of variables, including data availability, geographical and temporal resolution, and aquifer features. In this study, the WetSpass model and chloride mass balance were utilized to evaluate potential groundwater recharge from rainfall. It is important to note that the WetSpass model has been frequently applied in recent years for estimating recharge. This model calculates the spatial distribution of groundwater recharge on a monthly, seasonal, and annual basis by subtracting the surface runoff and evapotranspiration from the corresponding precipitation values. The results of the model showed that the annual groundwater recharge in the Gur catchment varied from 0 to 318 mm/year, with an average value of 106 mm/year. This means that, on average, 10% of the annual precipitation contributes to groundwater recharge. Furthermore, the study found that the recharge distribution within the catchment was not evenly distributed throughout the year. The majority, around 76%, of the annual groundwater recharge occurred during the wet season, which is typically the summer season. The remaining 24% of recharge took place during the dry seasons.

The north western parts of the study areas have high annual groundwater recharge due to the presence of permeable soils (loam and clay loam), high precipitation, deeply weathered and fractured volcanic rocks. On the contrary, the southern and eastern part of the catchment have less amounts of recharge due to low precipitation, impermeable soils which is deep clay soil and land use land cover which is cropland. In respective to the topography, the high values of groundwater recharge is located at medium high land area of the catchment. This is because, the high land of Gur catchment is characterized by loam soil and mixed forest and grassland which changed to bare land during dry season. In addition to these, the highland of the catchment has high precipitation than lowland. In general, high values of groundwater recharge are observed in the shrub land and grassland and mixed vegetation with loam and sandy loam soils. The amount of Groundwater recharge estimated by chloride mass balance was 103 mm/year and the average value of the two methods which is a mean annual groundwater recharge is 104.5 mm/year.

7.2 Aquifer Characterization

Based on the hydrogeological properties such as infiltration capacity of surficial materials, the permeability of the rocks outcropping in the catchment, degree of weathering and fracturing, topographic and morphologic position, and hydrologic features, the geological formation of the study area classified into three hydrogeological units. These are moderately productive porous aquifers, moderately productive fissured aquifers and Aquiclude consisting of gypsum and mudstone.

The quaternary unconsolidated sediments which consists of alluvial, colluvial and elluvial sediments of Quaternary age of Gur catchment are grouped into moderately productive porous aquifers. The porous aquifers altogether cover 7 % of the catchment. Aquifers consist of basalts and other volcanic rocks, including mixed units of various Tertiary rocks such as ignimbrites, basalts, and pyroclastic intercalated with sediments and Mesozoic sandstones. Volcanic rocks and Debre Libanos sandstone of the Gur catchment are moderately productive fissured aquifers which are the principal aquifers in the area with larger than 474.7km^2 areal coverage. They have fissured permeability, where groundwater is accumulating in and flowing through the weathered rock but mainly through fissures and joints developed in volcanic and sedimentary rocks.

The hydraulic properties of aquifers in the Gur catchment are influenced by several factors, including the geology, geological structure, surface morphology, slope, and land use. These factors collectively shape the characteristics of the aquifer system and affect the movement and storage of groundwater. Within the Gur catchment, the aquifer system exhibits a range of hydraulic conductivity values, varying from 0.01 to 5.7 m/day, with an average value of 1.2 m/day. The highest hydraulic conductivity values are typically found in highly fractured and weathered basalt formations. These formations allow for enhanced permeability, facilitating the movement of water through interconnected fractures and pore spaces. Different hydrogeological units present in the area possess distinct transmissivity values, which are influenced by factors such as hydraulic conductivity and aquifer thickness. The transmissivity values within the Gur catchment range from 25.8 to 339 m^2/day, with an average value of 89.53 m^2/day. Transmissivity represents the ability of an aquifer to transmit water under hydraulic gradients.

Groundwater flow within the Gur catchment generally occurs from the southern and north western corridors towards the central-northern gorge area. This indicates that the north western and southern regions, along with the fractured highlands, act as recharge areas, where groundwater is replenished. On the other hand, the central-northern lowlands serve as discharge zones within the catchment, where groundwater is discharged through natural or induced processes. To represent the boundaries of the aquifer system, a General Head Boundary has been assigned to the north eastern and northern boundaries. This boundary condition implies that the hydraulic head (water level) in these areas is specified. For all remaining lateral boundaries, a specified flow boundary (no flow boundary) has been designated, indicating that there is no groundwater flow across these boundaries.

7.3 Steady State Simulated Result

In the study, the conceptual model of the catchment area is translated into a numerical model to facilitate a more detailed analysis of groundwater flow. This transformation involves dividing the catchment boundary into discrete cells, which allows for a systematic representation of the spatial characteristics of the area. The numerical model is organized in rows and columns with a consistent spacing between them. This grid-like structure enables a more precise and structured representation of the catchment domain. Each cell in the model corresponds to a specific location within the catchment, and the properties and processes associated with that location are considered in the simulation.

To simulate the groundwater flow within the catchment, a finite-difference block-centered flow code is employed. This computational approach uses mathematical equations to calculate the hydraulic head at the center of each cell in the numerical model. By computing the hydraulic head values, the model can provide insights into the spatial distribution of groundwater flow and the behavior of the aquifer system. The simulation of the numerical model is conducted under steady-state conditions, meaning that the groundwater flow is assumed to be constant over time. This simplifies the analysis by focusing on the long-term equilibrium state of the system. The time unit used for the simulation is measured in days, allowing for a detailed examination of the groundwater flow patterns and characteristics within the catchment. The main outputs of the steady-state groundwater flow simulation in the study are the inflow and outflow water budgets and the hydraulic heads of the catchment. The water budgets provide information on the volume of water entering and leaving the system, helping to quantify the overall water balance within the catchment. The hydraulic heads indicate the water pressure distribution across the area, offering insights into the direction and intensity of groundwater flow.

7.3.1 Hydraulic head

The hydraulic head results are generated through the utilization of a mathematical groundwater flow model. The simulation results are then analysed by comparing them with the measured data. This analysis, which involves both the simulated and measured hydraulic head values, is summarized in Table 6.1.

Table 7.1 Results of calculated head with observed data

Well No	calculated value	observed value
OBS1	2936.1	2935
OBS2	2926.7	2933
OBS3	2638.9	2642
OBS4	2631.3	2637.8
OBS5	2631.3	2627
OBS6	2614.1	2614.3
OBS7	2619.8	2614
OBS8	2616.9	2614.6
OBS9	2616.3	2616.4
OBS10	2534.1	2536.3
OBS11	2633.8	2645
OBS12	2659.7	2661
OBS13	2621.4	2621
OBS14	2636.1	2639
OBS15	2620.5	2635
OBS16	2656.3	2653.3

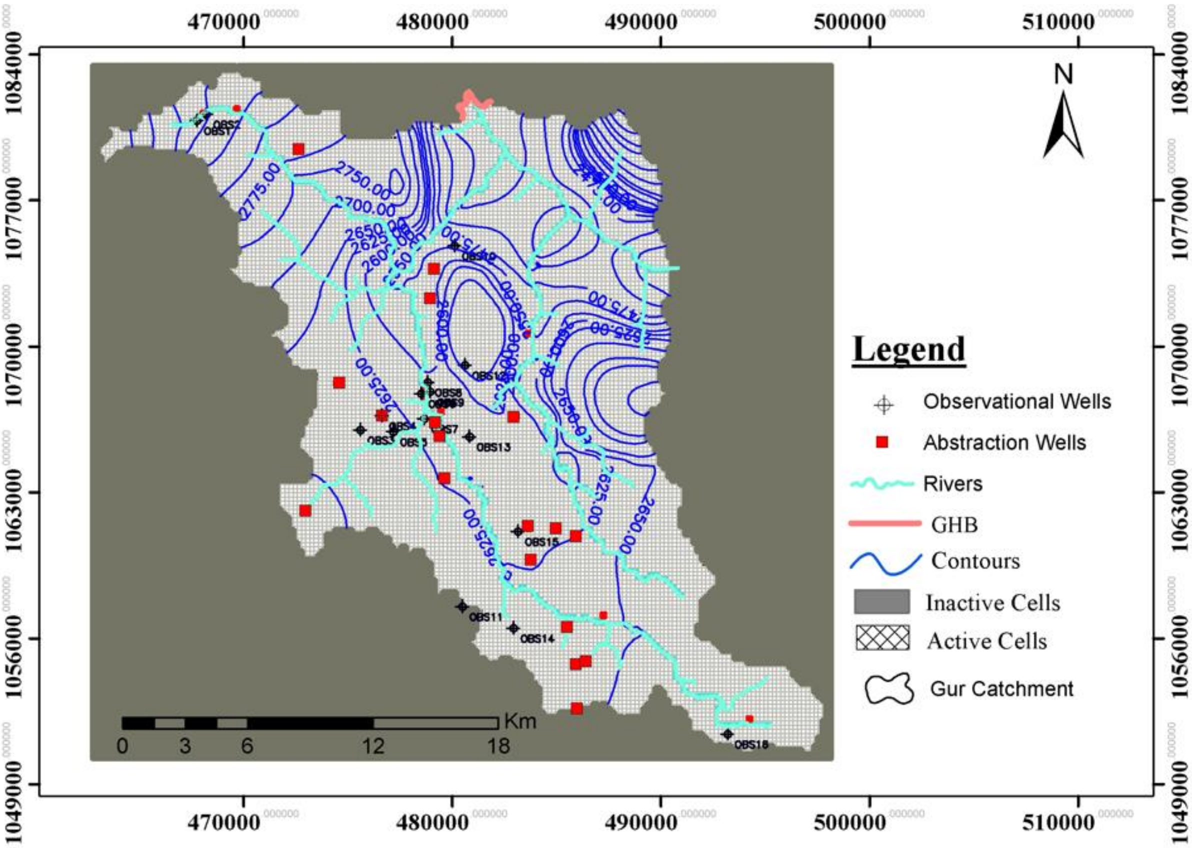

Figure 7.1 Simulated Groundwater contour map of the model domain

7.3.2 Water budget results

The major output of groundwater water modeling after proper calibration is water balance of the model domain (Gur catchment). Water budget in steady state flow is the balance between inflow and outflow. The final steady state calibration resulted in total inflow water balance of 246974 m^3/day and out flow 246972.7 m^3/day with discrepancy of 1.3 m^3/day (table 7.2).

The recharge of the study area (Gur catchment) is estimated using WetSpass method. The estimated recharge using WetSpass method was 106 mm/year. The simulated recharge of the model domain is 101.5 mm/year. The simulated value is close to the estimated recharge.

The percentage of inflows were 59.7% from recharge, and 40.3% from River leakage. The percentage of outflows were 87.8% from Groundwater discharge to River, 1.5% from head dependent boundary (inter aquifer flow), and 10.7% by pumping from wells. The model simulated that much of inflow to groundwater flow system is contributed from precipitation recharge. On contrary, out flow the catchment in general is dominantly through leakage to River.

Table 7.2 Water Budget summary for Gur catchment under steady state problem calculated by MODFLOW.

Water budget components	IN (m^3/day)	OUT(m^3/day)	IN-OUT (m^3/day)
Wells	0.000E+00	2.639E+04	-2.639E+04
Recharge	1.473E+05	0.000E+00	1.473E+05
River Leakage	9.963E+04	2.168E+05	-1.172E+05
Head Dependent Boundary	0.000E+00	3.734E+03	-3.734E+03
Sum	2.470E+05	2.470E+05	1.3E+00
DISCREPANCY (%)	0.0		

7.3.3 Model Sensitivity Analysis

Sensitivity analysis is the measure of uncertainty in the calibrated model caused by uncertainty in aquifer parameters and boundary conditions. Sensitivity analysis was performed by systematically changing the calibrated values of conditions (Anderson and Woessner, 1992). The main objective of a sensitivity analysis is to understand the influence of various model input parameters and hydrological stresses on the aquifer system and to identify the most sensible parameter(s), which will need special attention in future studies (Rejani et al., 20018). By running the calibrated model for the respective changed values of the input parameter and comparing the result with the calibrated head, the parameter sensitive to the model was established. The response of the calibrated model to changes in model parameters of hydraulic conductivity, Hydraulic Conductance of the Riverbed, and Groundwater Recharge was examined.

The calibration value of these parameters were varied by 25%, 50%, and 75%, increase and decrease at different times to test the sensitivity of the model to the parameters. During the model run, when the effect of one parameter was being tested, the other parameters were kept unchanged from the calibrated value. The amount of change in heads from the calibrated solution was used as a measure of the sensitivity of the model to that particular parameter. The sensitivity analysis’s findings were restricted to the model’s statistical calibration results and how altering the model’s parameters affected the simulated heads’ total root mean square error (RMSE).

Table 7.3 RMSE head changes with different recharge, hydraulic conductivity and hydraulic conductance of Riverbed from the calibrated values

Multiplier factors	Hydraulic conductivity	Groundwater Recharge	Hydraulic Conductance of the Riverbed
0.25	117.64	35.96	11.09
0.50	37.40	28.28	8.54
0.75	13.14	13.46	6.50
1.25	12.33	10.56	5.68
1.50	19.27	19.77	6.02
1.75	18.85	29.63	6.32
2.00	16.03	39.71	6.66

As indicated below in the graph, the hydraulic conductivity is more sensitive in this study. The hydraulic conductance of the Riverbed is less sensitive to changing the simulated heads. But, both hydraulic conductance of the Riverbed and Groundwater recharge significantly affect the entire model's water budget. In general, the model is highly sensitive to decrease of calibrated hydraulic conductivity mainly to decrease beyond 50% of the calibrated values. Results of the sensitivity analysis show that small errors in estimating values of the aquifer properties to which the model is most sensitive, which in this case is recharge and hydraulic conductivity, can have a significant effect on the model simulation results.

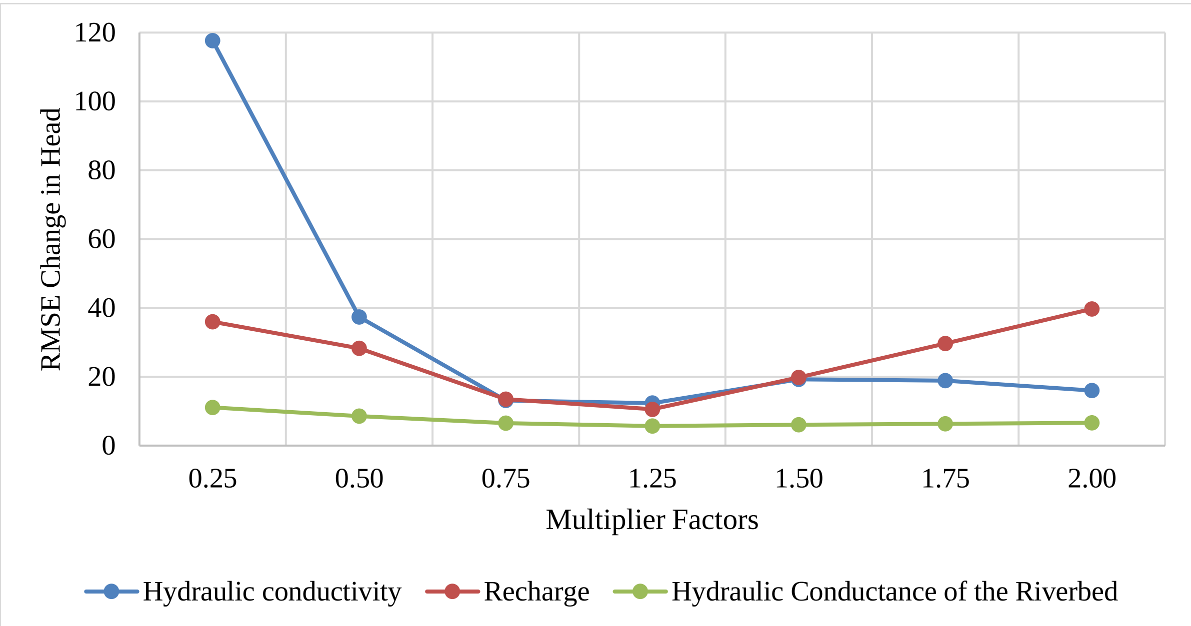

Figure 7.2 Sensitivity analysis of the effect of selected parameters on the RMSE value of water level

7.3.4 Scenario Analysis

The basic advantage of numerical groundwater flow modeling is that the results can be tailored for various scenario analyses (Ayehu et al., 2018). A calibrated flow model can be used as a tool to evaluate and compare the responses of an aquifer system to potential future stresses. As it has been clearly stated in the objectives, the numerical groundwater flow model that was simulated in this study is intended to test the response of the hydrologic system to different scenarios. Three scenarios were built for this study area: Scenarios 1, 2, and 3 involve increasing the current groundwater pumping rate, decreasing groundwater recharge, and increasing pumping rate and decreasing recharge at the same time, respectively. In all scenarios, other model parameters were kept to steady-state values except the stress for which the projection was carried out, and the resulting changes in water levels and fluxes are interpreted as responses of the system to the changes introduced to it. The scenarios were selected based on the possibility of an increasing rate of groundwater abstraction and decreasing recharge due to expected increasing demand and climatic change, respectively, in the future. The increasing demand for groundwater for drinking and irrigation will put pressure on drilling additional boreholes, which will result in the extraction of much more water relative to the current abstraction rate from the subsurface.

It should be noted that the outcomes of the scenarios depend on future land use, population growth, hydrologic stressors, etc. and may not be used as a prediction tool to generate absolute amounts in the future. Instead, they are used largely to examine how the system responds. (Ayehu et al., 2018; Hamid, 2019). In general, the results of the scenarios or their accuracy depend on the validity of the assumptions behind the scenarios. Additionally, mistakes introduced as a result of numerical model restrictions have an impact on the scenario's results and should be taken into account when interpreting and using the findings.

Scenario One: The increase in abstraction

Fiche town and other small towns in the Gur catchment are growing rapidly. Especially in the Debre Tsige area, many water wells are being dug by various institutions, including Addis Ababa University, for drinking, irrigation, and industry purposes. So it is realistic to think that the demand for access to water will increase.

This truth can be seen from the large number of wells drilled recently in the catchment around Debre-Tsige town. So it is logical to think that groundwater withdrawal will increase in the catchment, and it is necessary to project its future effects on the groundwater table and fluxes of the area so that appropriate water management practices that could mitigate the likely adverse effect of increased withdrawal may be proposed. To evaluate this condition, three scenarios of increased groundwater withdrawals have been conducted.

Based on the information obtained from different water offices, the total current abstraction rate of the catchment is 29072.736 m^3/day. The steady state withdrawal rate was increased by 50%, 100%, and 200% to study the response of the system in this scenario. These increases are equivalent to withdrawing additional 14536.4 m^3/d, 29072.7 m^3/d, and 58145.5 m^3/d from the existing abstraction over the whole catchment, respectively, and the increased withdrawals were distributed among the existing wells (not assigned as new wells). System responses to increased groundwater withdrawal for the above scenarios are shown in table6.4 and figure 6.3 below.

Table 7.4 Decline in hydraulic head simulated by increasing from the current pumping rate

Well No	observed Head	Calibrated Head	Head at Scenario # 50	Decline in head, (in m)	Head at Scenario # 100	Decline in head, (in m)	Head at Scenario # 200	Decline in head, (in m)
OBS1	2935.0	2936.1	2935.199	0.9	2934.504	1.6	2933.1	3.0
OBS2	2933.0	2926.7	2925.969	0.7	2925.086	1.6	2923.3	3.4
OBS3	2642.0	2638.9	2637.523	1.4	2636.152	2.8	2633.4	5.5
OBS4	2637.8	2631.3	2630.081	1.2	2628.88	2.4	2626.4	4.9
OBS5	2627.0	2631.3	2630.187	1.1	2629.114	2.2	2626.9	4.3
OBS6	2614.3	2614.1	2612.217	1.9	2610.31	3.8	2606.3	7.9
OBS7	2614.0	2619.8	2619.262	0.5	2618.737	1.1	2617.7	2.1
OBS8	2614.6	2616.9	2616.665	0.2	2616.503	0.4	2616.1	0.8
OBS9	2616.4	2616.3	2615.996	0.3	2615.729	0.6	2614.6	1.7
OBS10	2536.3	2534.1	2531.959	2.1	2531.344	2.7	2525.3	8.8
OBS11	2645.0	2633.8	2633.447	0.4	2633.063	0.8	2632.3	1.5
OBS12	2661.0	2659.7	2658.64	1.1	2657.841	1.9	2657.2	2.5
OBS13	2621.0	2621.4	2621.157	0.3	2621.074	0.4	2620.7	0.7
OBS14	2639.0	2636.1	2635.228	0.8	2634.396	1.7	2632.7	3.3
OBS15	2635.0	2620.5	2618.614	1.9	2616.683	3.9	2612.8	7.8
OBS16	2653.3	2656.3	2656.15	0.1	2656.04	0.2	2655.8	0.4

The average decline in groundwater head due to the steady state withdrawal rate was increased by 50%, 100%, and 200% in the model domain (m) at 0.9, 1.7, and 3.7, respectively. In general, increasing steady-state well discharges by above rates resulted in insignificant declines in groundwater levels in most of the model domain. This reveals that, the area is not yet developed and the water demand is relatively low compared to the available groundwater resources. In areas with ample groundwater reserves and low water abstraction rates, the aquifer system can often accommodate additional pumping without significant declines in groundwater levels.

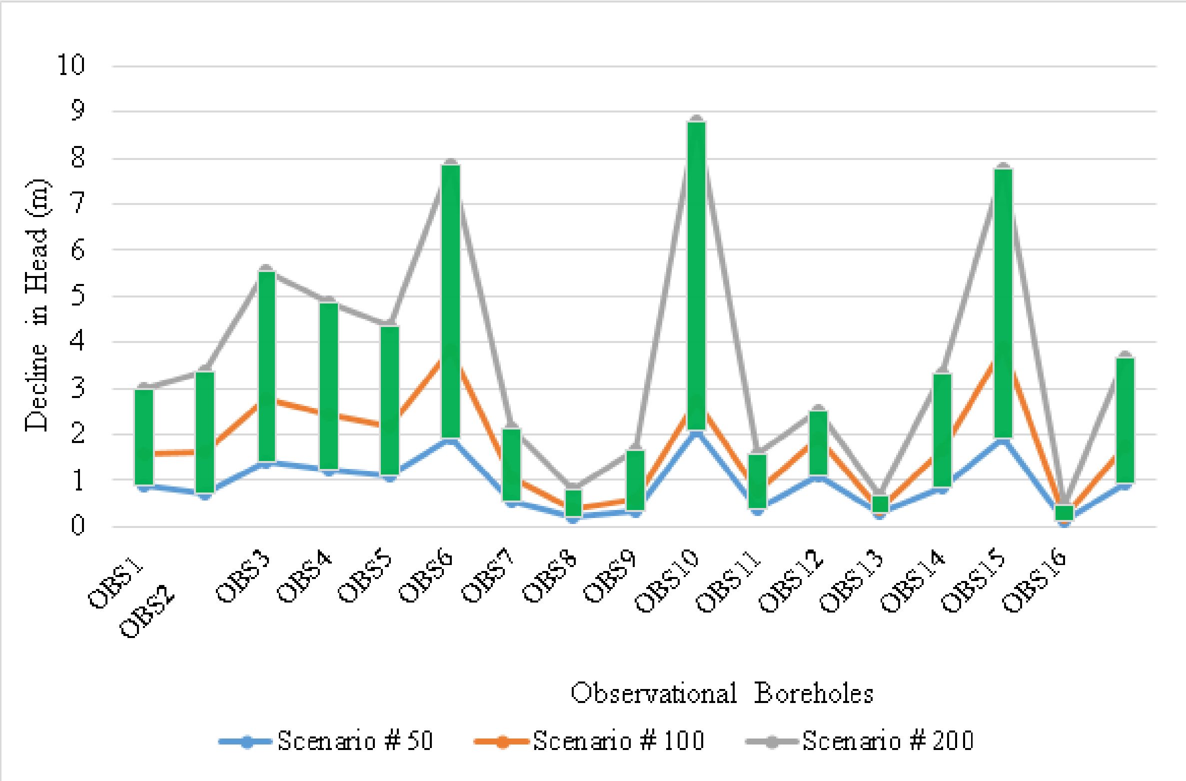

Figure 7.3 Response of aquifer to increased groundwater withdrawal

Generally, if future water demand conditions force groundwater to be withdrawn at rates simulated in these scenarios with other parameters not changed, there will be a hydrologic imbalance between groundwater inflow and outflow conditions that may cause a sustainable decline in groundwater level.

Scenario Two: The decrease in recharge

This scenario simulates a case of decreasing recharge to aquifers that may result from lower than normal precipitation (environmental changes), expansion of agriculture, deforestation, and town expansion. It is a real concern that changes in climatic conditions from time to time are affecting precipitation amounts in the country adversely and are reducing recharge to groundwater, as the main source of recharge is precipitation. Although it is difficult to quantify other factors assumed to remain unchanged, the future decrease in recharge amount will be inevitable, and the rough estimates made above can be used to study system response.

Therefore, in this scenario, the simulated response of the system to decreased recharge was compared with the steady-state calibrated water levels. The differences showed changes induced by the decreased recharge. The steady-state simulated recharge was decreased by 25%; the simulation result shows an average head decrease of 21 m over the whole area. This outcome suggests that groundwater head of the study area is highly sensitive to changes in recharge rates compared to changes in withdrawal rates. This sensitivity may be attributed to the specific hydrogeological characteristics of the region, including aquifer properties and geological formations. Therefore, acquiring a comprehensive understanding of the local hydrogeology and conducting site-specific studies can offer more precise insights into the sensitivity of groundwater levels in the Gur catchment area to changes in recharge. Consequently, the reduction in recharge has an adverse impact on the groundwater table, demanding the formulation of strategies to mitigate this environmental concern. Some of the most important measures that should be taken are decreasing the expansion of agriculture, afforestation, and constructing soil and water conservation structures. These actions aim to enhancing natural recharge processes, and optimizing water retention in the catchment.

Scenario Three: The worst-case scenario

Combining an increase in abstraction with a decrease in recharging is the worst case scenario (Sileshi et al., 2021). This scenario simulated a case of decreasing recharge used during calibration by 25% due to low rainfall and an increase in withdrawal by four times. This scenario was modeled to explore how the aquifer system would react if the demand for groundwater quadrupled as a result of urban sprawl and population growth while recharge decreased by 25% due to lower rainfall. As a result, the minimum and maximum groundwater table decline for a 25% reduction in recharge and a 200% increase in withdrawal are 1.3 and 82.2 m, respectively, with an average value of 24.2 m.

7.3.5 Model Limitations

As a model is a device that represents an approximation of a field situation, it is true that there are a number of limitations associated with it. Because they contain simplifications and assumptions during conceptual model development and converting the conceptual model into a numerical model. Numerical groundwater flow models are only approximations of complex natural systems and have uncertainty. Therefore, it is essential that for any groundwater model to be interpreted and used properly, these limitations be understood. In the numerical groundwater flow simulation of Gur Catchment, some of the associated limitations are:

- The simulation of the groundwater system was based on various assumptions regarding the real natural system being modeled. In this study, some of these assumptions were that the system was represented as a single layer, the aquifer is unconfined, and a simulation was made assuming that the system is under steady state conditions, which can never be known in the absence of long-term water level data. Another deficiency is a lack of understanding of detailed geology in most parts of the area. Complex geology controls groundwater flows.

- The degree of uncertainty in the model was raised due to the poor quality and limitations of the existing data, such as model geometry (screen length and aquifer thickness), which are not well documented, and the available records of the water level measurements are not continuous and mostly are only single measurements.
- The model was calibrated but not verified because no independent measured heads were able to validate the model. Moreover, the results from the model should not be interpreted as a perfect simulation; instead, these results can be interpreted as a system response within reasonable and realistic model input parameters.
- The uncertainty also occurred while defining the boundary conditions of the model domain. The boundary conditions were defined based on surface physical features such as impervious geology, surface water division, and groundwater division. The locations of the groundwater catchment boundaries are uncertain since they might not coincide with their surface expressions.

8. CONCLUSIONS AND RECOMMENDATIONS

8.1. Conclusion

The Gur catchment is located in the central part of Ethiopia, in the Middle Abay basin within the north Shewa zone of the Oromia region. Using different approaches and methodologies that have been discussed so far in each section of the research, the following conclusions have been forwarded:

The total study area is about 530 km^2. Gorges, flatlands, and ridges are the main part of the topography of the study area, which has a range of elevation from 1402 to 3341 m. Even though the slope of the north-eastern part of the study area is very steep, most of the area falls in the range of 0 – 4 degrees. According to the traditional classification system, which mainly relies on altitude and temperature, the Gur catchment is characterized by Dega, Woina Dega, and Kola climatic zones, with the mean annual rainfall ranging from 1029 to 1198 mm and a temperature range of 14.4 to 16.5 °C. As the European Space Agency (ESA) released in October 2021 a freely accessible global land cover product at 10 m resolution for 2020, about 83% of the study area is covered by crop land. According to a detailed study by the Engineering Corporation of Oromia (ECO) region on the Abay basin, about 68 and 20% of the soil textures of the catchment are clay and loam, respectively. Two distinct Mesozoic sedimentary rock formations (Muger Mudstone and Upper Coarse Grained Sandstone), lower to upper Tertiary volcanic rock units, and Quaternary superficial sediments are exposed in the study area.

Groundwater recharge was estimated using the WetSpass Model and CMB methods. The use of WetSpass provided estimations for evapotranspiration, surface runoff, and groundwater recharge by using meteorological data and grids of groundwater depth, topography, slope, land use, and soil texture. Based on the WetSpass Model output, the estimated annual runoff, AET, and groundwater recharge of the catchment are 426 mm (39% of the precipitation), 561mm (51% of the precipitation), and 106mm (10% of the precipitation), respectively. The amount of groundwater recharge obtained from the CMB method is103 mm/year and the average value of the two methods which is a mean annual groundwater recharge is 104.5 mm/year.

The conceptualization of a groundwater system in the Gur catchment started with identifying the hydro-stratigraphic units that contain similar hydrogeologic properties. By integrating the hydrogeological properties that were obtained from field observation, borehole lithological logs, and pumping test results, the lithostratigraphic units discussed in the above section are transformed into hydrogeological units. Based on this, the qualitatively grouped lithostratigraphic units showing similar hydrogeological characteristics are: moderately productive porous aquifers; moderately productive fissured aquifers; and aquiclude consisting of gypsum and mudstone. The quaternary unconsolidated sediments, consisting of alluvial, colluvial, and elluvial sediments, are grouped under moderately productive porous aquifers. Tertiary volcanic rocks and the Debre Libanos sandstone of the Gur catchment are moderately productive fissured aquifers, which are the principal aquifers in the area with greater than 474.7 km^2 of areal coverage.

After data quality and consistency were checked from the water point inventory, 74 wells and 65 springs holding information on location (UTM coordinate) and static water level were used for this study. The transmissivity and hydraulic conductivity of the area range from 2.25 to 3966 m^2/day and 0.0064 to 11.3 m/day, respectively. Determining the flow direction and groundwater level of the catchment to be modeled helps determine the boundary condition of the Gur catchment. The hydraulic heads and flow direction were determined by interpolating the borehole records. There is a record of more than 74 static water levels within and very near the study area, and these static water levels were converted into hydraulic heads. The inverse distance weighted (IDW) technique was applied to interpolate the Gur catchment's groundwater level properly, taking into account the topographic variability of the catchment. A map of the equipotential line and groundwater flow direction was developed, and the general flow direction was determined as a south-to-north direction. Groundwater recharge is from precipitation and groundwater inflow from the south Jema sub basin. The outflow from the ground system includes well withdrawal and subsurface outflow.

To represent the Gur catchment with a numerical model, steady state conditions, a two-dimensional flow system, and one unconfined aquifer layer were considered, and the model domain was discretized into a regular rectangular grid and a finite difference block-centered groundwater flow model. The computer code applied in this numerical modeling is processing the MODFLOW package. Fundamental input parameters used for MODFLOW simulation and calibration of the regional steady state groundwater model require layer top elevation taken from ASTER DEM, and layer bottom elevation is found by subtracting the aquifer thickness from layer top elevation.

The second input to the model is boundary conditions, and for active cell 1, which includes all working areas, inactive cell 0 is assigned an area outside the catchment. The other input parameter is the initial hydraulic head that is specified for each cell, and the first steady-state simulation uses the initial and prescribed hydraulic heads by subtracting 30 m from the top of the layer. The other important parameter in the model is horizontal hydraulic conductivity, and

for the first simulation, a value of 0.11 m/day to 5.71 m/day is used, which was adopted from well pumping test reports collected from different drilling companies. The flow packages treated in the model are General Head Boundary (GHB), Recharge, Well, and River Package.
The groundwater model calibration showed that the calculated hydraulic heads matched well with the observed values in the steady state. The water budget components and hydraulic heads were simulated for the calibrated model. The final steady-state calibration resulted in a total inflow water balance of 246974 m^3/day and an outflow of 246972.7 m^3/day, with a discrepancy of 1.3 m^3/day. The simulated recharge of the model domain and the estimated recharge using the WetSpass method are 101.5 mm/year and 106 mm/year, respectively, which is 59.7% of the simulated total inflow water balance. The sensitivity analysis result shows that the model is very sensitive to a change in hydraulic conductivity and groundwater recharge and less sensitive to the hydraulic conductance of the riverbed.
Three types of scenario analysis were done. The first scenario is by increasing the amount of groundwater extraction by 50, 100, and 200% from the current pumping rate. The simulation results in an average decline in water level of 0.9, 1.7, and 3.7, respectively. The second scenario is analyzed by decreasing the recharge by 25% while keeping the current rate of pumping. The simulation result shows an average head decrease of 21m over the whole area. Finally, the third scenario is simultaneously decreasing the current recharge by 25% and increasing the groundwater abstraction by 200%; in this case, the model shows an average decline in the head by 24.2 m from the current water levels.

8.2 Recommendations

In order to enhance future studies and improve groundwater resource management in the Gur catchment, the following recommendations have been proposed:

To enhance the overall usability and reliability of the groundwater flow model, it is recommended to use a different set of data for model verification. This means gathering additional field data from the catchment and using it to evaluate and update the model. By incorporating more data, the model can be validated and refined, leading to increased confidence in its predictions.

To visualize and assess the hydraulic characteristics of three-dimensional groundwater flows, it is suggested to represent the model with multiple layers. This multi-layer representation will provide a more comprehensive understanding of the flow patterns and dynamics within the aquifer system. It allows for a more accurate assessment of groundwater movement in different directions and depths.

During model calibration, it was observed that aquifer properties vary within short distances. To improve the model's accuracy and applicability to the natural conditions, a comprehensive investigation of aquifers is recommended. This would involve extensive field measurements of hydraulic head, hydraulic conductivity, and other sensitive parameters to enhance the understanding of the catchment and upgrade the model's precision.

Many shallow and deep boreholes in the area lack observational wells, making it challenging to monitor the present groundwater levels. It is crucial to install observation wells equipped with pressure transducers that can record water level fluctuations in real-time. Continuous monitoring of abstraction rates and professional follow-up is necessary to facilitate accurate transient groundwater flow modeling and predict system responses.

To ensure efficient groundwater utilization and minimize excessive water loss from borehole over-pumping, it is essential to establish systematic and planned groundwater pumping practices. Additionally, promoting the development of well-developed springs can help increase discharge, reducing the reliance on borehole extraction.

Further research should be conducted in the study region to enhance the precision and comprehensiveness of the groundwater flow model for the entire catchment. This research should focus on improving the understanding of groundwater reserves, including recharge and abstraction rates, borehole separation distances, and groundwater flow patterns.

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