Delineation of Groundwater Potential Zone Using AHP, GIS, and Remote Sensing Techniques in Sirkole Watershed, Western Ethiopia.

Wakgari Yadeta Hirpa

A Thesis Submitted to the Department of Applied Geology

School of Applied Natural Science

Presented in Partial Fulfillment of the Requirement for the Degree of Master's in Hydrogeology

Office of Graduate Studies

Adama Science and Technology University

November, 2024

Adama, Ethiopia

Delineation of Groundwater Potential Zone Using AHP, GIS, and Remote Sensing Techniques in Sirkole Watershed, Western Ethiopia.

Wakgari Yadeta Hirpa

Advisor: Shankar Karuppannan (PhD)

A Thesis Submitted to the Department of Applied Geology

School of Applied Natural Science

Presented in Partial Fulfillment of the Requirement for the Degree of Master's in Hydrogeology

Office of Graduate Studies

Adama Science and Technology University

November, 2024

Adama, Ethiopia

DECLARATION

I hereby declare that this Master thesis entitled "**Delineation of Groundwater Potential Zone Using AHP, GIS, and Remote Sensing Techniques in Sirkole Watershed, Western Ethiopia.**" is my own work. That is, it has not been submitted for the award of any academic degree, diploma, or certificate in any other university. All sources of materials that are used for this thesis have been duly acknowledged through citation.

Wakgari Yadeta Hirpa	________________________	________________
Name of student	Signature	Date

RECOMMENDATION

I, the major advisor of this thesis, hereby certify that I have advised the revised version of the thesis entitled **"Delineation of Groundwater Potential Zone Using AHP, GIS, and Remote Sensing Techniques in Sirkole Watershed, Western Ethiopia."** prepared under my guidance by **Wakgari Yadeta Hirpa**, submitted in partial fulfillment of the requirements for the degree of Masters of Science in Hydrogeology.

Therefore, I recommend the submission of the revised version of the thesis to the department following the applicable procedures.

Dr. Shankar Karuppannan ____________________ ________________

Major Advisor Signature Date

APPROVAL PAGE OF THESIS

I, the advisor of the thesis entitled **"Delineation of Groundwater Potential Zone Using AHP, GIS, And Remote Sensing Techniques in Sirkole Watershed, Western Ethiopia."** and developed by Wakgari Yadeta Hirpa hereby certify that the recommendation and suggestions made by the board of examiners are appropriately incorporated into the final version of the thesis.

Dr. Shankar Karuppannan	____________________	________________
Major Advisor	Signature	Date

We, the undersigned, members of the Board of Examiners of the thesis Wakgari Yadeta Hirpa have read and evaluated the thesis entitled "Delineation of Groundwater Potential Zone Using AHP, GIS, and Remote Sensing Techniques in Sirkole Watershed, Western Ethiopia." and examined the candidate during open defense. This is, therefore, to certify that the thesis is accepted for partial fulfillment of the requirement of the degree of Master of Science in Hydrogeology.

____________________	____________________	________________
Chairperson	Signature	Date
____________________	____________________	________________
Internal examiner	Signature	Date
____________________	____________________	________________
External Examiner	Signature	Date

Finally, approval and acceptance of the thesis are contingent upon submission of its final copy to the Office of Postgraduate Studies (OPGS) through the Department Graduate Council (DGC) and School Graduate Committee (SGC).

____________________	____________________	________________
Department Head	Signature	Date
____________________	____________________	________________
School Dean	Signature	Date
____________________	____________________	________________
Office of Postgraduate Studies Dean	Signature	Date

ACKNOWLEDGMENT

First of all, I would like to thank God Almighty for helping me to be where I am now. Next, I would like to thank Dr. Shankar Karuppannan for his advice and encouragement during my research work. I would also like to thank the Department of Applied Geology, School of Applied Natural Science, Adama Science and Technology University for their support and thoughtful cooperation during our stay together, and I am deeply grateful to the offices for their invaluable assistance in furnishing the diverse datasets that have been instrumental to my research. I would also like to take this opportunity to thank all my friends and elders who have been advising and encouraging me especially Mr. Dechasa Diriba, Department of Geology, College of Natural and Computational Science, Dilla University, Dilla, Ethiopia.

Lastly, I will offer my most profound gratitude to my family, especially my elder brother, Naol Yadeta. Naol has been the very foundation upon which I have built my life under the grace of God. His tireless sacrifices, unending resources, and thoughtful guidance have been the bedrock that has supported me from the beginning until now. In my darkest moments, Naol's counsel, support, and unwavering belief in me have lifted me up and propelled me forward.

TABLE OF CONTENTS

Contents **Pages**

LIST OF TABLES

LIST OF FIGURES

LIST OF APPENDIXES

LIST OF ACRONYMS AND ABBREVIATIONS

AHP	Analytic Hierarchy Process
Arc-SDM	Arc Spatial Data Modeler
AUC	Area Under the Curve
BGRS	Benishangul Gumuz Regional State
CI	Consistency Index
CR	Consistency Ratio
DD	Drainage Density
DEM	Digital Elevation Models
ERDAS	Earth Resource Data Analysis System
ETM+	Enhanced Thematic Mapper Plus
FAO	Food and Agriculture Organization
GIS	Geographic Information Systems
GSE	Geological Survey of Ethiopia
GWPI	Groundwater Potential Index
GWPZ	Groundwater Potential Zone
IDW	Inverse Distance Weighted
LU/LC	Land Use Land Cover
MCDA	Multi-Criteria Decision Analysis
MCDM	Multicriteria Decision Making
NMSA	National Meteorological Sonde Agency
OLI	Operational Land Imager
PCM	Pairwise Comparison Matrix
ROC	Receiver Operating Characteristic
RS	Remote Sensing
SRTM	Shuttle Radar Topography Mission
TRMM	Tropical Rainfall Measurement Mission
USDA	United States Department of Agriculture
USGS	United States Geological Survey
WIOA	Weight Index Overlay Analysis

ABSTRACT

Thes thesis discusses the use of remote sensing and geographic information system (GIS) techniques to evaluate groundwater potential zones in a section of the Sirkole watershed in Western Ethiopia. The study analyzed various spatial data layers, including land use, drainage density, lineaments, slope, lithology, rainfall, geomorphology, and soil type, to understand the factors influencing groundwater occurrence and movement. Lineaments were extracted using PCI Geomatical software, and their orientations were determined. Parameters were weighted using the Analytical Hierarchy Process (AHP), and each feature class was ranked based on its characteristics and relationship with groundwater. The resulting groundwater potential zone map categorized the watershed into five zones: very high, high, moderate, low, and very low. Approximately 44.5% was categorized as having high to very high groundwater potential, and 25.4% of the watershed was classified as having very low to low. Validation against existing pumping wells showed a prediction accuracy of 75.9%, affirming the reliability of the GIS and remote sensing techniques used to identify potential zones in the study area.

Keywords: *AHP, GIS, Groundwater Potential Zone, Remote Sensing, Sirkole Watershed*

CHAPTER ONE

1. INTRODUCTION

1.1. Background

Globally, groundwater accounts for a significant portion of freshwater usage, with approximately one-third of total withdrawals originating from this source. It plays a crucial role in supporting economic and social development, especially in regions where water resources are scarce (Ifediegwu, 2022). Groundwater is vital for the global economy, serving as a primary source of drinking water and sustaining key sectors like industry and agriculture (Kumar and Krishna, 2018; Tamesgen et al., 2023; Thapa et al., 2017). About 22% of the Earth's freshwater is estimated to be groundwater, making up around 97% of all liquid freshwater available for human consumption. However, mismanagement of groundwater resources to meet growing demand can ultimately result in water shortages and pollution (Rajaveni et al., 2017).

In recent times, digital satellite data has become a valuable resource for quickly accessing foundational information regarding the factors that influence the occurrence and movement of groundwater. This data includes updated details on geology, land cover, lineaments, and other relevant factors, which are readily available at no cost (Condon and Maxwell, 2015; Diriba et al., 2024; Li et al., 2018; Rukundo and Dogan, 2019). However, due to data scarcity and a lack of integrating tools, comprehensive studies of all these controlling factors have been rare. Nowadays, geospatial tools have emerged as effective means for handling spatial data and facilitating decision-making across various fields such as engineering and environmental management. Remote sensing (RS) and geographic information systems (GIS) are particularly crucial among these tools, playing significant roles in analyzing extensive hydrogeological data and simulating complex features (Berhanu et al., 2013; Bhowmick et al., 2023; Fenta et al., 2015; Gebru et al., 2020; Kaliraj et al., 2014).

Utilizing geophysical technologies for groundwater investigation can be costly and time-intensive, prompting the exploration of alternative methods due to resource constraints (Kumar and Krishna, 2018; Naghibi et al., 2015; Sivakumar et al., 2019). Technologies such as GIS and remote sensing have been increasingly employed to assess groundwater potential zones, offering a rapid and efficient means to study large areas with limited resources (Ifediegwu, 2022; Thapa et al., 2017). Numerous studies worldwide have utilized RS and GIS techniques to delineate groundwater potential zones (Allafta and Opp, 2021). Factors such as geology, geomorphology, slope, soil type, rainfall, land use/land cover, lineament structures, and drainage patterns are considered when groundwater resources are identified using RS and GIS methods. The ability to identify groundwater potential zones is crucial for effective long-term resource management, aiding planners, decision-makers, and policymakers in safeguarding groundwater resources from quantity and quality-related threats.

Integrating remote sensing and GIS tools significantly enhances groundwater exploration in the Sirkole Watershed. These advanced techniques play a key role in pinpointing fractured and weathered zones within the basement rocks, which are essential for groundwater storage. Through the adoption of a multi-criteria decision analysis (MCDA) approach, this study has successfully mapped potential groundwater zones with increased accuracy. The utilization of GIS and the analytic hierarchy process (AHP) enables a comprehensive evaluation of factors impacting groundwater occurrence and movement, leading to a more precise delineation of these crucial resources. This innovative methodology simplifies the identification process and establishes a robust framework for sustainable groundwater management in the area.

1.2. Statement of the Problem

Accurate and reliable assessment of groundwater potential and recharge is essential for sustainable groundwater exploitation due to increasing demand and the complexity of basement and volcanic aquifers. Assessing the hydraulic characteristics of basement rock aquifers is challenging and often yields unreliable results due to their unique assemblages. Unsustainable use of these resources is often linked to a lack of understanding of groundwater occurrence, transport, and recharge in basement terrains. Thus, in-depth expertise and skills are necessary for properly exploring and managing groundwater resources. The research area, spanning 909.17 km^2, has a growing population. With this population growth, rising living standards, and increased irrigation, the water needs in the area are also escalating. There is limited information on agricultural and watershed-level groundwater potential in the region. Identifying and understanding groundwater potential at the watershed level is crucial to determine groundwater flow direction and describe the aquifer for sustainable management. Delineating groundwater potential is vital for managing areas with high groundwater resources sustainably. It can aid in developing management strategies, prioritizing development and exploration, identifying potentially contaminated areas, and evaluating the impacts of climate change on groundwater resources. Therefore, this study aims to assess the groundwater potential of the Sirkole Watershed using remote sensing, Geographic Information Systems (GIS), and Analytical Hierarchy Process (AHP) techniques to produce a reasonable estimate of the resource's potential at the watershed level.

1.3. Objective of the study

1.3.1. General Objectives

The general objective of this study is to map and delineate groundwater potential zones in the Sirkole watershed using AHP, GIS, and Remote sensing methods.

1.3.2. Specific Objectives

- To identify the factors most controlling groundwater occurrence in the study area.
- To delineate groundwater potential zones through the integration of different controlling factors.
- To assign the weights and validation of groundwater Potential zone mapping.

1.4. Research Questions

- Which factors is the most controlling the occurrence of groundwater in the study area?
- Where do we get groundwater with high potentiality?
- How can assign weights and validate the Groundwater Potential zone?

1.5. Significance of the Study

The study underscores the underutilized groundwater resources in Ethiopia, emphasizing their potential to enhance residential, agricultural, and energy sectors. It identifies key areas for groundwater recharge and informs the development of water and soil conservation strategies in Assosa. The findings will assist the local Water Resource and Energy Management Office in zoning for sustainable urban planning and help businesses and farmers choose operation sites. Additionally, the research supports drought mitigation, ecosystem and community water security and promotes environmentally-conscious groundwater extraction. It also aids in infrastructure development, improves living standards in impoverished communities, and contributes to global water management solutions.

1.6. Limitations of the study

The main problems with this research are the unequal distribution of data points and the lack of complete groundwater inventory data.

CHAPTER TWO

2. LITERATURE REVIEW

2.1. Introduction

This chapter overviews groundwater status and previous research that defined groundwater potential zone mapping using GIS and remote sensing techniques. Next, a review of the factors influencing the zoning of groundwater potential and the use of RS and GIS for identifying groundwater potential will be covered.

2.2. Definition of groundwater

Groundwater is defined differently by different writers at different times. According to Rashman (2016), Groundwater is one of the most significant natural resources that can be found beneath the surface of the earth and is kept in voids of geological formations. It is used for domestic purposes, economic growth, and living variety. Also, he concludes that the occurrence and flow system of groundwater is also dependent on the porosity and permeability of the underlying geology, as well as the formation of landforms like high mountains, rift valleys, and flat plains, and the influence of these features on surface runoff and infiltration into the ground.

According to Kebede, (2013), Water in the saturated zone is known as groundwater. Also, the names of rocks that cover groundwater are different. The aquifer is a rock that efficiently stores and transfer’s water. Aquiclude is a type of rock in which water cannot be held or transferred efficiently. Aquitard is a type of rock that can store water but not efficiently transfer it to wells. Groundwater is found in exposed areas known as rock porosities and rock fractures. Open areas occur either during or after the actual formation of the rocks. Therefore, the quantity of open spaces in rocks and the general shape of these rocks determine how much groundwater is present below the surface. Variations in groundwater potential between continents, countries, and regions are intrinsically linked to the types and extent of rocks present as well as to conditions and rates of recharge. The amount of water that enters the groundwater from outside sources, such as rivers, lakes, precipitation, or any other adjacent aquifer, is referred to as recharge in this context.

2.3. Factor affecting Groundwater potential Zone

Several previous research investigations demonstrate that the groundwater potential zone is influenced by various factors that either control or encourage this process according to Prasad et al. (2008), GIS can be used to interpret the ground potential zone in hard rock water. He partly covered lithology, geomorphology, lineament, soil, slope, drainage pattern, land usage, and rainfall. In summary, those characteristics are important in mapping recharge zones and groundwater potential. According to Lammesa (2017), using remote sensing data derived from the indirect study of visible terrain features such as geological formations, geomorphology, land-use/land cover, slope, rainfall, drainage density, and lineaments, investigate the origin of groundwater occurrence and movement location.

According to Boru (2007) groundwater potential is determined by several parameters, such as elevation, drainage, geomorphologic features, hydrological variables (water availability for recharge), geological factors (lithology and structures), LU/LC, etc. These factors' relative importance changes depending on the location. For instance, the hydrologic component has a greater influence on groundwater occurrence than the geologic control in regions with unconsolidated sediment lithology.

2.4. Groundwater in Ethiopia

According to Lammesa (2017) he examined the availability and utilization of groundwater in fifteen sub-Saharan African nations. In summary, he states that sub-Saharan Africa's hydrological conditions control subsurface groundwater more than any other country. He further divides the sub-Saharan hydrological aquifer parameters into four categories: crystalline basement complex rock, consolidated sedimentary rock, unconsolidated sedimentary rock, and volcanic rocks.

Alemayehu (2006) discusses the occurrence of groundwater in Ethiopia and outlines the key factors influencing the flow and storage of groundwater in volcanic rocks. Furthermore, he concludes that variations in the mineralogy, texture, and structure of volcanic rocks lead to differences in the area's capacity to hold water. Kebede (2013) researched the occurrence of groundwater in Ethiopia. The study classified the sources of groundwater recharge in Ethiopia into four categories: flood, wadi flood, rainfall, mountain block, and runoff from graben. The results summarized the water isotope as the evidence.

According to Yitbarek et al. (2012) Describe the types and distribution of Ethiopian lithology. They classify rocks into the following categories: quaternary volcanic rocks, old Precambrian rocks, metamorphic rocks, and fractured intrusive rocks in the western part of Ethiopia; sedimentary and Mesozoic sandstone in the southern part; karstic rocks in the eastern and southeast; and unconsolidated sediments in the rift valley and low land depression area.

2.5. Applications of GIS and RS in Groundwater Potential Zone

Several studies have been conducted on the impact of remote sensing and GIS on the recharge zone and groundwater potential investigation. Among those, according to Arulbalaji et al. (2019) Geographic information systems and remote sensing are the most advanced technologies for many scientific applications, such as monitoring landslides, earthquakes, volcanoes, agricultural management, and the exploration of minerals and groundwater. They can also access large amounts of data at the same time that are otherwise impossible to reach, such as cliffs, mountains, and gorges.

Elbeih (2015) describes the use of GIS and remote sensing in groundwater delineation and compares it with different methods, including, numerical modeling, and geophysical techniques. He concluded that the aforementioned techniques are very costly, time-consuming, and destructive. Different from the methods mentioned above, Gintam (2015) states that groundwater cannot be directly observed by the naked eye because it is found underground. However, numerous methods can provide information about potential groundwater zones, such as hydrological investigation, geophysical and geoelectrical methods, or geophysical seismic refraction methods, all of which are expensive and time-consuming. The latest, fastest, and most cost-effective technologies for studying groundwater are GIS and remote sensing, which provide complete information and easy access to all the parameters of variables that affect groundwater potentials by using various software.

2.6. Analytical Hierarchy Process

The weight overlay and decision-making analysis methods used by different researchers vary. According to Lammesa (2017), using thematic layers of elevation, land use/cover, lineaments, and drainage provided accurate information about groundwater occurrence and allowed for the generation of weight overlay analysis results through analytical hierarchy process methods. The analytical hierarchy process is one of the most hopeful approaches for groundwater investigation. AHP is a useful method in an MCDA, assigning weight to various deciding or influencing factors (Ajayi et al. 2022). Currently, finding a suitable location for groundwater investigation might be difficult. Therefore, it's essential to comprehend how to approach areas with groundwater potential. To identify the groundwater potential zones using the GIS-based AHP technology in conjunction with remote sensing data (Gdoura et al. 2015).

2.6. Conceptual framework

Satellite data, existing geological and hydrological data, and meteorological data are utilized to identify groundwater potential zones. These datasets are preprocessed and prepared using ERDAS IMAGINE and ArcGIS software. The data is transformed into thematic layers, each representing factors like drainage density, land use/land cover (LULC), lineament density, slope, lithology, rainfall, geomorphology, and soil type. The conceptual framework for this methodology is illustrated in Figure 2.1, ensuring a systematic approach from data collection and preprocessing to the generation of a groundwater potential map. This framework aids in effective water resource management and planning by identifying and mapping areas with different groundwater potentials.

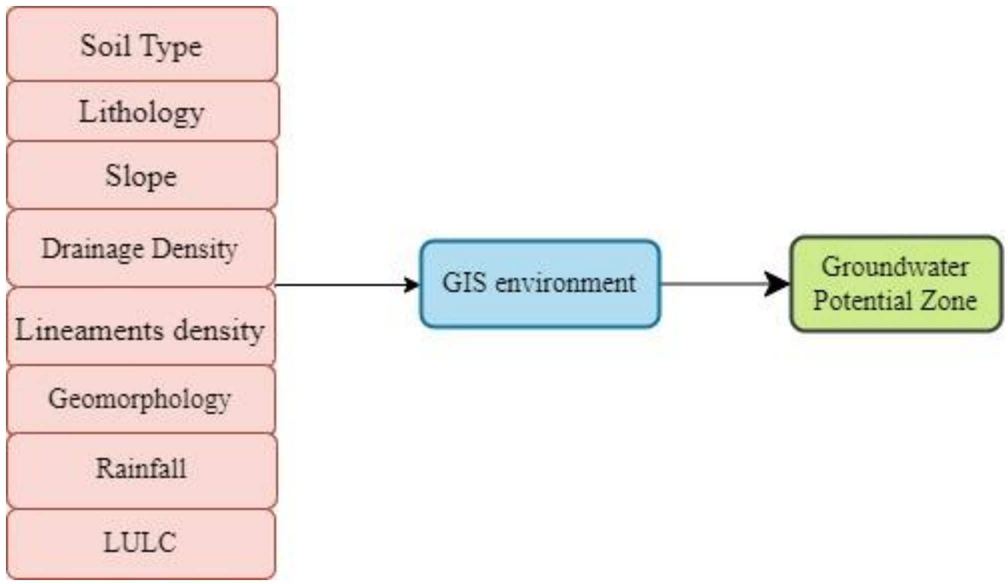


Figure 2. 1: Conceptual framework

CHAPTER THREE

3. DESCRIPTION OF THE STUDY AREA

3.1. Location and Accessibility

Sirkole watershed is located in the western region of Ethiopia, some 687 km from Addis Ababa in Benishangul Gumuz Regional State (BGRS), Assosa woreda. geographically is located between a Latitude 10°04′N- 10.067°N and Longitude of 34°31′E – 34, 517°E, 1,570m Elevation with the total coverage area 909.17 km^2. Ambo, -Nekemte, - Gimbi, - Nejo, - Mendi, - Bambasi, - and finally, the study area.

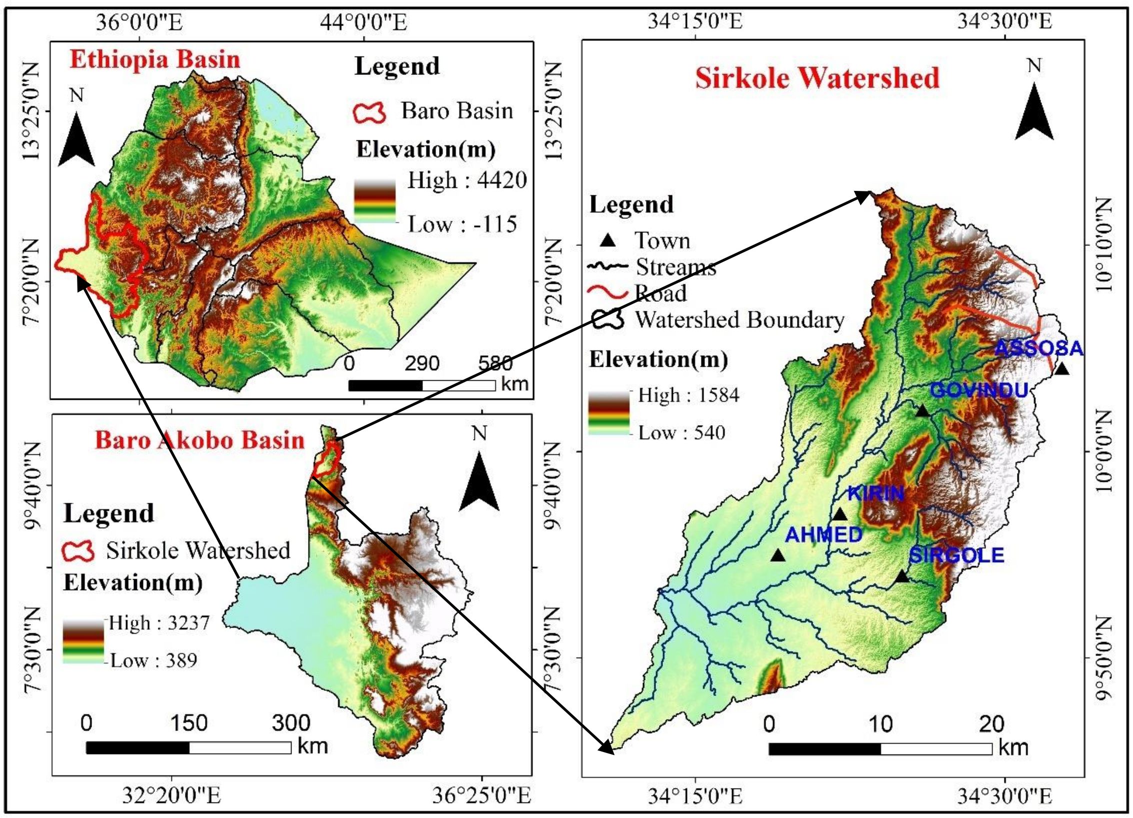


Figure 3. 1: Location Map of Study Area.

3.1.1. Climatic condition of the area

3.1.1.1. Seasonality of rainfall in the study area

Precipitation data stands out as a crucial meteorological variable frequently considered for analysis. By examining data from selected stations, insights into rainfall variability, average monthly and annual rainfall, and regional precipitation distribution can be collected. Analyzing monthly rainfall records from a specific station over an extended period enables researchers to identify patterns associated with rainfall distribution in the region. These patterns have been documented by the National Meteorological Sonde Agency (NMSA) at the Assosa station. High rainfall records are observed in the study area in August and September, whereas January, February, and March exhibit very low rainfall levels (refer to Figures 3.2 and Table 3.1 Appendix 1).

Table 3. 1: Mean monthly rainfall in the Study Area.

Station	**Jan**	**Feb**	**Mar**	**Apr**	**Ma**	**Jun**	**Jul**	**Aug**	**Sep**	**Oct**	**Nov**	**Dec**	**Annual total**	**Mean monthly**
Assosa	1.88	0.72	12.22	59.34	167.59	180.17	166.52	267.40	243.08	189.67	95.95	140.53	1525.08	127.09

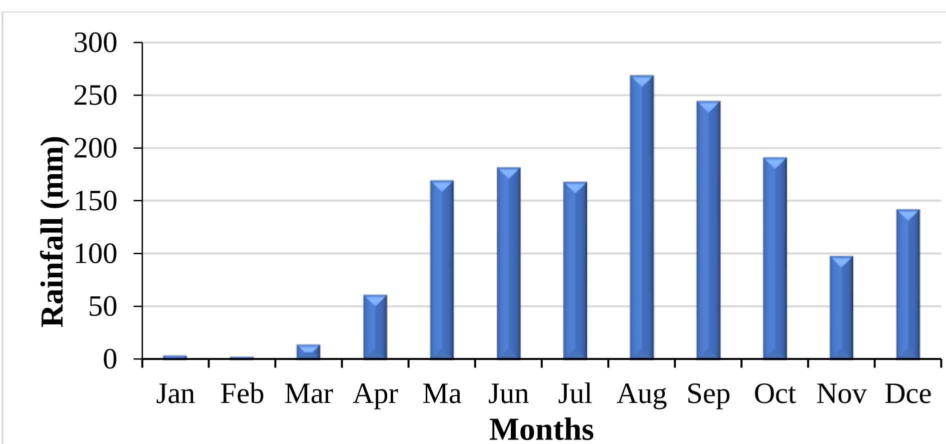


Figure 3. 2: Mean monthly rainfall in the Study Area.

3.1.1.2. Temperature

In the research Area, similar to other regions across Ethiopia, the sun's elevation remains consistently high, resulting in intense solar radiation. Daytime temperatures soar and drop significantly at night, leading to a substantial daytime temperature variation. The area's peak temperatures vary from 31.74 °C to 23.45°C, while the lowest temperatures range from 14.08 °C to 16.01°C (Figures 3.3 and Table 3.2). Temperature records from Assosa station spanning the years 2010 to 2022 have been compiled, with the average monthly temperatures (Figure 3.4). Analysis of this data indicates that the warmest months are January, February, March, April, and December. Conversely, the coolest temperatures are recorded in June, July, and August, with the remaining months experiencing moderate temperatures (Figure 3.3). The mean monthly temperature variations are further detailed in the subsequent section (Appendix 2).

Table 3. 2: Maximum, minimum, and average temperature of the study area.

	Jan	Feb	Mar	Apr	Ma	Jun	Jul	Aug	Sep	Oct	Nov	Dec
Max Temperature	29.32	31.74	31.17	29.84	26.79	24.58	23.39	23.45	24.42	25.48	27.44	28.80
Min Temperature	14.70	15.89	15.80	15.47	15.83	15.72	14.83	15.99	16.01	15.14	14.08	14.74
Mean Temperature	22.01	23.82	23.48	22.65	21.31	20.15	19.11	19.72	20.22	20.31	20.76	21.77

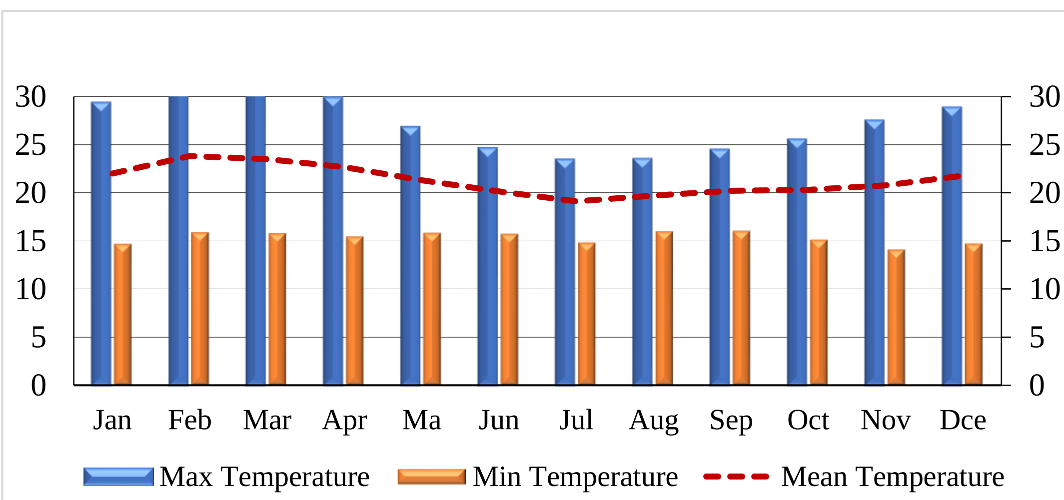


Figure 3. 3: Maximum, mean, and minimum monthly temperature of the study area.

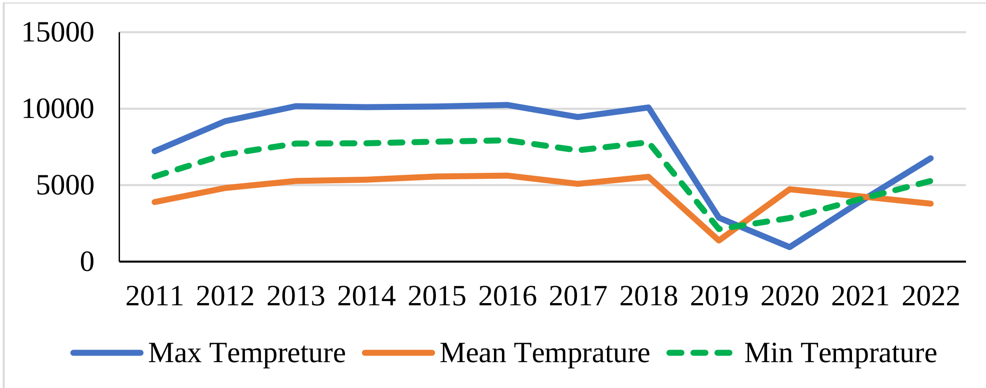


Figure 3. 4: Maximum, mean, and minimum Annual temperature of the study area.

3.1.2. Physiography of the study Area

The landscape's form and structure are largely shaped by continuous tectonic forces, accompanied by processes of intrusion and erosion. The region's network and configuration of watercourses are influenced to some extent by these tectonic movements and the geological diversity present. Many of the recently formed linear features act as conduits for rivers. The area's highest mountains are typically the summits of volcanic formations or the peaks of recent intrusive geological structures, highlighting the significant impact of volcanic activity on the landscape's development.

The western region is distinguished by several distinct physiographic features: a series of ridges and deep gorges shaped by volcanic activity found at the southwest edge of Gimbi and parts of southeastern Tosho, a plateau crafted by ancient lava flows and dotted with weathered granite outcrops, located in the south-central zone of Gimbi and neighboring areas of southeast Tosho, and a varied, rugged landscape formed by ancient Precambrian rocks, including basic and ultrabasic rocks, gneiss, and schists, particularly noticeable in the southeast within the Birbir River basin and areas west of the Abo Bikilal gabbroic mass. This terrain exhibits moderate elevation changes, shaped by river valleys and intermountain plains.

The variation in drainage density and the depth of valleys created by waterways is influenced by differences in rock types, the developmental stages of the rivers, and geological structures

(Figure 3.5). The Sirkole Catchment Zone is one of western Ethiopia's six distinct physiographic regions. The rest are the Dabus Catchment area, the Central Highlands region, the Abbay Dedisa Catchment Basin, the Birbir Catchment area, and the Daka Catchment Basin, which are integrated into the larger Baro Basin System.

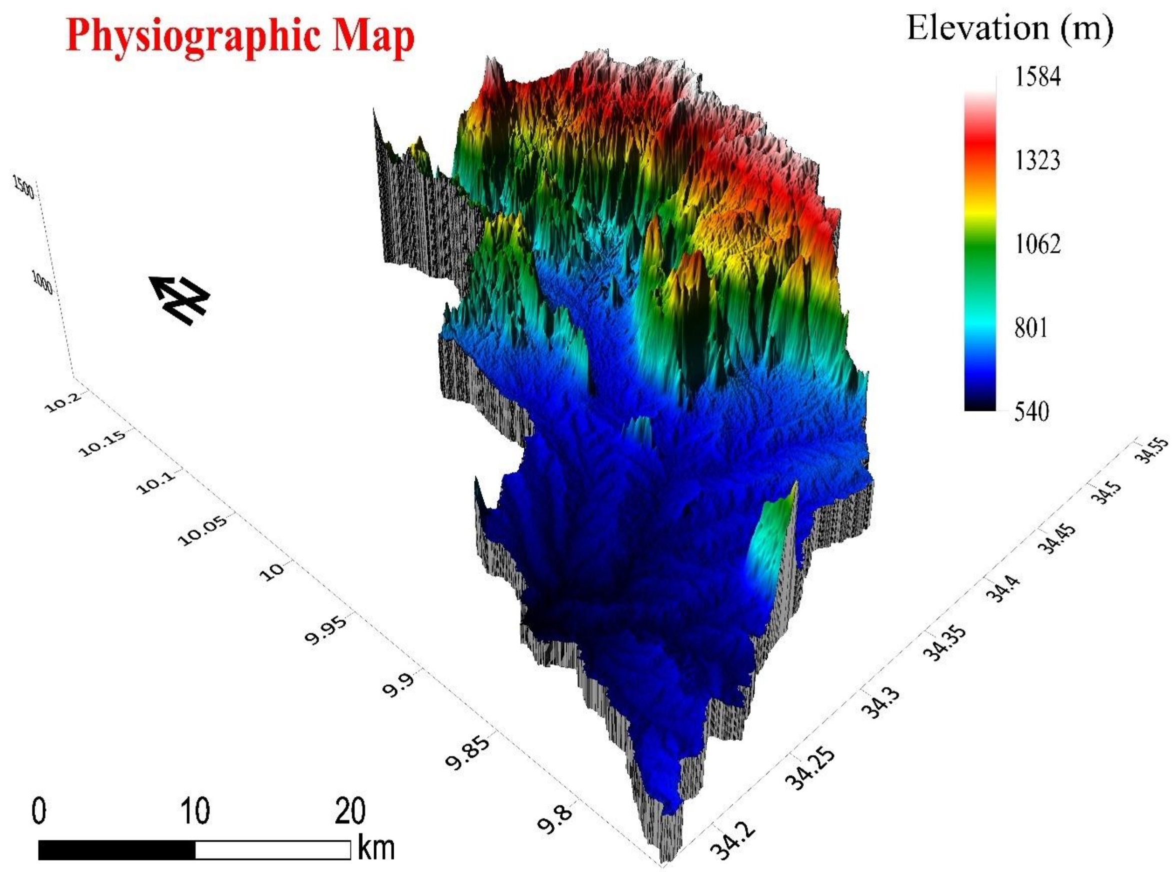


Figure 3. 5: Physiographic Map of the study area.

3.1.3. Drainage patterns of the study area

Drainage patterns of water bodies are influenced by several factors, such as the terrain's shape, the type of soil, the bedrock's structure, climatic conditions, and vegetation. In the region under study, the design of the drainage system is greatly affected by tectonic shifts and the variety in geology. As a result, the region shows a rectangular drainage pattern in areas where the bedrock is fractured; along the slopes of mountains, a sub-parallel pattern is observed, which often aligns with geological faults or the paths of erosion; and a tree-like, dendritic pattern is seen in areas where the bedrock is uniformly resistant to erosion and not influenced by other structural conditions (Figure 3.6).

In areas of higher elevation, the drainage density tends to be greater, particularly where there is a thick layer of weathered material. Typically, the highlands are characterized by valleys that can range from deep and narrow to shallow. Conversely, in the lowlands, the river channels are broader. These channels and the tectonically affected landscapes constitute the map's lowest or most level areas. But, even in these lowland areas, the depth of the channels can vary depending on the rock's compactness and its susceptibility to erosion.

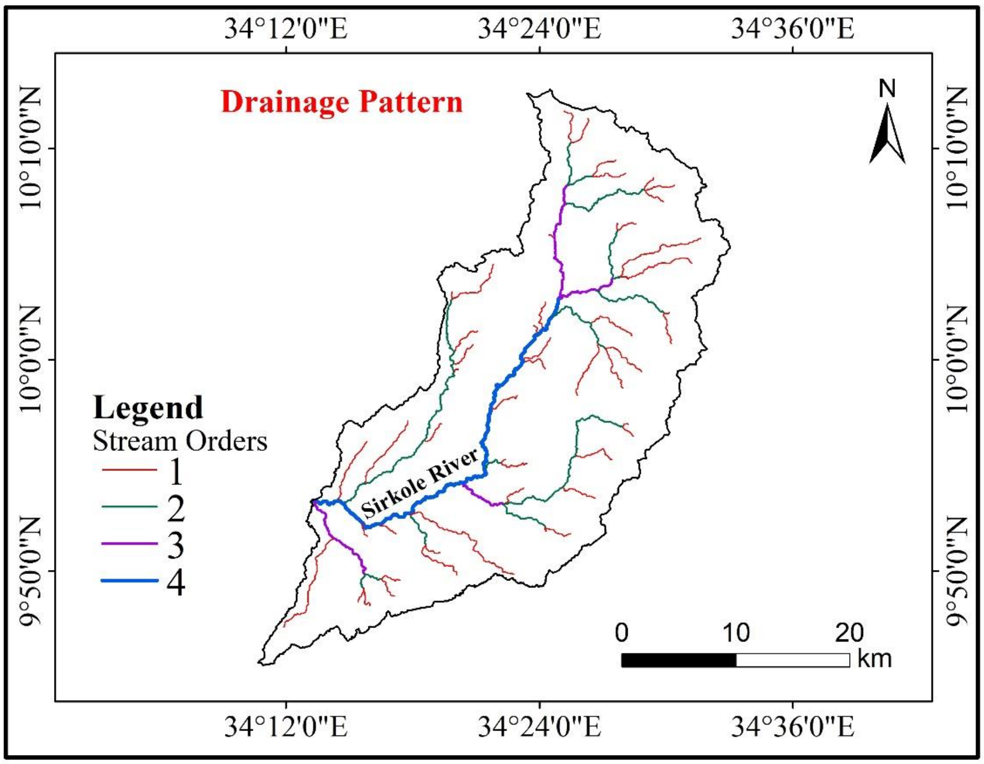


Figure 3. 6: Drainage pattern and stream order of study area

3.1.4. Geological of the Study Area

Numerous lithologic units, including Quaternary age groups of lacustrine and alluvial deposits, Tertiary age groups of volcanic rocks, and Precambrian rocks, are exposed within the study region (Figure 3.7).

3.1.4.1. Precambrian rocks

Precambrian rocks are broadly classified into two categories: stratified and intrusive. Stratified Precambrian rocks include a variety of units such as Biotite and hornblende-biotite gneiss, Meta-ultramafic rocks, Amphibolite, and quartzo-feldspathic schist, among others. These sedimentary and metamorphic layers reflect the Earth's ancient geological processes. On the other hand, Precambrian intrusive rocks are typically composed of deeper-origin units like Metagabbro and Meta-granite. According to (Assosa-Kurmuk Geologic Map by GSE, 2004) these rock type vary in their formation and geographical distribution, often found at higher elevations within certain catchments.

Meta-granite

Meta-granite, an intrusive Precambrian rock, predominantly exhibits a light to pinkish-grey type and is commonly exposed in stream cuts. Its composition includes medium to coarse-grained minerals, with quartz, feldspars, and micas being the most visible. This rock type is often associated with other granitoids, such as granites, and typically forms higher-altitude landforms. Characterized by multiple fracture systems, some fractures are filled with quartz veins and pegmatite. North of the study area, the granitic mass has an irregular shape with a north-south trending foliation. Within the Tertiary basalt terrain near Assosa, small granite outcrops are widespread but unmappable. This same meta-granite mass largely underlies the area beneath the basalt cover. Larger masses of meta-granite are found north of the study area, with some plutons likely emplaced during the final stages of regional deformation, indicated by local deformation evidence, making them late tectonic. Generally massive, the unit displays strong deformational fabrics in certain localities and is known in some areas to have a small number of fractures due to post-tectonic granite intrusion.

Metasediments

The geological composition and structure exhibit considerable variability across different locations. Predominantly, it consists of various schists such as graphite, chlorite, talc-chlorite, amphibole biotite-feldspar-quartz, amphibole-biotite, muscovite-feldspar-biotite-amphibole, chlorite-biotite, quartz muscovite, biotite, and quartz-muscovite-sericite of volcanic origin. The degree of deformation ranges from minimally altered massive forms to highly deformed schistose and foliated types. In some areas, intense weathering is evident. Three principal metasedimentary schist units have been identified within the area. The first is located in the north-western sector, stretching south from Geissan; the second is situated east of Geissan, extending south from Mudul village towards Menge town; and the third lies in the south-western quadrant, spanning from northwest of Assosa to Kashmangal village and further southwest to the boundary of the surveyed region. These units are interspersed with granitoid intrusions and overlain by Tertiary volcanic deposits.

3.1.4.2. Tertiary volcanic rocks

Alkali olivine basalt (Te)

In the Assosa region and its locality, the flow extends. The deception series, which rests unconformably upon Precambrian formations in the Assosa area, is subject to the lateralization process due to the warm climate's weathering effects. Basalt was reached at depths of 37 and 30 meters in Selga boreholes but was not fully penetrated. Typically, the basalt lies at a lower altitude than the basement rocks within this location. The thickness of tertiary volcanic rocks does not exceed 100 meters, and they exhibit intense weathering alongside a lateritic crust. Alkali olivine basalt remnants, which are basalt flow covers, are found in limited parts of the region with thicknesses under 100 meters. The basalts are deeply weathered in the western sectionand possess a lateritic crust (Assosa-Kurmuk Geologic Map by GSE, 2004).

3.1.4.3. Quaternary Sediments

Alluvial sediments

The alluvial deposits are predominantly located within the river valleys of major watercourses. Notably, such sedimentary formations are evident at the Hoha River and Selga locales, situated beneath scant layers of basaltic flows. These layers encompass a variety of gravel, sand, and silt, remnants of an ancient riverbed. This geological structure is expected to extend along the present-day Hoha River valley, with these recent alluvial deposits being restricted to fluvial valleys. Compositionally, this stratum is largely made up of sand and gravel, products of the physical breakdown of granitoids and gneisses. In certain areas, the riverine systems have mobilized and laid down basaltic material along their pathways. Numerous such deposits are identified as sources of placer gold and are also significant for groundwater reserves.

Eluvial Deposit

In the Assosa region, the predominant eluvial deposit is laterite, typically formed in situ atop parent rocks. This deposit is expected to develop in a tropical climate marked by alternating dry and wet seasons, accompanied by dense forests and substantial rainfall. The region is characterized by red clay soil resulting from basalt weathering, which is prevalent around areas such as the Assosa University and Selga well, as well as other research zones. The terrain here is mostly flat or gently sloping, where the soil transitions to a dark loamy clay that retains water, leading to marshy conditions.

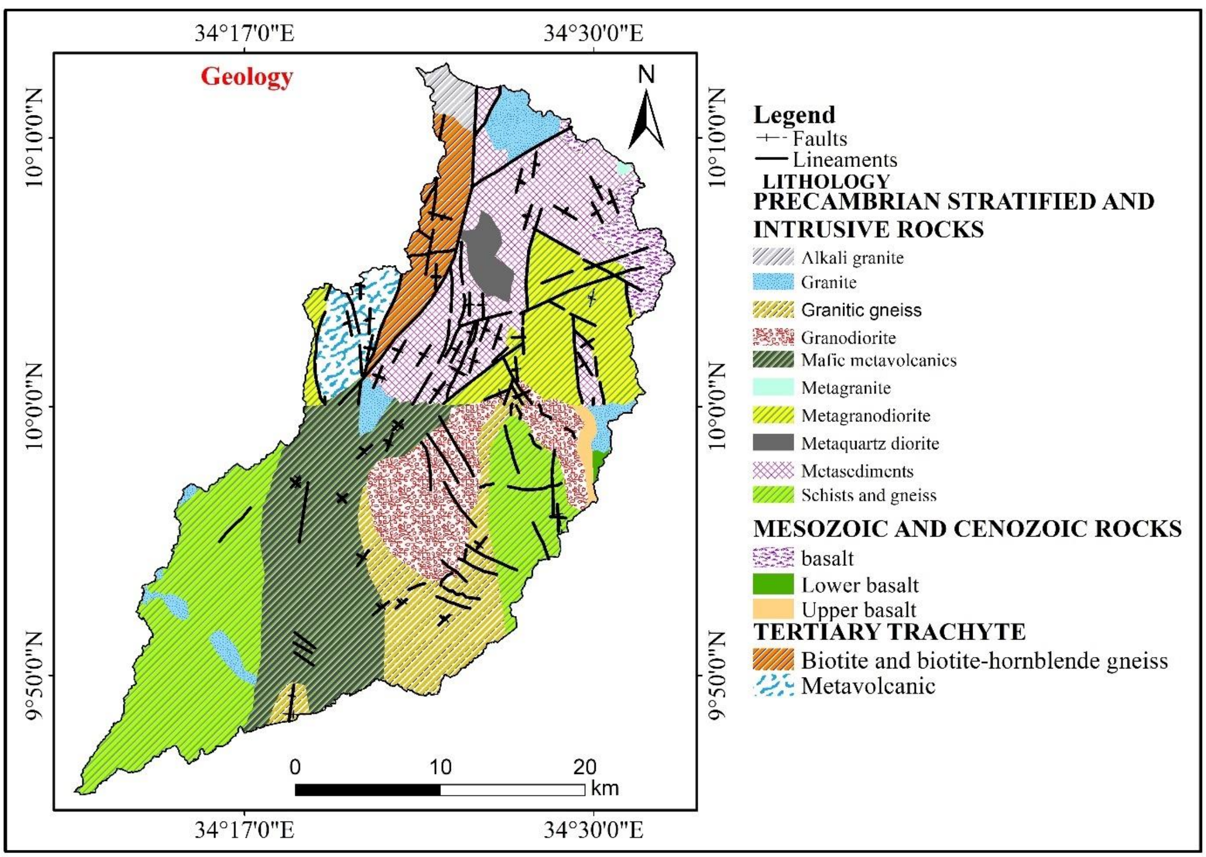


Figure 3. 7: Geology map of study Area (take from GSE).

3.1.5. Structural Geological Setting

The dominant planar features in the crystalline basement rocks of the map region are gneissosity, schistosity, and foliation. As in the basement rocks elsewhere in western and southwestern Ethiopia, they typically strike north-south. Nevertheless, the western part of the map is mostly affected by northeasterly strikes. The long axes of mineral lenticels and prismatic minerals like amphiboles, to a lesser extent, are examples of linear structures. Mineral aggregate lineation is the main representative of linear structures. Across the map area, they usually plunge gently to the north or south and trend parallel or subpar to the foliation strike. They are a northeast-to-north-northeast set and a northwest-northwest-to-northwest set. These two lineaments are typical in western and south-western Ethiopia. Most of them have been identified from aerial photographs. Several have been shown to have faults during ground traveling, with horizontal offsets of up to several kilometers. The western area of the map region is where northerly and north-westerly trending lineaments are most prominent. On some, sheared and mylonitized zones indicate movement (Bekele and Kebede, 2017).

According to Assosa-Kurmuk Geologic Map by GSE, (2004), Faults with both dextral and sinistral senses of displacement are present, with the dextral sense appearing to dominate. Both lateral and vertical movements are assumed to have occurred along the Kurmuk fault, which divides the uplifted Ethiopian plateau on the east from the Kurmuk plain on the west, it also serves as a significant border between the throw-grade terrain to the east and the high-grade terrain to the west. The primary tectonic and structural characteristics throughout the area trend N-S, N-W, N-E, and E-W.

3.1.6. Hydrogeology of the study area

Hydrogeology is the area of geology that deals with the distribution and movement of groundwater in the soil and rocks of the Earth's crust (commonly in aquifers). Three important geological patterns control the nature and distribution of hydro-geological units in geologic systems. These are lithology, stratigraphy, and structures of the geologic formation. Lithology is the physical makeup of the sediments (rock) that comprise the geologic system, such as mineral composition, grain size, and grain packing. Stratigraphy describes the geometrical and age relationships between various formations in a geologic system. Structural features, such as fractures and faults, are the geometrical properties of geologic systems produced by tectonics or during crystallization.

According to Assosa-Kurmuk Geologic Map by GSE, (2004) The geological formations of the study area are categorized into three distinct aquifer-aquitard systems based on their hydrogeological importance.

Moderately productive fissured Aquifers

Usually, the basalt cover in certain locations develops non-conformably on the crystalline foundation, forming flat-topped outcrops. However, the basalt is at a lower elevation than the underlying rocks in the center part of the area. the outcrop's thickness varies as well, with the thickest section measuring around 100 meters and some places having thicknesses as low as 15 meters. Additionally, the degree of weathering varies from location to location. It is somewhat weathered in some areas and strongly lateralized in others but in other large locations. This unit mostly covers parts of the ASU region, including the borehole and the Selga wells. There are many intercalated pebble strata in a Hoha River well. Hence, local variations exist in the hydrogeological quality of basalt across different locations. Because such particular soils have a lower clay content, permeability or percolation to depth will be higher if the soil cover is thick and oxidized. This will improve the ability of the underlying broken rock layers to store groundwater. Aquifers with a modest yield are often found in basalt, mostly with fracture permeability. This deposit contains a variety of aquifer properties, according to Assosa-Kurmuk Geologic Map by GSE, (2004): Q = 5 – 1 l/s, T = 100 – 10 m^2/d.

Low-productive fissured Aquifers

This type of aquifer is made up mostly of basement rock, which covers a large portion of the area. The aquifer's outcrops include Meta granite, which has a coarse grain size and is found associated with other granitoids such as granites. The rocks' hydraulic conductivity, capacity to store groundwater, and spring yield vary depending on their location. Local groundwater accumulation is expected in areas with penetrative faulting and related brecciated rock sections. The thickness of the weathered zone varies depending on the locality, whether there is a larger proportion of basic mineral components or more assimilation with other rocks like diorite. Lowyielding springs and local groundwater accumulation are expected in these locations. Compared to other catchment units, this unit covers most of the study's area. According to the Assosa-Kurmuk Geologic Map by GSE, (2004), the transmissivity (T) value of the region's low productive fissured aquifer typically ranges from 1 to 10 m^2/d.

Aquitards

There are some intrusive rocks in it. Aquitard outcrops in the watershed that grow in clusters and along fracture lines include phonolite and Trachyte plugs. Phonetic Fine-grained igneous rocks, or plugs, are light-colored volcanic rocks with phenocrysts in a modified groundmass and the presence of alkali feldspar and porphyritic nepheline phonolite. These plugs, which have a diameter of several meters, create noticeable topographic features. Up to 200 meters may be seen rising over the surrounding area on some plugs. Another fine-grained volcanic rock type with alkali feldspar crystals present is called trachyte. These volcanic plugs are locally linked with thin flows of phonolite and trachyte. The phonolite and trachyte plugs are considered aquitards due to their small extent, topographic location, and relatively poor permeability. According to Assosa-Kurmuk Geologic Map by GSE, (2004), the aquifer parameter ranges for this formation are T = 0.01 -1 m2 /d and Q = 0.05–0.5 l/s.

3.1.6.1. Weathering Depth

The study area's geology is mostly composed of basement rock covered with regolith, or weathered material, naturally created as the underlying bedrock weathers. The degree of weathering and fracture in the basement rocks determines its significance as an aquifer. Since fractures don't make up a significant portion of the rock, fractured rocks often have low porosity. Surface weathering and further weathering along the fracture zone can significantly increase hard rocks' water-holding and bearing capacity. Drills that penetrate a thicker layer of regolith may provide a higher yield than those that simply penetrate the fractured zone.

The research region has a year-round water supply thanks to hand-dug wells that only draw water from the higher, worn mantle. These wells ' depths are increased when drawdown causes a significant water deficit. A recorded increase in depth was from 5 to 18 meters. This demonstrates that excavated wells do not fully penetrate the weathered section of the basement rock. The following are the causes of incomplete penetration:

- Deep penetration is challenging since excavations are completed using human labor.
- An increase in water level. Digging becomes challenging over a certain level as the water column rises.
- The excavation season is the other aspect. Wells dug soon after the rainy season reach shallow groundwater at a comparatively shallower depth than wells dug during the dry season.

In the research area, where there is an extended period of rainfall and high air temperatures, the weathering zone provides a considerable groundwater source. Either manual well excavating or shallow well drilling might be economically beneficial ways to use this groundwater. Consequently, weathering depth is shown to be a critical factor in identifying groundwater potential zones.

CHAPTER FOUR

4. MATERIALS AND METHODS

4.1. Materials

The groundwater potential zone site for the Sirkole watershed is determined by this investigation using various technological tools. This study utilizes computer hardware and software for data preparation, organization, analysis, and output production. The materials, methods, and procedures used to identify groundwater potential zones using GIS and remote sensing techniques, data types used in these studies are also covered, along with a description of the study area including topography, slope, and geology, as well as the creation of various themed maps and reclassification by standard Techniques for using a Geographic Information System and Remote sensing. Furthermore, the material is listed in Table 4.1.

Table 4. 1: Software's used.

No	Software	Purpose
1	ArcGIS 10.8	Integration of both spatial and non-spatial data, creation of thematic maps, and preparation of map layout
2	ERDAS Imagine 2015	Digital image processing includes layer stacking, LULC classification, preprocessing, and image enhancement.
3	IDRISI Selva	Utilizing the relative significance value, determine the weights for each element and combine them.
4	Arc Swat	Used for watershed delineation
5	Surfer and Global Mapper 20.0	Creation of physiograph map.

4.2. Methods

4.2.1. Description of the procedures

The steps of this research work are as follows: i) selection of criteria; ii) Data Acquisition and preprocessing; iii) input dataset; iv) reclassification of input layers; v) Pairwise comparison of criteria and assigning weights with Analytical Hierarchy Process (AHP); vi) overlay analysis with Weight sum overlay analysis in ArcGIS tools, Ranking the final value. The general procedures are shown in (Figure 4.2).

4.2.1.1. Selection and Assessment of Criteria

In the current study, eight groundwater governing variables have been selected based on an expert's opinion and literature review. Thes variables include: drainage density, slope, geomorphology, rainfall, LULC, lineament density, lithology, and soil type.

a. Lithology

The groundwater recharge rate depends largely on the types of rocks exposed at the surface, as they determine how much water can infiltrate and flow through the subsurface (Rajaveni et al., 2017). Geology also influences the occurrence and distribution of groundwater potential zones, which are areas where groundwater is more abundant and accessible. The aquifer characteristics of each lithological unit are sedimentary rock, which is very high; igneous rock, which is moderate; and metamorphic rock, which is low aquifer characteristic (Lammesa, 2017). The lithology of the study area was digitized from the geological map in the ArcGIS environment.

b. Geomorphology

Geomorphology is the study of the shape and structure of the land, such as hills, plateaus, pediment/Pedi plains, and rift floors (Abrar et al., 2023). These features help to understand the hydrological formations of a region. The geomorphological value depends on the characteristics and spatial distribution of the features for groundwater potential and recharge processes, which are Hill Very Poor, Plateau Poor, Pediment/Pedi Plain Moderate, and Valley/flat Good (Nagaraju et al., 2016). The geomorphology of the study area was prepared from DEM data.

c. Lineament density

According to Mogaji et al., (2011),lineaments are curved or linear features on the earth's surface that represent underlying structural discontinuities such as bedding planes, joints, foliations, and faults. These characteristics are crucial for the hydrogeological investigation of a region because they show the permeability and weak points where water can seep through the subsurface. Lineament Density Classification for Groundwater potentials based on Low Lineament are Poor, Moderate Lineament Moderate, and High Lineament are Good or inverse to Drainage Density (Waikar and Nilawar, 2014). Lineaments were digitized from geological map in an ArcGIS environment. Then, line density in the spatial analysis tool was utilized to create lineament density of the study area.

d. Slope

The rate of water seeping into the ground and the slope of the land influences the suitability of groundwater potential. When the slope is high, more water runs off the surface, and less water infiltrates into the ground, resulting in poor groundwater prospects. On the other hand, when the slope is low, more water infiltrates into the ground and less water runs off the surface, resulting in good groundwater prospects as indicated in Role of Slope on Groundwater Potential Flat are Very High Infiltration, Gentle slopes are High Infiltration, High slope are Low Infiltration, Hill are Very Low Infiltration (Lammesa, 2017). DEM was used to create a slope map of the study area.

e. Drainage Density

Drainage Density is the total length of the stream per unit area. A drainage basin is a region where water runoff gathers at a common place or at a lower elevation. The drainage density and pattern expose the amount of water that flows off the surface, how porous the rock and soil are, and how much water may fill them. Several kinds of drainage networks exist, including coarse, parallel, dendritic, and rectangular drainage. Groundwater potentials are classified according to their drainage density: low density corresponds to good, moderate density to moderate, and high density to poor (Elbeih, 2015). Drainage density of the study area was prepared from DEM using ArcGIS software.

f. Land use/Land Cover

The pattern of land use and land cover influences how much surface runoff occurs because different types of vegetation and soil affect how much water is lost through evapotranspiration, infiltrated into the ground, or condensed on the surface. Therefore, the pattern of land use and land cover significantly impact the replenishment of groundwater resources. Land use/ Land cover Classification for Groundwater potential based on Rock exposure is very poor, Settlement is poor, Vegetation is Moderate, and Water body is Good (Ifediegwu, 2022).

g. Soil Type

The amount of water that may fill a soil depends on its nature and the degree of saturation or unsaturation of its pores. The porosity of the soil, which differs throughout soil types, determines how much water can travel through the soil. While fine-grained soils have limited porosity and poor groundwater potential, coarse-grained soils have both high porosity and high groundwater potential. Classification of soil texture: Sandy soils are good, loamy soils are moderate, and clayey soils are low for groundwater potential (Ghosh et al., 2020).

h. Rainfall

The quantity of water that seeps through the precipitation determines how much the groundwater system replenishes, which is the primary source. Precipitation and infiltration levels are directly correlated (Nampak et al., 2014). Rainfall, a vital element of the hydrologic cycle, determines groundwater potential. There are more chances for groundwater recharging in places with heavy rainfall than in areas with low rainfall. The annual rainfall data is obtained from the National Meteorological Sonde Agency (NMSA). The inverse distance weighted interpolation method was utilized to create a rainfall map of the study area.

4.2.1.2. Data Acquisition and Preprocessing

The following hydrogeological data were collected and analyzed to identify the zones of groundwater potential in the study area and to summarize their characteristics.

Table 4. 2: Data type and sources.

Data	Format/Scale	Source	Function
DEM	SRTM (30m) resolution	United States Geological Survey (USGS)	To generate a map of Geomorphology, Drainage Density, and slope
Landsat 8 ETM+	ETM+(30m)	USGS	To generate a map of Land Use /Cover
Rainfall	Excel Format	National metrological agency	To generate a map of the research area's rainfall
Geological map	1:250,000	Geological Survey of Ethiopia	Utilized to generate a lineament and geological map of the study's region.
Digital soil map	Shapefile	Ministry of Agriculture and FAO.	Utilized to generate a soil map of the study's area.
Water point inventory data	Excel Format	Ministry of Water and Energy, Water Resource Bureau, and Zonal water offices.	To verify the groundwater potential results.

4.2.1.3. Reclassification of Input Layers

Different criteria were applied to the selected thematic layers, and the correlation attribute was used to convert them into a raster data format. Every converted layer was resampled to the same 30 m cell size and reclassified by the site-specific criteria. To compare and evaluate the most and least suitable areas, reclassification simplified the understanding of raster data by grouping ranges of cell values into a single value based on the same ranking process.

Reclassification is crucial in spatial analysis, particularly when preparing data for a weighted overlay process. It involves converting scale values, no data values, and limited values into a common scale that aligns with the objectives of the study. This ensures that each influencing factor is properly categorized and utilized in the analysis. The rank of each influencing factor was categorized from 1 to 5 based on suitability for GWPZ, 1 is very low 5 is very high, respectively. Groundwater Potential Mapping employs a weighted overlay method to evaluate different geographic elements for their impact on groundwater recharge and flow. Each element is categorized and assigned a weight according to its significance.

4.2.1.4. Analytical Hierarch Process (AHP)

The methodology for delineating Groundwater Potential Zones through multi-criteria decision analysis involved assigning weights to various factors. These weights were determined based on the unique physical attributes of the study region and understandings from previous research. Following (Saaty, 1987). a systematic approach was adopted for weight allocation to each factor in this investigation.

Firstly, to construct the pairwise comparison matrix, values from 1 to 9 were allocated to each factor, reflecting their relative significance. 1 indicates equal importance on this scale, whereas 9 indicates extreme importance (Table 4. 3).

Then, a normalized pairwise comparison matrix was developed. This was completed by dividing each entry in the pairwise comparison matrix's column by the total of that column.

Finally, in the third step, the weight for each factor was calculated. This was done by dividing the sum of each row in the normalized pairwise comparison matrix by the total number of factors, which are eight (Geology, Geomorphology, Lineament Density, Slope, Rainfall, Soil texture, Land Use Land Cover, and Drainage Density) for this particular study.

AHP was used to normalize the assigned weights, based on Saaty's scale, by comparing two themes and classes at a time according to their relative importance for determining the groundwater potential zone. Then, pairwise comparison matrices of assigned weights to different thematic layers and their classes were built using AHP and normalized by the eigenvector approach (Eq 2). Consistency Ratio (CR) was computed to check the normalized weights of various thematic layers and their classes following (Saaty, 1987).

The following steps were carried out to compute the CR of various thematic layers and their classes. After calculating the weights for each factor influencing the Groundwater Potential Zone, a verification process was undertaken to employ the equations below to ascertain the accuracy and reliability of the comparisons. The Consistency Index (CI) was determined by Equation 4, as delineated.

$$A_{=}(a_{ij}) = \begin{bmatrix} a11 & a12 & \cdots & a1n \\ a21 & a22 & \cdots & a2n \\ \vdots & \vdots & \vdots & \vdots \\ an1 & an2 & \cdots & ann \end{bmatrix}, a_{ij} = \frac{aij}{\sum aij} \; for \; i, j \; 1,2 \ldots n \qquad \text{Eq. (1)}$$

Such that $[a_{ij}] > 0$

The square matrix's diagonal elements are always 1 because the same components have the same weight (Table 5. 9). Therefore, as a result, by comparing the components with one another, the upper and lower triangular matrices should be created.

The eigenvalue and eigenvector are calculated by:

$$w = \begin{bmatrix} w_1 \\ w2 \\ \vdots \\ w_n \end{bmatrix} \; and \; Wi = \frac{\sum_1^n a_i j}{n} \; for \; all \; n = \; 1,2 \ldots n \; and \; W' = \begin{bmatrix} w_{1'} \\ w_{2'} \\ \vdots \\ wn' \end{bmatrix} \qquad \text{Eq. (2)}$$

$$\lambda max = \frac{1}{n}\left(\frac{w'}{w1} + \frac{w'}{w2} + \cdots + \frac{w'}{wn}\right) \qquad \text{Eq. (3)}$$

W= eigenvector

Wi=eigenvalue of criterion I, and

λ_{max}=average eigenvalue of the pair-wise comparison matrix.

$$CI = \frac{\lambda max - n}{n-1} \qquad \text{Eq. (4)}$$

Where CI is the consistency index, n is the number of factors being compared in the matrix, and λ_{max} is the highest eigenvalue of the pairwise comparison matrix.

we determined the maximum eigenvalue (λ_{max}) of the comparison matrix as outlined in Table 5.10. This process entailed:

1. Multiplying the non-normalized matrix table values by their corresponding criteria weights.

2. Summing these values across each row to obtain a weighted sum.

3. Dividing each row's weighted sum by its criterion weight to find their ratios.

4. Calculating the average of these ratios to estimate the criteria weight.

To ensure the reliability of the comparisons made, the consistency ratio (CR) was determined using the equation (Eq. 5) as recommended by (Saaty, 1987).

$$CR = \frac{CI}{RI} \qquad \text{Eq. (5)}$$

Where CI is the consistency index and RI is the random consistency index which varies according to the number of factors used in the pairwise matrix

Saaty, (1987) suggests that a Consistency Ratio (CR) of 0.10 or lower is acceptable for proceeding with an analysis. Should the consistency value exceed 0.10, it indicates a need for reassessment of the judgments to identify and modify any inconsistencies. A CR value of 0 signifies an ideal consistency level in the pairwise comparisons. As long as the threshold value does not surpass 0.1, the judgment matrix is considered to be reasonably consistent.

Table 4. 3: Constant Rating Scale of Saaty's AHP (Saaty, (1987).

Intensity of Importance	**Definition**	**Explanation**
1	Equal importance	Two activities contribute equally to the objective
2	Weak or slight	
3	Moderate importance	Experience and judgment slightly favor one activity over another
4	Moderate plus	
5	Strong importance	
6	Strong plus	Experience and judgment strongly favor one activity over another
7	Very Strong importance	
8	Very, very Strong	
9	Extreme importance	An activity favored very strongly over another; its dominance demonstrated in practice

Table 4. 4: The RI Raio of the distinct value of N (Saaty, 1987).

N	**1**	**2**	**3**	**4**	**5**	**6**	**7**	**8**	**9**	**10**
RI	0.00	0.00	0.58	0.90	1.12	1.24	1.32	1.41	1.45	1.49

4.2.1.5. Weighted Overlay Method

The Groundwater Potential Index (GWPI) is a dimensionless parameter utilized for demarcating groundwater potential zones within a region (Kumar and Krishna, 2018). The weighted overlay analysis method was employed to identify these zones. This involved multiplying the weights of thematic layers by the weights of features within each thematic layer, summing the products of all attributes, and obtaining the GWPI, as described by Muralitharan and Palanivel, (2015), using the following formula 2

$$GWPI = \sum_{w=1}^{m} \sum_{j=1}^{n} Wj \times Xi \quad (6)$$

Where, Wj is the normalized weight of the jth thematic layer, and Xi is the rank associated with classes of ith thematic layer, m is the number of total thematic layers used, and n is the total classes of thematic layers.

4.2.2.6. **Validation**

To verify the validity of the qualitative results, such as those obtained from the GIS and RS techniques to Groundwater point, the identified groundwater potential zones were compared with the ground data that was already available from boreholes, springs, and hand-dug wells in the study watershed. This would increase confidence in the use of qualitative results such as those obtained from GIS and RS analysis. To verify the accuracy of the analysis, the results were validated through Receiver Operating Curves (ROC) and Area Under the Curve (AUC) analysis. AUC measures group independence, while ROC measures a probability curve. Figure 4.1 illustrates the procedural flowchart utilized in this investigation to validate the groundwater potential zone. The relationship between prediction assessment and AUC can be summed up as shown in Figure 4.1 and Table 4.5.

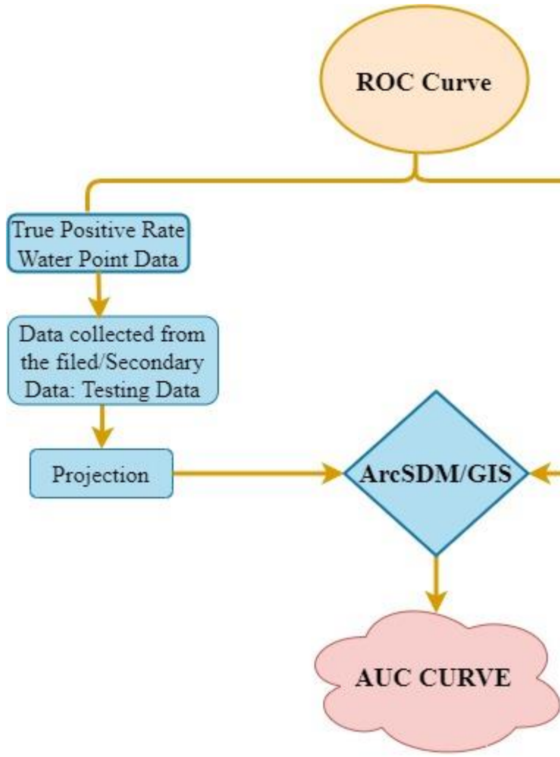


Figure 4. 1: ROC Curve procedure.

Table 4. 5: AUC value with the range indicates prediction accuracy.

AUC Value	Test Quality
0.5-0.6	Unsatisfactory (Weak)
0.6-0.7	Satisfactory (medium)
0.7-0.8	Good
0.8-0.9	Very Good
0.9-1.0	Excellent

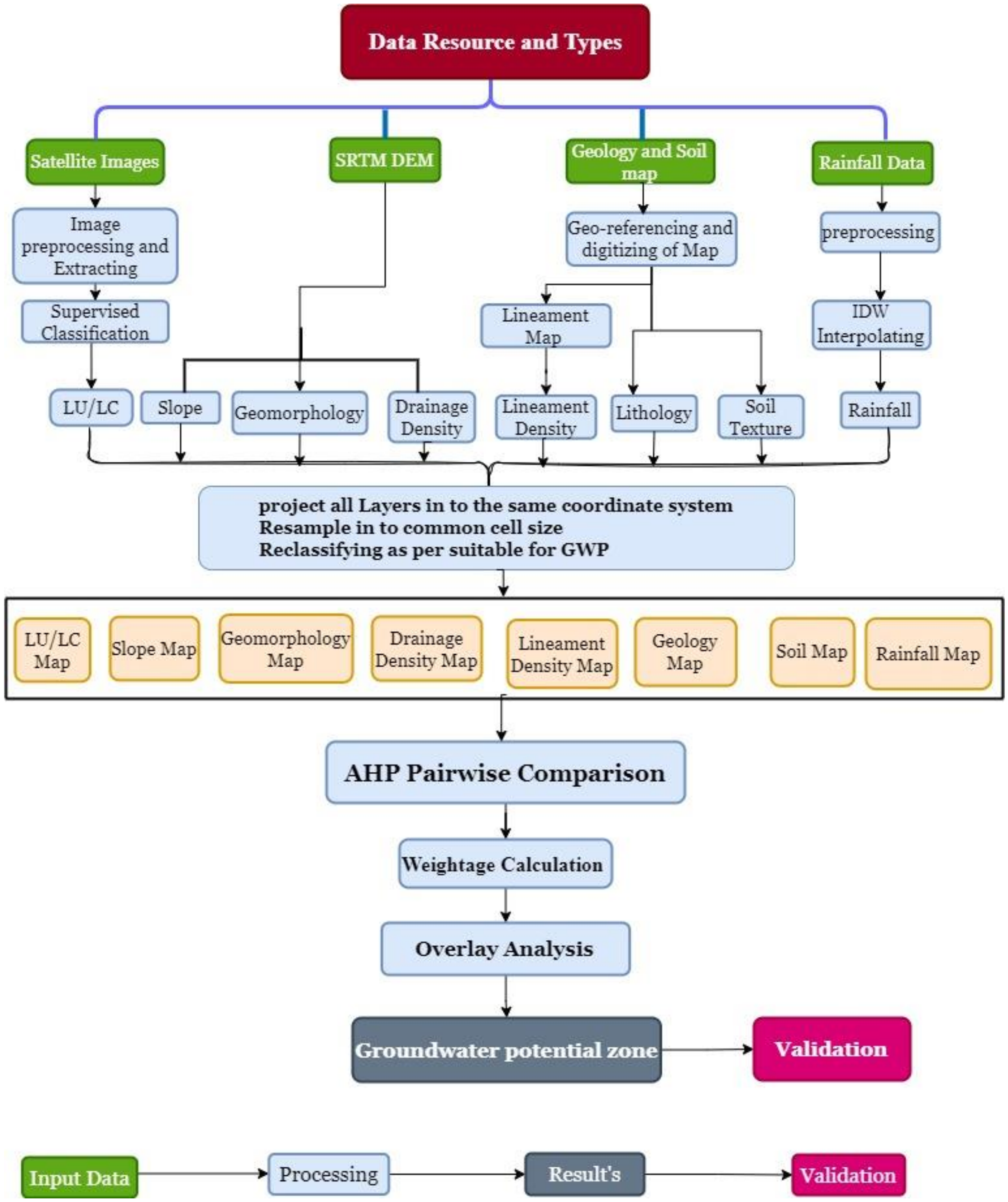


Figure 4. 2: Flow chart Methodology.

CHAPTER FIVE

5. RESULTS AND DISCUSSION

5.1. Analysis of Groundwater Indicator Parameters

5.1.1. Lithology

Lithology is essential in identifying potential groundwater zones due to its direct impact on the porosity and permeability of aquifer rocks (Rahmati et al., 2015). However, some researchers neglect this factor when evaluating lineament and drainage characteristics as indicators of primary and secondary porosity (Muralitharan and Palanivel, 2015). The presence and distribution of groundwater are significantly influenced by lithology, as groundwater availability in a region depends on the porosity, size, and connectivity of pore spaces, which affect the storage and permeability of the geological medium (Anteneh et al., 2022).

The lithology map of the study area was digitized from a geological map in ArcGIS environment (Figure 3.7), and lithologies were classified into five categories based on their potential for groundwater occurrence, as shown in Figure 5.1. This classification helps categorize areas based on their lithology and hydro-characteristics. In the study area, basalt, Granite, and Granodiorite is ranked very high (5) to high (4) for groundwater potential, because those are weathered and fractured rock covering 159.49 km² (17%) of the area. Conversely, schists and gneiss are ranked lowest (1) due to their unsuitability for groundwater occurrence, implying that about 320.49 km² (35%) of the study area has very low groundwater occurrence (Table 5.1).

Table 5. 1: Lithology and its rank as suitable for Groundwater potential.

Factor	Class	Suitability	Rank	Area (km^2)	Area (%)
Lithology	basalt,	Very High	5	31.00	3%
	Granite, Granodiorite	High	4	128.49	14%
	Mafic metavolcanic, Metasediments	Medium	3	298.16	33%
	Meta-granodiorite, Meta-granite, Metavolcanic, Meta-quartz diorite	Low	2	131.10	14%
	Schists and gneiss, gneiss	Very Low	1	320.49	35%

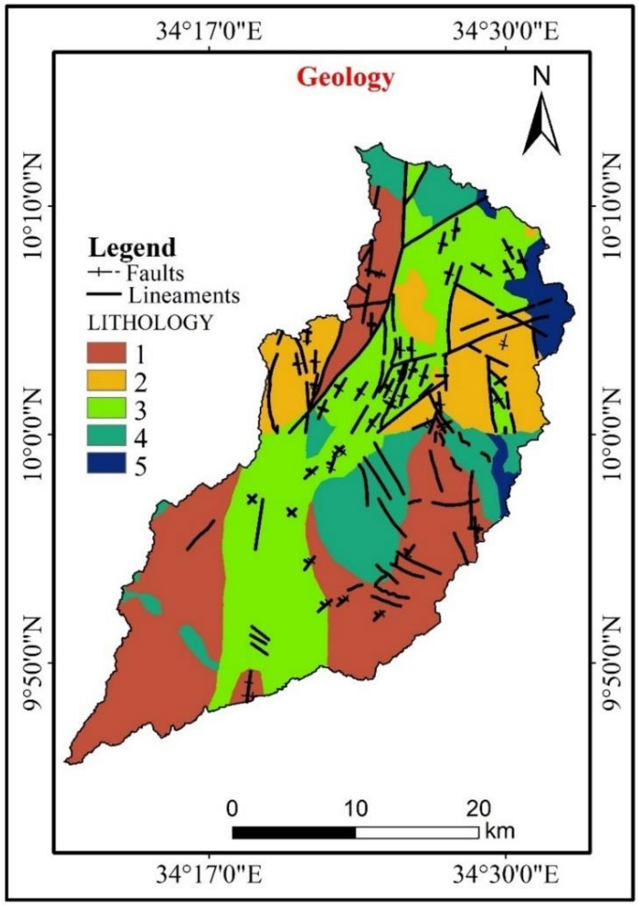


Figure 5. 1: Reclassified lithology map

5.1.2. Slope

Slope is a crucial factor influencing groundwater occurrence and recharge in a specific area (Diriba et al., 2024). The steepness of the slope directly affects rainfall infiltration and serves as an indicator of groundwater potential. Steeper slopes generally experience reduced recharge due to increased surface runoff, which limits the time for surface infiltration and groundwater recharge (Ghosh et al., 2023; Magesh et al., 2012). Such slopes lead to rapid runoff and higher erosion rates, resulting in minimal recharge potential. The slope impacts the velocity, direction, and infiltration of water on the surface and into the soil, thereby affecting groundwater replenishment in a catchment area (Kumar et al., 2020; Diriba et al., 2024).

A slope map of the study region was created using DEM data in ArcGIS 10.8. The slopes in the area range from 0 to 58 degrees and are divided into five categories: 0-5, 5.1-11, 12-19, 20-28, and 29-58 degrees (Figure 5.2A). These classes covered 525.49 km^2 (58%), 162.3 km^2 (18%), 105.04 km^2 (12%), 75.18 km^2 (8%), and 35.6 km^2 (4%) of the study area, respectively (Table 5.2). These slope categories were then reclassified and ranked based on their potential for groundwater recharge (Figure 5.2B, Table 5.2). Very gentle slopes (0-5 degrees) received the highest rank due to their ability to retain water and enhance infiltration. Conversely, very steep slopes (29-58 degrees) were assigned the lowest rank because they result in high runoff and low infiltration, reducing groundwater recharge (Nigussie et al., 2019).

Table 5. 2: Slope classes and their rank as suitable for Groundwater potential.

Factor	Class	Suitability	Rank	Area (km^2)	Area (%)
Slope (degree)	0-5	Very Low	5	525.49	58%
	5.1-11	Low	4	162.30	18%
	12-19	Moderate	3	105.04	12%
	20-28	High	2	75.18	8%
	29-58	Very High	1	35.60	4%

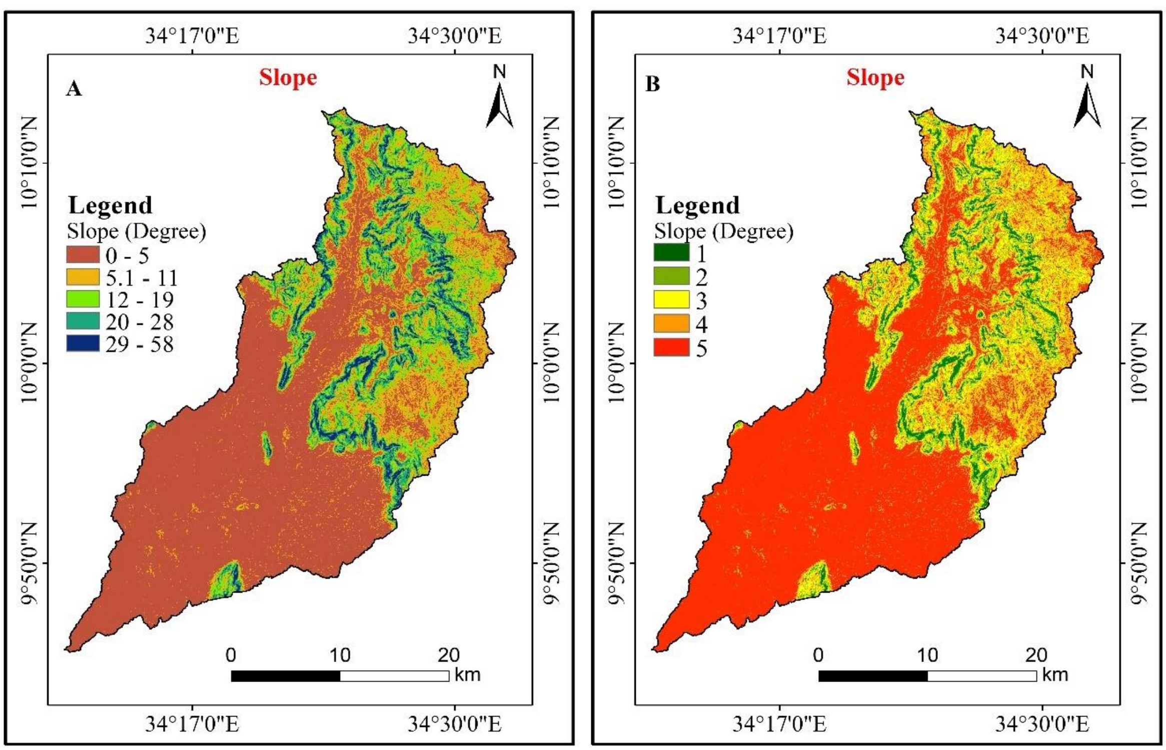


Figure 5. 2: Slope map (A), reclassified slope Map (B)

5.1.3. Geomorphology

The geomorphology map identifies landforms associated with groundwater occurrence and potential. Landform units were delineated using DEM data (Gintamo, 2015). Research integrating geomorphology, hydrogeology, and structural features/lineaments has effectively identified Groundwater potential zones (Berhanu and Hatiye, 2020). The geomorphology of an area, reflecting various landforms and structural characteristics, plays a crucial role in evaluating groundwater potential by influencing the subsurface movement of groundwater (Kumar and Krishna, 2018; Tamesgen et al., 2023).

This study identified six geomorphological units, like Valleys, Open Slopes, Plains, Upper Slopes, Mid-slope Ridges, and High Ridges (Figure 5.3A), using DEM data (30 m). These units were reclassified based on their suitability for groundwater occurrence. Valleys were given the highest rank of 5, while High Ridges and Mid-slope Ridges were assigned the lowest rank of 1 (Table 5.3, Figure 5.3B). Plains and valleys have a high potential for groundwater occurrence and recharge due to low runoff and large area coverage. Conversely, landforms with hill slopes exhibit high runoff and low potential for groundwater occurrence and recharge (Berhanu and Hatiye, 2020). The study area predominantly comprises valley geomorphologic units, covering 212 km^2 (23%), while upper slopes occupy only a small area of 464 km^2 (5%), as shown in Table 5.3.

Table 5. 3; Geomorphology and its rank as suitable for Groundwater potential.

Factor	**Class**	**Suitability**	**Rank**	**Area (km^2)**	**Area (%)**
Geomorphology	High Ridges & Mid-slope Ridges	Very Poor	1	163	18%
	Upper Slopes	Poor	2	464	5%
	Open Slopes	Moderate	3	114	13%
	Plains	High	4	374	41%
	Valleys	Very High	5	212	23%

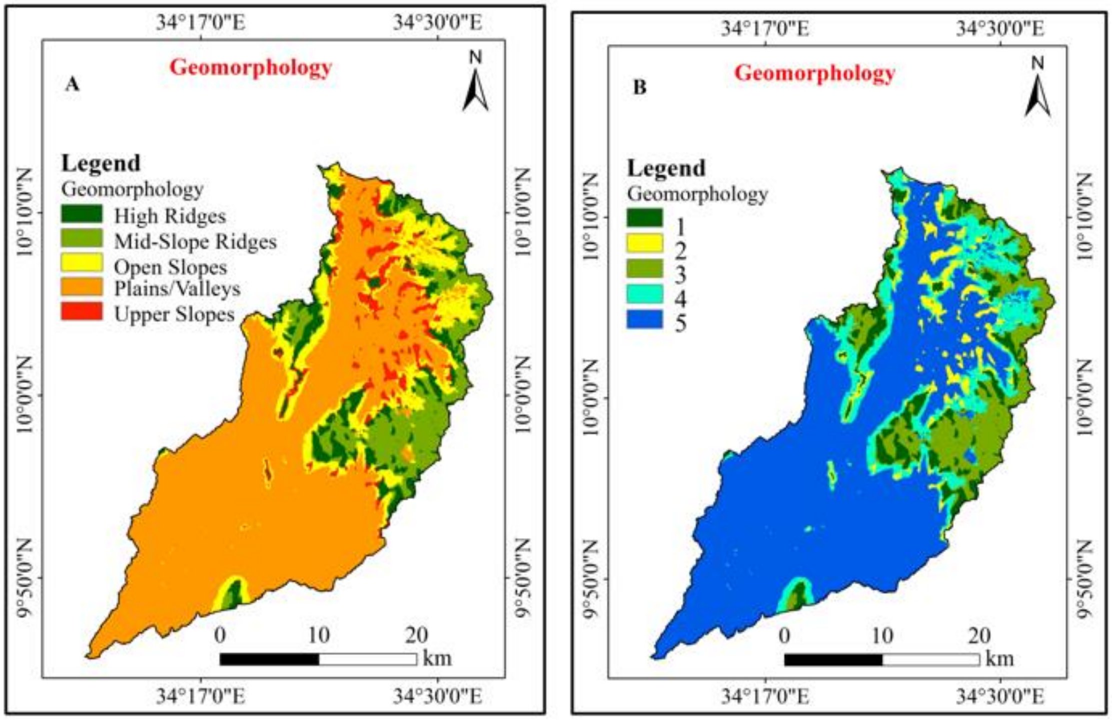


Figure 5. 3: Geomorphology map (A), Reclassified geomorphology map(B)

5.1.4. Drainage Density

Drainage density (DD) measures the length of streams per unit area within a watershed (Anteneh et al., 2022; Nigussie et al., 2019). Factors such as rocks' geological nature and structure soil characteristics, and slope gradient influence DD (Nampak et al., 2014). It indicates Permeability, with DD being inversely proportional to permeability (Agarwal and Garg, 2016; Chowdhury et al., 2008; Kaliraj et al., 2014). making it a crucial parameter for identifying groundwater potential zones.

The DD of the study area was prepared using DEM data in an ArcGIS environment. In the study area, DD ranged from 0 to 3.8 km/km² and was classified into five categories: 0-0.25 km/km² (Very high), 0.26-0.78 km/km² (High), 0.79-1.4 km/km² (Moderate), 1.5-2.2 km/km² (Low), and 2.3-3.8 km/km² (Very low) (Figure 5.4A). Higher DD levels increase surface runoff, reducing groundwater recharge, while lower DD values are more favorable for groundwater potential (Figure 5.4B, Table 5.4). Areas with high DD experience more surface water flow and less infiltration into the soil, resulting in reduced groundwater recharge (Diriba et al., 2024). The lowest DD category (0-0.25 km/km²) covers a large portion of the study area, spanning 378.72 km² (42%), while the very high DD category (2.3-3.8 km/km²) covers 47.78 km² (5%) (Table 5.4).

Table 5. 4: Drainage Density and its rank as suitable for Groundwater potential.

Factor	Class	Suitability	Rank	Area (km^2)	Area (%)
Drainage Density (km/km^2)	2.3-3.8	Very High	1	47.78	5%
	1.5-2.2	High	2	89.39	10%
	0.79-1.4	Medium	3	180.31	20%
	0.26-0.78	Low	4	212.95	23%
	0-0.25	Very Low	5	378.72	42%

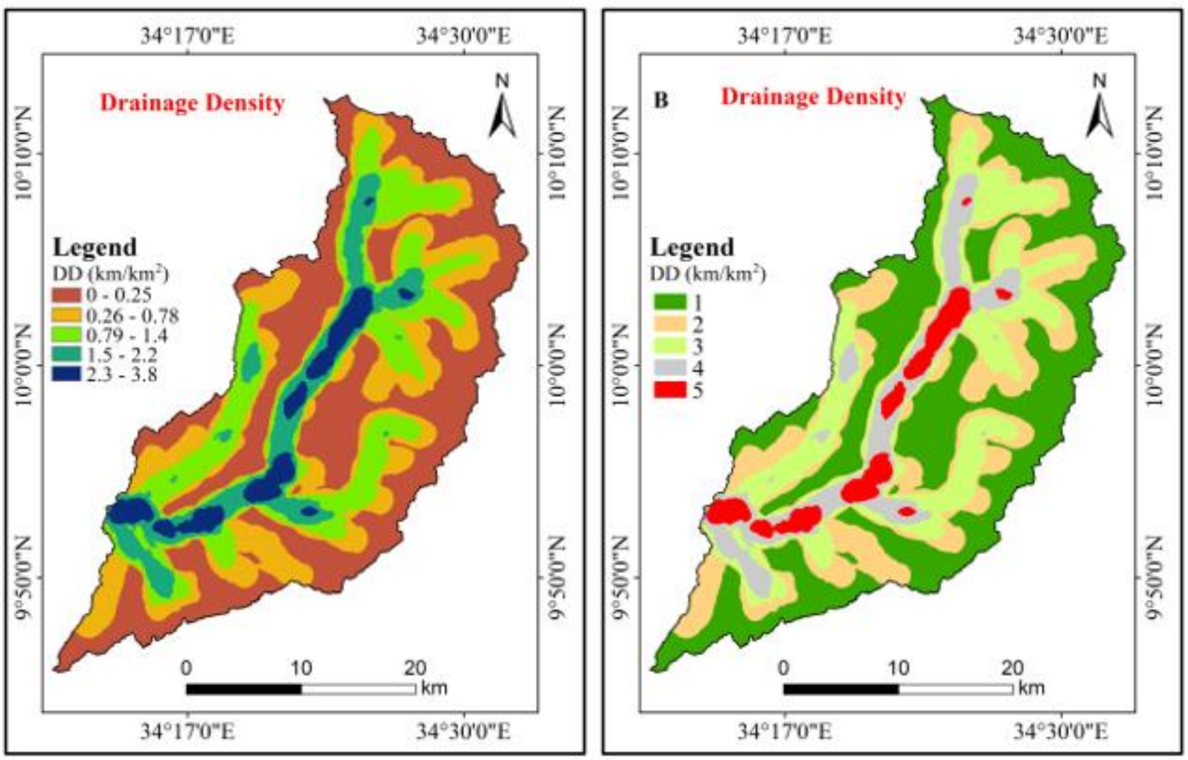


Figure 5. 4: Drainage density map(A), Reclassified drainage density map (B)

5.1.5. Lineaments density

A lineament can be a fault, fracture, master joint, long linear geological formation, straight-running valleys or streams, topographic linearity, borders between different lithological units, vegetation patterns, or man-made structures like roads or bridges (Adiri et al., 2017). Lineament density within a watershed is calculated by summing the lengths of all lineaments and dividing by the catchment area. Lineaments are significant structural features related to groundwater, appearing as straight or curved linear alignments of structural, lithological, topographical, and drainage irregularities. These features facilitate the infiltration of surface runoff into the subsurface and are critical for groundwater flow and storage. In hard rock terrains, groundwater occurrence and movement are primarily influenced by secondary porosity, particularly the presence of lineaments and fractures (Genetie et al., 2019; Kumar and Krishna, 2018).

The lineament map of the study area was digitized from the geological map of the region (Figure 5.5). The lineament density in the study area ranges from 0 to 2 km/km² and is classified into five classes (Figure 5.6): 0-0.4 km/km² covering 45% of the study area, 0.5-0.8 km/km² covering 27%, 0.9-1.2 km/km² covering 16%, 1.3-1.6 km/km² covering 9%, and 1.7-2 km/km² covering 4% of the study area (Table 5.5A, Table 5.5). Figure 5.6B and Table 5.5 illustrate the reclassified lineament density classes.

Table 5. 5: Lineament Density and its rank as suitable for Groundwater potential.

Factor	Class	Suitability	Rank	Area (km^2)	Area (%)
Lineament (km/km^2)	0. -0.4	Very Low	1	407.48	45%
	0.5-0.8	Low	2	244.28	27%
	0.9-1.2	Moderate	3	144.31	16%
	1.3-1.6	High	4	80.12	9%
	1.7-2	Very High	5	32.98	4%

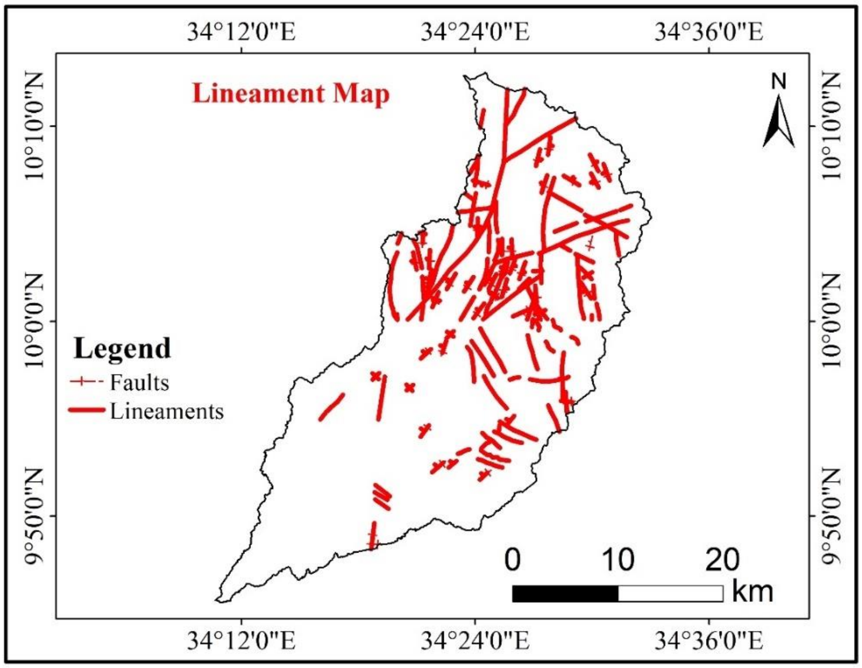


Figure 5. 5: Lineament Map of the Study Area.

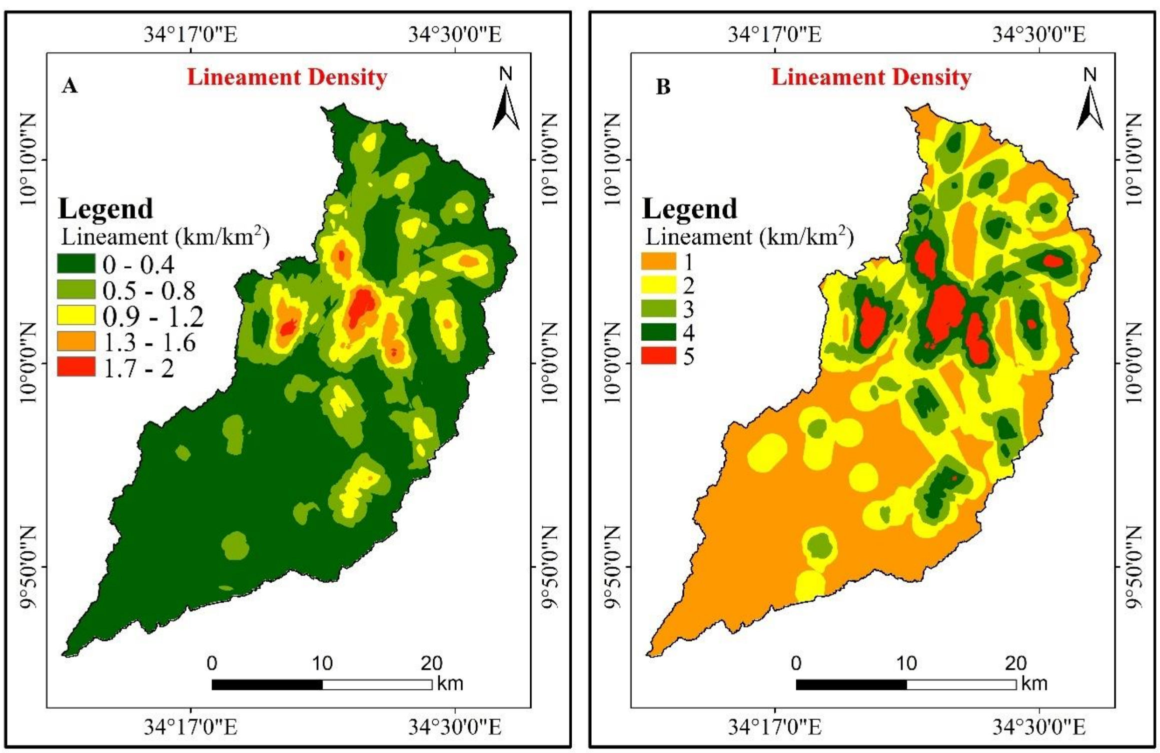


Figure 5. 6: Lineament density map(A), Reclassified density map (B).

5.1.6. LULC

LULC are critical factors in groundwater availability because they influence various hydrologic components, such as evapotranspiration, surface runoff, infiltration, and interception. While roads, parking lots, built-up areas, and bare grounds limit infiltration and increase runoff, forests, and vegetated lands reduce runoff and enhance infiltration (Anteneh et al., 2022b). LULC plays a crucial role in groundwater recharge, as highlighted by Ghosh and Sahu, (2023). Understanding current and future LULC patterns is essential for effective resource management, as Singh et al. emphasized(2010). Shaban et al., (2006) demonstrated various ways vegetation cover aids groundwater recharge, including root decomposition facilitating water percolation and vegetation trapping and retaining water. Conversely, built-up and rocky areas hinder groundwater recharge by increasing surface runoff, particularly during rainfall.

Six different types of LULC were identified in the study area, including Settlements, Barren lands, Farmland, Grassland, Agroforest, and Water Bodies (Figure 5.7A). These categories were reclassified based on their suitability for groundwater availability. For instance, Water Bodies exhibited a high potential for groundwater recharge and were assigned a high rank of 5 compared to other LULC types (Table 5.6). Conversely, Settlements showed a low potential for groundwater recharge and occurrence, receiving the lowest rank of 1 (Figure 5.7B). Agroforests covered a significant portion of the area, accounting for 38% of the total coverage, while Settlements occupied a smaller area, only 1% (Table 5.6).

Table 5. 6: LULC and its rank as suitable for Groundwater potential.

Factor	Class	Suitability	Rank	Area (km^2)	Area (%)
	Settlements	Very Low	1	9.57	1%
LULC	Barren lands	Low	2	200.01	22%
	Farmland	Moderate	3	57.67	6%
	Grass Land	Moderate	3	262.24	29%
	Agroforest	High	4	341.60	38%
	Water Body	Very High	5	32.69	4%

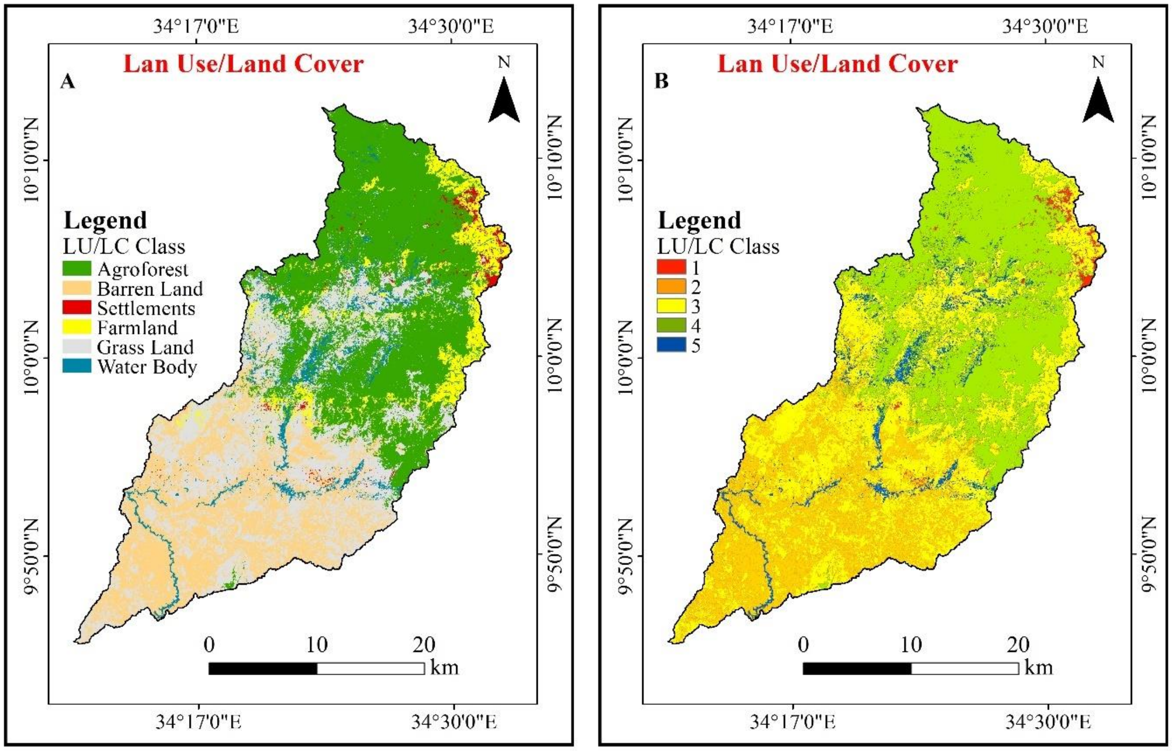


Figure 5. 7: LULC map (A), Reclassified LULC map (B)

5.1.7. Soil type

Soil composition plays a crucial role in identifying groundwater potential zones, affecting both percolation rates and groundwater recharge, as indicated by Anuraga et al., (2006), Berhanu et al., (2013), Wakwoya et al. (2023). In the research area, there are seven types of soil, including Dystic Nitosols, Gypsic Yermsols, Leptosols, Orthic Solonchaks, Chromic Vertisols, Orthic Acrisols, and Dystric Cambisols (Figure 5.8A). These soil types were evaluated and assigned weights based on differences in soil texture affecting infiltration rates. They were then reclassified into five classes suitable for groundwater potential occurrence (Figure 5.8B). The highest rank, 5, was given to Gypsic Yermsols and Orthic Acrisols, covering 160.48 km² (18%) of the study area. The lowest rank, 1, was assigned to Chromic Vertisols and Orthic Solonchaks, as they are not suitable for groundwater occurrence (Table 4.7, Figure 5.8B). The areas classified as very low suitable for groundwater occurrence covered 425 km² (47%) of the watershed.

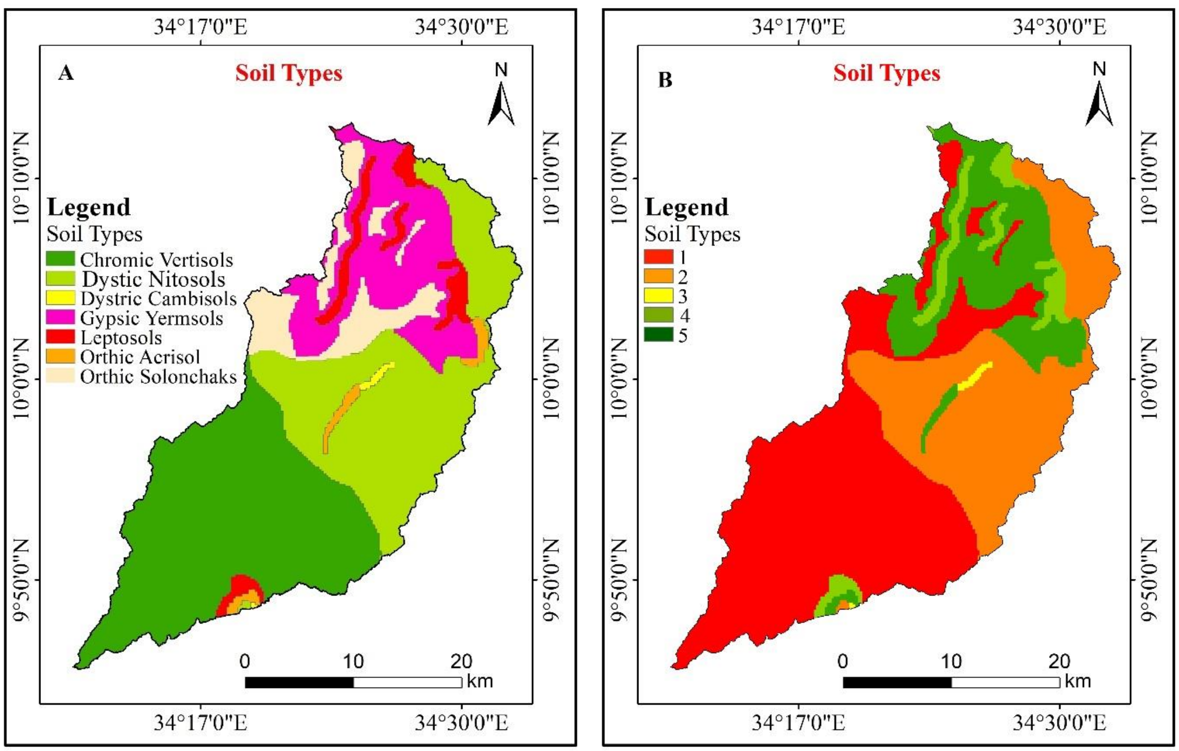


Figure 5. 8: Soil map (A), Reclassified soil type (B)

Table 5. 7: Soil type and its rank as suitable for Groundwater potential.

Factor	Class	Texture	Suitability	Rank	Area (km^2)	Area (%)
Soil type	Gypsic Yermsols, Orthic Acrisol	Sandy-Loam Sandy	Very High	5	160.48	18%
	Leptosols	Sandy-Loam	High	4	42.25	5%
	Dystric Cambisols	Loam-Sandy Loam	Moderate	3	2.68	0%
	Dystic Nitosols	Sandy-Loam-Clay	Low	2	278.64	31%
	Chromic Vertisols, Orthic Solonchaks	Clay	Very Low	1	425.00	47%

5.1.8. Rainfall

Rainfall plays a pivotal role in the hydrological cycle and profoundly influences groundwater potential and recharge. It serves as the primary source of groundwater storage and regulates its fluctuations. Precipitation is instrumental in replenishing groundwater reserves, dictating the volume of water accessible for infiltration into the groundwater system. Greater rainfall in an area signifies a higher potential for recharge, as emphasized by Machiwal et al., (2011). The availability of rainfall is acknowledged as a primary source of recharge, as discussed by Magesh et al., (2012), Shekhar and Pandey, (2015).

A rainfall map of the study area was generated using the Inverse Distance Weighted (IDW) interpolation method in ArcGIS. This map was divided into five categories based on precipitation levels: 1110-1140 mm (Very low), 1141-1169 mm (Low), 1170-1197 mm (Moderate), 1198-1227 mm (High), and 1228-1295 mm (Very high) (Figure 5.9A). These categories covered 130 km^2 (14%), 161.21 km^2 (18%), 210.3 km^2 (23%), 210.94 km^2 (23%), and 196.56 km^2 (22%) of the Sirkole watershed, respectively (Table 5.8). The relationship between rainfall amount and groundwater recharge is direct: more rainfall leads to more recharge, while less rainfall results in less recharge. This correlation highlights the significance of rainfall intensity in replenishing groundwater (Nigussie et al., 2019). Consequently, rainfall in the study area was reclassified into five categories based on their suitability for groundwater availability, as depicted in Figure 5.9B and Table 5.8.

Table 5. 8: Rainfall and its rank as suitable for Groundwater potential.

Factor	Class	Suitability	Rank	Area (km^2)	Area (%)
Rainfall (mm)	1110-1140	Very Low	1	130.09	14%
	1141-1169	Low	2	161.21	18%
	1170-1197	Medium	3	210.30	23%
	1198-1227	High	4	210.94	23%
	1228-1295	Very High	5	196.56	22%

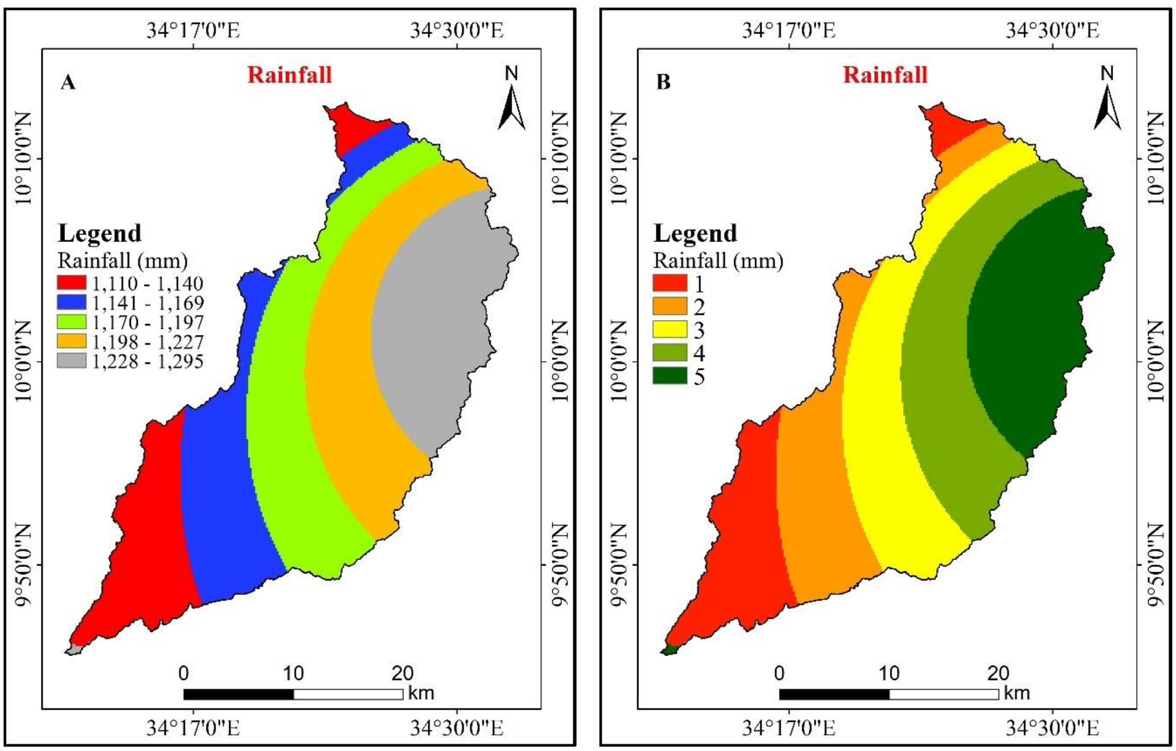


Figure 5. 9: Rainfall Map (A), Reclassified rainfall Map (B)

5.1.9. Assigned weights for parameters

The weights of all groundwater controlling factors were calculated utilizing the Analytical Hierarchy Process (AHP). Table 5.9 illustrates all groundwater controlling factors' Pairwise Comparison Matrix (PCM). The AHP outcome reveals that lithology carries the highest weight (0.32), followed by geomorphology and lineament density, contributing 0.223 and 0.159, respectively (refer to Table 5.10). Conversely, the lowest weights are assigned to DD and soil type. Slope, drainage density, soil type, land use/land cover (LULC), and rainfall are assigned weights of 0.051, 0.033, 0.026, 0.068, and 0.121, respectively. The model's consistency was evaluated, resulting in a Consistency Index (CI) of 0.11, λmax of 8.79, and a Consistency Ratio (CR) of 0.08. The CR value being less than 0.1 indicates a reasonable level of consistency (Saaty 1980).

Table 5. 9: PCM of groundwater controlling factors.

Factors	LT	GM	LD	RF	LULC	SL	DD	SI
LT	1	2	3	5	6	6	7	5
GM	1/2	1	2	3	5	5	7	6
LD	1/3	1	1	1	4	5	6	8
RF	1/5	1/3	1	1	2	5	5	5
LULC	1/5	1/5	1/4	1/2	1	2	3	5
SL	1/6	1/5	1/5	1/5	1/2	1	1	6
DD	1/7	1/7	1/6	1/5	1/3	1	1	2
ST	1/5	0	1/8	1/5	1/5	1/6	1	1

Note: **Fac=** factors**, LT**= Lithology, **GM**= Geomorphology, **LD**= Lineament Density, **RF**= Rainfall, **LU/LC** = Land Use/Land Cover, **SL**=Slope, **DD**= Drainage Density, **SO**= Soil.

Table 5. 10: Normalized weight of factors.

Factors	LT	GM	LD	RF	LULC	SL	DD	ST	Weight
LT	0.369	0.440	0.388	0.450	0.315	0.238	0.230	0.132	0.320
GM	0.185	0.220	0.258	0.270	0.263	0.199	0.230	0.158	0.223
LD	0.123	0.110	0.129	0.090	0.210	0.199	0.197	0.211	0.159
RF	0.074	0.073	0.129	0.090	0.105	0.199	0.164	0.132	0.121
LULC	0.062	0.044	0.032	0.045	0.053	0.079	0.098	0.132	0.068
SL	0.062	0.044	0.026	0.018	0.026	0.040	0.033	0.158	0.051
DD	0.053	0.031	0.022	0.018	0.018	0.040	0.033	0.053	0.033
ST	0.074	0.037	0.016	0.018	0.011	0.007	0.016	0.026	0.026

Note: **Fac=** factors**, LT**= Lithology, **GM**= Geomorphology, **LD**= Lineament Density, **RF**= Rainfall, **LU/LC** = Land Use/Land Cover, **SL**=Slope, **DD**= Drainage Density, **SO**= Soil.

5.2. Groundwater Potential zone of Sirkole watershed

The groundwater potential map was generated through weighted overlay analysis, integrating the weight values of various thematic layers, including slope, drainage density, rainfall, lineament density, lithology, LULC, geomorphology, and soil type. High-weighted areas were identified as prospective groundwater zones, following the approach that Ibrahim and Ahmed outlined(2016). The groundwater potential map of the study area was categorized into five classes based on groundwater potentiality, ranging from very low to very high, employing the Jenk classification method (Figure 5.10). These classes encompass 15.2% (very high), 29.3% (high), 30.3% (moderate), 15.7% (low), and 9.7% (very low) of the total area (Table 5.11, Figure 5.11).

The GWPZ model output highlights that groundwater occurrence is significantly influenced by factors such as lithology, geomorphology, rainfall, and lineament density. The groundwater potential map indicates that the north, north-central, north-east, central, and small portions of the south and south-west region of the Sirkole watershed exhibit high groundwater potential. These areas are characterized by ample surface water storage, including higher rainfall, gentle slopes, high lineament density, and lithological units like Granite, Basalt, and Meta-sediments, which facilitate groundwater infiltration. Consequently, these factors collectively create favorable conditions for groundwater availability in this part of the study area. Conversely, the eastern, east-southern, and northwestern parts of the study area depict very low to low GWPZ due to the presence of lithologies such as schists and gneiss, Meta granodiorite, and Biotite and biotite-hornblende gneiss, steep slopes, lower lineament density, reduced rainfall, and elevated ridges, which have a minimal influence on groundwater availability.

Overall, the combined area of very high to high GWPZ constitutes approximately 44.5%, while the combined area of very low to low potential zones covers about 25.4%. Hence, it is evident that the prevalence of High groundwater potentiality zones is higher in the study area. These findings are consistent with previous studies conducted in the Megech Watershed, Ethiopia (Berhanu and Hatiye, 2020); Upper Blue Nile River Basin, Ethiopia (Duguma, 2023), Gandheswari watershed, West Bengal (Ghosh et al., 2020) and Lafia district, Nasarawa State, Nigeria (Ifediegwu, 2022).

Table 5. 11: Groundwater Potential Zone and its areal coverage

GWPZ classes	Area in km^2	Area in %
Very low	86.4	9.7
Low	140.2	15.7
Moderate	270.7	30.3
High	261.7	29.3
Very high	135.5	15.2

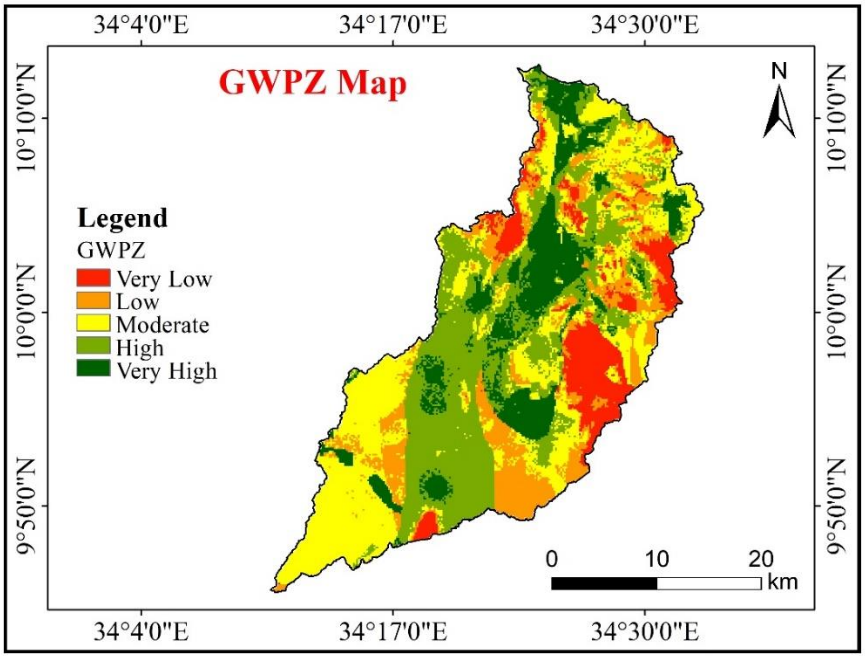


Figure 5. 10: Groundwater potential zone map of the study area.

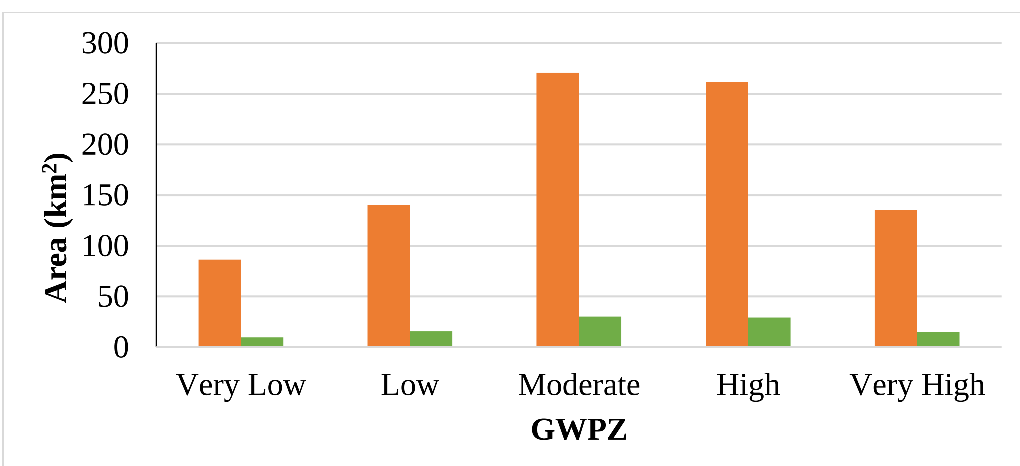


Figure 5. 11: Groundwater potential zone and its areal coverage

5.2.1. **Validation of Groundwater Potential Zones**

To validate the study quantitatively, a Receiver Operating Characteristic (ROC) curve analysis was performed by comparing existing groundwater well locations (Appendix 3) with the developed groundwater potential map using Multi-Criteria Decision Analysis (MCDA), as per the methodologies of Tamesgen et al., (2023) and Moghaddam et al., (2015). The collected well points were overlaid on the groundwater potential zones map (Figure 5.12). The ROC curve (Figure 5.13) demonstrates the accuracy of the groundwater potential map created using GIS and remote sensing techniques. The validation results showed that the MCDA method achieved a prediction accuracy of 75.9%, indicating a fairly good predictive capability. Therefore, the groundwater potential maps derived from the AHP, GIS, and remote sensing methods are considered reliable.

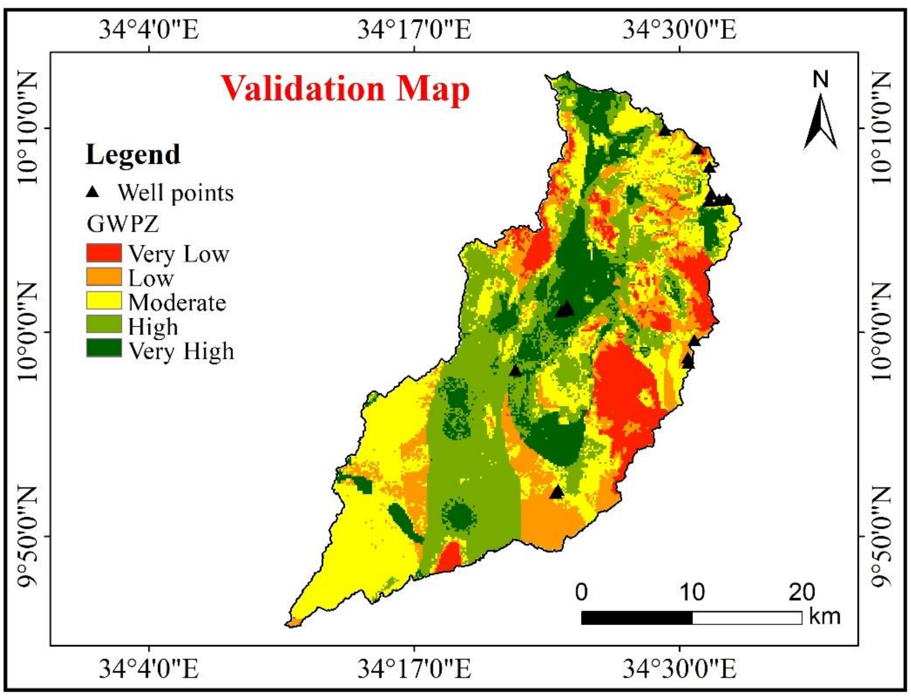


Figure 5. 12: Validation of GWPZM using observation well Data.

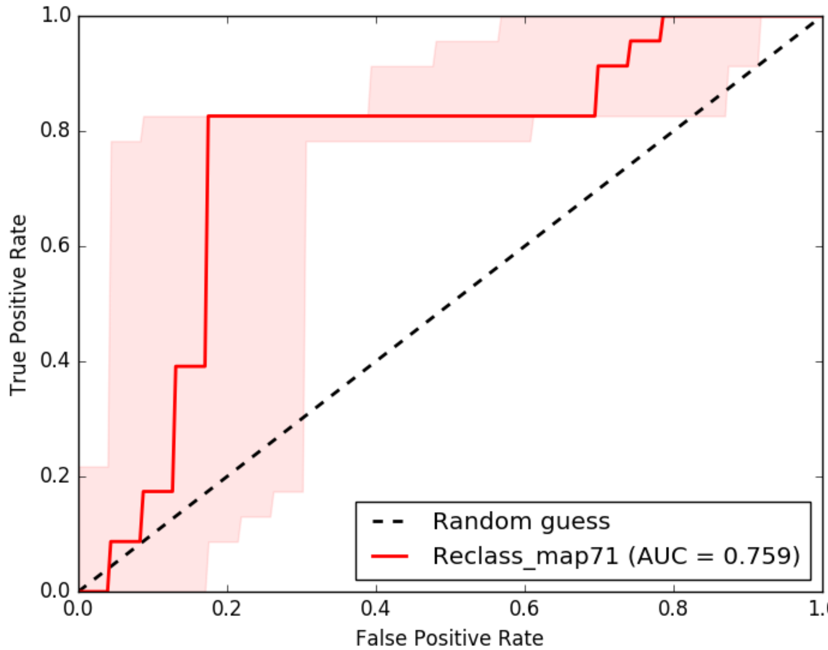


Figure 5. 13: ROC Curve.

CHAPTER SIX

6. CONCLUSION AND RECOMMENDATIONS

6.1. Conclusion

Mapping groundwater potential using remote sensing data and GIS techniques has become increasingly popular due to its applicability in inaccessible areas and its time and cost efficiency. This study utilized qualitative analysis to assess groundwater potential zones in the Sirkole watershed, western Ethiopia, using GIS and remote sensing methods. The analysis integrated the effects of various factors influencing groundwater occurrence and movement, including drainage density, LULC, lineament density, lithology, rainfall, slope, geomorphology, and soil type, with respective weights of 0.033, 0.068, 0.159, 0.32, 0.121, 0.051, 0.223, and 0.026. The weighted overlay analysis method aggregates all these factors to identify potential groundwater zones. The resulting map categorized the sub-basin into five zones: "very high" (15.2% of the area), "high" (29.3%), "moderate" (30.3%), "low" (15.7%), and "very low" (9.7%). This indicates that 25.4% of the watershed is classified as having very low to low groundwater potential, while 44.5% is classified as high to very high. The results were validated and found to be reasonable.

6.2. Recommendation

Based on the findings of this study, several recommendations are proposed to guide policy makers and environmental managers toward sustainable groundwater development and management in the Sirkole watershed.

- ❖ The methodology used in this study, which is based on logical conditions and reasoning, can be applied with appropriate modifications in regions where groundwater occurrence and distribution are more complex.
- ❖ The groundwater potential map and other thematic maps serve as a valuable resource information database. This database can be updated periodically by incorporating new information.

- ❖ For further validation, field geophysical investigations at potential well drilling sites are recommended.
- ❖ Detailed hydro-chemical analysis of the area should be prioritized to determine the basin's hydrodynamic conditions.

REFERENCE

Abrar, H., Legesse Kura, A., Esayas Dube, E., & Likisa Beyene, D. (2023). AHP based analysis of groundwater potential in the western escarpment of the Ethiopian rift valley. *Geology, Ecology, and Landscapes*, *7*(3), 175–188. https://doi.org/10.1080/24749508.2021.1952761

Adiri, Z., El Harti, A., Jellouli, A., Lhissou, R., Maacha, L., Azmi, M., Zouhair, M., & Bachaoui, E. M. (2017). Comparison of Landsat-8, ASTER and Sentinel 1 satellite remote sensing data in automatic lineaments extraction: A case study of Sidi Flah-Bouskour inlier, Moroccan Anti Atlas. *Advances in Space Research*, *60*(11), 2355–2367. https://doi.org/10.1016/j.asr.2017.09.006

Agarwal, R., & Garg, P. K. (2016). Remote Sensing and GIS Based Groundwater Potential & Recharge Zones Mapping Using Multi-Criteria Decision Making Technique. *Water Resources Management*, *30*(1), 243–260. https://doi.org/10.1007/s11269-015-1159-8

Ajay Kumar, V., Mondal, N. C., & Ahmed, S. (2020). Identification of Groundwater Potential Zones Using RS, GIS and AHP Techniques: A Case Study in a Part of Deccan Volcanic Province (DVP), Maharashtra, India. *Journal of the Indian Society of Remote Sensing*, *48*(3), 497–511. https://doi.org/10.1007/s12524-019-01086-3

Ajayi, O. G., Nwadialor, I. J., Odumosu, J. O., Adetunji, O. O., & Abdulwasiu, I. O. (2022). Assessment and delineation of groundwater potential zones using integrated geospatial techniques and analytic hierarchy process. *Applied Water Science*, *12*(12). https://doi.org/10.1007/s13201-022-01802-4

Alemayehu (bsc, T. (2006). Groundwater Occurrence In Ethiopia.

Allafta, H., & Opp, C. (2021). GIS-based multi-criteria analysis for flood prone areas mapping in the trans-boundary Shatt Al-Arab basin, Iraq-Iran. *Geomatics, Natural Hazards and Risk*, *12*(1), 2087–2116. https://doi.org/10.1080/19475705.2021.1955755

Andualem, T. G., & Demeke, G. G. (2019). Groundwater potential assessment using GIS and remote sensing: A case study of Guna tana landscape, upper blue Nile Basin, Ethiopia. *Journal of Hydrology: Regional Studies*, *24*. https://doi.org/10.1016/j.ejrh.2019.100610

Anteneh, Z. L., Alemu, M. M., Bawoke, G. T., Kehali, A. T., Fenta, M. C., & Desta, M. T. (2022a). Appraising groundwater potential zones using geospatial and multi-criteria decision analysis (MCDA) techniques in Andasa-Tul watershed, Upper Blue Nile basin, Ethiopia. *Environmental Earth Sciences*, *81*(1). https://doi.org/10.1007/s12665-021-10083-0

Anteneh, Z. L., Alemu, M. M., Bawoke, G. T., Kehali, A. T., Fenta, M. C., & Desta, M. T. (2022b). Appraising groundwater potential zones using geospatial and multi-criteria decision analysis (MCDA) techniques in Andasa-Tul watershed, Upper Blue Nile basin, Ethiopia. *Environmental Earth Sciences*, *81*(1). https://doi.org/10.1007/s12665-021-10083-0

Anuraga, T. S., Ruiz, L., Kumar, M. S. M., Sekhar, M., & Leijnse, A. (2006). Estimating groundwater recharge using land use and soil data: A case study in South India. *Agricultural Water Management*, *84*(1–2), 65–76. https://doi.org/10.1016/j.agwat.2006.01.017

Arulbalaji, P., Padmalal, D., & Sreelash, K. (2019). GIS and AHP Techniques Based Delineation of Groundwater Potential Zones: a case study from Southern Western Ghats, India. *Scientific Reports*, *9*(1). https://doi.org/10.1038/s41598-019-38567-x

Assosa-kurmuk Geologic map by GSE. (2004).

Bekele, G., & Kebede, S. (2017). Aquifer Characterization of Assosa Area, Benishangul-Gumuz Regional State, Western Ethiopia.

Berhanu, B., Melesse, A. M., & Seleshi, Y. (2013). GIS-based hydrological zones and soil geo-database of Ethiopia. *Catena*, *104*, 21–31. https://doi.org/10.1016/j.catena.2012.12.007

Berhanu, K. G., & Hatiye, S. D. (2020). Identification of Groundwater Potential Zones Using Proxy Data: Case study of Megech Watershed, Ethiopia. *Journal of Hydrology: Regional Studies*, *28*. https://doi.org/10.1016/j.ejrh.2020.100676

Bezabih, B., & Bezabih Bashe, B. (2017). Groundwater Potential Mapping using Remote Sensing and GIS in Rift Valley Lakes Basin, Weito Sub Basin, Ethiopia. *International Journal of Scientific & Engineering Research*, *8*(2), 43. http://www.ijser.org

Bhowmick, A., Yate, T. A., Shanka, A. S., Sandhar, B. S., Chaturvedi, S. K., & Ojha, J. R. (2023). Delineation of Ground Water Prospect Zones of Mojo Watershed, Ethiopia, East Africa, Using GIS, Remote Sensing and Analytical Hierarchy Process. *Journal of the Indian Society of Remote Sensing*. https://doi.org/10.1007/s12524-023-01761-6

Boru, G. L. (2007). Delineation Of Groundwater Potential Zones of Upper Tumet Catchment, Menge Area, Western Ethiopia Using Remote Sensing and Gis

Chowdhury, A., Jha, M. K., Chowdary, V. M., & Mal, B. C. (2008). Integrated remote sensing and GIS-based approach for assessing groundwater potential in West Medinipur district, West Bengal, India. *International Journal of Remote Sensing*, *30*(1), 231–250. https://doi.org/10.1080/01431160802270131

Condon, L. E., & Maxwell, R. M. (2015). Evaluating the relationship between topography and groundwater using outputs from a continental-scale integrated hydrology model. *Water Resources Research*, *51*(8), 6602–6621. https://doi.org/10.1002/2014WR016774

Dibaba, W. T., Demissie, T. A., & Miegel, K. (2020). Watershed hydrological response to combined land use/land cover and climate change in highland ethiopia: Finchaa catchment. *Water (Switzerland)*, *12*(6). https://doi.org/10.3390/w12061801

Diriba, D., Karuppannan, S., Takele, T., & Husein, M. (2024). Delineation of groundwater potential zonation using geoinformatics and AHP techniques with remote sensing data. *Heliyon*, *10*(3), e25532. https://doi.org/10.1016/j.heliyon.2024.e25532

Duguma, T. A. (2023). RS and GIS analysis of the groundwater potential zones in the Upper Blue Nile River Basin, Ethiopia. *Journal of Hydrology: Regional Studies*, *46*. https://doi.org/10.1016/j.ejrh.2023.101344

Elbeih, S. F. (2015). An overview of integrated remote sensing and GIS for groundwater mapping in Egypt. In *Ain Shams Engineering Journal* (Vol. 6, Issue 1, pp. 1–15). Ain Shams University. https://doi.org/10.1016/j.asej.2014.08.008

Fenta, A. A., Kifle, A., Gebreyohannes, T., & Hailu, G. (2015). Spatial analysis of groundwater potential using remote sensing and GIS-based multi-criteria evaluation in Raya Valley, northern Ethiopia. *Hydrogeology Journal*, *23*(1), 195–206. https://doi.org/10.1007/s10040-014-1198-x

Gdoura, K., Anane, M., & Jellali, S. (2015). Geospatial and AHP-multicriteria analyses to locate and rank suitable sites for groundwater recharge with reclaimed water. In *Resources, Conservation and Recycling* (Vol. 104, pp. 19–30). Elsevier. https://doi.org/10.1016/j.resconrec.2015.09.003

Gebru, H., Gebreyohannes, T., & Hagos, E. (2020). Identification of Groundwater Potential Zones Using Analytical Hierarchy Process (AHP) and GIS-Remote Sensing Integration, the Case of Golina River Basin, Northern Ethiopia. *International Journal of Advanced Remote Sensing and GIS*, *9*(1), 3289–3311. https://doi.org/10.23953/cloud.ijarsg.460

Genetie, A., Beyene, D., & Befekadu, A. (2019). Analyzing the Sustainability of Urban Water Supply and Distribution System; In Case of Assosa Town Water Supply and Distribution System, Benishangul Gumuz National Regional State, Western Ethiopia. In *I Appl. J. Envir. Eng. Sci* (Vol. 5).

Ghosh, D., Mandal, M., Karmakar, M., Banerjee, M., & Mandal, D. (2020). Application of geospatial technology for delineating groundwater potential zones in the Gandheswari watershed, West Bengal. *Sustainable Water Resources Management*, *6*(1). https://doi.org/10.1007/s40899-020-00372-0

Ghosh, M., & Sahu, A. S. (2023). Delineation of groundwater potential zones using AHP and GIS techniques: a case study in Barakar river basin, India. *Arabian Journal of Geosciences*, *16*(3). https://doi.org/10.1007/s12517-023-11253-z

Ghosh, S., Das, D., Gayen, S. K., & Bhardwaj, P. (2023). Delineation of groundwater potential zones using the AHP technique: a case study of Alipurduar district, West Bengal. *Modeling Earth Systems and Environment*, *9*(4), 4507–4537. https://doi.org/10.1007/s40808-023-01733-2

Gintamo, T. T. (n.d.). *Ground Water Potential Evaluation Based on Integrated GIS and Remote Sensing Techniques, in Bilate River Catchment: South Rift Valley of Ethiopia*. http://asrjetsjournal.org/

Gintamo, T. T. (2015). *Ground Water Potential Evaluation Based on Integrated GIS and Remote Sensing Techniques, in Bilate River Catchment: South Rift Valley of Ethiopia*. http://asrjetsjournal.org/

Haile, M. M., Tafesse Yadeta, J., & Amena Gambe, L. (2022). Delineation of groundwater potential zones using geo-spatial and AHP techniques: Ambo area, Blue Nile Basin, Ethiopia. *Sustainable Water Resources Management*, *8*(1). https://doi.org/10.1007/s40899-022-00622-3

Ifediegwu, S. I. (2022). Assessment of groundwater potential zones using GIS and AHP techniques: a case study of the Lafia district, Nasarawa State, Nigeria. *Applied Water Science*, *12*(1). https://doi.org/10.1007/s13201-021-01556-5

Kaliraj, S., Chandrasekar, N., & Magesh, N. S. (2014). Identification of potential groundwater recharge zones in Vaigai upper basin, Tamil Nadu, using GIS-based analytical hierarchical process (AHP) technique. *Arabian Journal of Geosciences*, *7*(4), 1385–1401. https://doi.org/10.1007/s12517-013-0849-x

Kebede, S. (2013). Groundwater in Ethiopia: Features, numbers and opportunities. In *Groundwater in Ethiopia: Features, Numbers and Opportunities*. Springer Berlin Heidelberg. https://doi.org/10.1007/978-3-642-30391-3

Kitaro, A. A. (2021). Groundwater Potential Evaluation of Western Dabus River Catchment, Abay Basin, Ethiopia.

Kumar, A., & Krishna, A. P. (2018). Assessment of groundwater potential zones in coal mining impacted hard-rock terrain of India by integrating geospatial and analytic hierarchy process (AHP) approach. *Geocarto International*, *33*(2), 105–129. https://doi.org/10.1080/10106049.2016.1232314

Lammesa, B. (2017). Groundwater potential and Recharge zone mapping by using GIS and Remote sensing Techniques in the case of Middle Awash River Basins, Ethiopia

Li, S., Yang, H., Lacayo, M., Liu, J., & Lei, G. (2018). Impacts of land-use and land-cover changes on water yield: A case study in Jing-Jin-Ji, China. *Sustainability (Switzerland)*, *10*(4). https://doi.org/10.3390/su10040960

Machiwal, D., Jha, M. K., & Mal, B. C. (2011). Assessment of Groundwater Potential in a Semi-Arid Region of India Using Remote Sensing, GIS and MCDM Techniques. *Water Resources Management*, *25*(5), 1359–1386. https://doi.org/10.1007/s11269-010-9749-y

Magesh, N. S., Chandrasekar, N., & Soundranayagam, J. P. (2012). Delineation of groundwater potential zones in Theni district, Tamil Nadu, using remote sensing, GIS and MIF techniques. *Geoscience Frontiers*, *3*(2), 189–196. https://doi.org/10.1016/j.gsf.2011.10.007

Moges, D. M., Bhat, H. G., & Thrivikramji, K. P. (2019). Investigation of groundwater resources in highland Ethiopia using a geospatial technology. *Modeling Earth Systems and Environment*, *5*(4), 1333–1345. https://doi.org/10.1007/s40808-019-00603-0

Moghaddam, D. D., Rezaei, M., Pourghasemi, H. R., Pourtaghie, Z. S., & Pradhan, B. (2015). Groundwater spring potential mapping using bivariate statistical model and GIS in the Taleghan Watershed, Iran. *Arabian Journal of Geosciences*, *8*(2), 913–929. https://doi.org/10.1007/s12517-013-1161-5

Muralitharan, J., & Palanivel, K. (2015). Groundwater targeting using remote sensing, geographical information system and analytical hierarchy process method in hard rock aquifer system, Karur district, Tamil Nadu, India. *Earth Science Informatics*, *8*(4), 827–842. https://doi.org/10.1007/s12145-015-0213-7

Nagaraju, A., Sreedhar, Y., Thejaswi, A., & Dash, P. (2016). Integrated Approach Using Remote Sensing and GIS for Assessment of Groundwater Quality and Hydrogeomorphology in Certain Parts of Tummalapalle Area, Cuddapah District, Andhra Pradesh, South India. *Advances in Remote Sensing*, *05*(02), 83–92. https://doi.org/10.4236/ars.2016.52007

Naghibi, S. A., Pourghasemi, H. R., Pourtaghi, Z. S., & Rezaei, A. (2015). Groundwater qanat potential mapping using frequency ratio and Shannon's entropy models in the Moghan watershed, Iran. *Earth Science Informatics*, *8*(1), 171–186. https://doi.org/10.1007/s12145-014-0145-7

Nampak, H., Pradhan, B., & Manap, M. A. (2014). Application of GIS based data driven evidential belief function model to predict groundwater potential zonation. *Journal of Hydrology*, *513*, 283–300. https://doi.org/10.1016/j.jhydrol.2014.02.053

Nigussie, W., Hailu, B. T., & Azagegn, T. (2019). Mapping of groundwater potential zones using sentinel satellites (−1 SAR and -2A MSI) images and analytical hierarchy process in Ketar watershed, Main Ethiopian Rift. *Journal of African Earth Sciences*, *160*. https://doi.org/10.1016/j.jafrearsci.2019.103632

Prasad, R. K., Mondal, N. C., Banerjee, P., Nandakumar, M. V., & Singh, V. S. (2008). Deciphering potential groundwater zone in hard rock through the application of GIS. *Environmental Geology*, *55*(3), 467–475. https://doi.org/10.1007/s00254-007-0992-3

Rahmati, O., Nazari Samani, A., Mahdavi, M., Pourghasemi, H. R., & Zeinivand, H. (2015). Groundwater potential mapping at Kurdistan region of Iran using analytic hierarchy process and GIS. *Arabian Journal of Geosciences*, *8*(9), 7059–7071. https://doi.org/10.1007/s12517-014-1668-4

Rajaveni, S. P., Brindha, K., & Elango, L. (2017). Geological and geomorphological controls on groundwater occurrence in a hard rock region. *Applied Water Science*, *7*(3), 1377–1389. https://doi.org/10.1007/s13201-015-0327-6

Rukundo, E., & Doğan, A. (2019). Dominant influencing factors of groundwater recharge spatial patterns in Ergene river catchment, Turkey. *Water (Switzerland)*, *11*(4). https://doi.org/10.3390/w11040653

Saaty. (1980). Marketing Applications of the Analytic Hierarchy Process.

Saaty, R. W. (1987). The Analytic Hierarchy Process-What it is and How it is Used (Vol. 9, Issue 5).

Shaban, A., Khawlie, M., & Abdallah, C. (2006). Use of remote sensing and GIS to determine recharge potential zones: The case of Occidental Lebanon. *Hydrogeology Journal*, *14*(4), 433–443. https://doi.org/10.1007/s10040-005-0437-6

Shekhar, S., & Pandey, A. C. (2015). Delineation of groundwater potential zone in hard rock terrain of India using remote sensing, geographical information system (GIS) and analytic hierarchy process (AHP) techniques. *Geocarto International*, *30*(4), 402–421. https://doi.org/10.1080/10106049.2014.894584

Sivakumar, V., Vidhya, S., Vinay, L. Y., & Reddy, K. (2019). Identification of Groundwater Potential Zones Using Gis And Remote Sensing. http://www.acadpubl.eu/hub/

Tamesgen, Y., Atlabachew, A., & Jothimani, M. (2023). Groundwater potential assessment in the Blue Nile River catchment, Ethiopia, using geospatial and multi-criteria decision-making techniques. *Heliyon*, *9*(6). https://doi.org/10.1016/j.heliyon.2023.e17616

Tamiru, H., & Wagari, M. (2022). Comparison of ANN model and GIS tools for delineation of groundwater potential zones, Fincha Catchment, Abay Basin, Ethiopia. *Geocarto International*, *37*(23), 6736–6754. https://doi.org/10.1080/10106049.2021.1946171

Teshome, A., Halefom, A., Ahmad, I., & Teshome, M. (2021). Fuzzy logic techniques and GIS-based delineation of groundwater potential zones: a case study of Anger river basin, Ethiopia. *Modeling Earth Systems and Environment*, *7*(4), 2619–2628. https://doi.org/10.1007/s40808-020-01035-x

Thapa, R., Gupta, S., Guin, S., & Kaur, H. (2017). Assessment of groundwater potential zones using multi-influencing factor (MIF) and GIS: a case study from Birbhum district, West Bengal. *Applied Water Science*, *7*(7), 4117–4131. https://doi.org/10.1007/s13201-017-0571-z

Tolcha Bekele, T., & Daniel, A. (2019). Groundwater Potential Zone delineation using GIS and Remote sensing Techniques in Sululta and Surrounding Watershed, Ethiopia.

Tolche, A. D. (2021). Groundwater potential mapping using geospatial techniques: a case study of Dhungeta-Ramis sub-basin, Ethiopia. *Geology, Ecology, and Landscapes*, *5*(1), 65–80. https://doi.org/10.1080/24749508.2020.1728882

Waikar, M. L., & Nilawar, A. P. (2014). *International Journal of Multidisciplinary and Current Research Morphometric Analysis of a Drainage Basin Using Geographical Information System: A Case study*. http://ijmcr.com

Wakwoya, M. B., Woldeyohannis, W. H., & Yimamu, F. K. (2023). Characterization and classification of soils of upper Hoha sub-watershed in Assosa District, Western Ethiopia. *Heliyon*, *9*(4). https://doi.org/10.1016/j.heliyon.2023.e14866

Yihunie, D., & Halefom, A. (n.d.). *Investigation of groundwater potential zone using Geospatial Technology in Bahir Dar Zuria District, Amhara, Ethiopia*. www.worldscientificnews.com

Yitbarek, A., Razack, M., Ayenew, T., Zemedagegnehu, E., & Azagegn, T. (2012). Hydrogeological and hydrochemical framework of Upper Awash River basin, Ethiopia: With special emphasis on inter-basins groundwater transfer between Blue Nile and Awash Rivers. *Journal of African Earth Sciences*, *65*, 46–60. https://doi.org/10.1016/j.jafrearsci.2012.01.002

APPENDIX

Appendix: 1 Long-Term Rainfall of the Study Area in Assosa Station.

YEAR	JAN	FEB	MAR	APR	MAY	JUN	JUL	AUG	SEP	OCT	NOV	DEC
2011	0	0	0	10.55	94.92	94.92	63.28	89.65	79.1	63.28	5.27	0
2012	0	0	0	5.27	79.1	68.55	121.29	189.84	189.84	42.19	26.37	0
2013	0	0	0	0	200.39	158.2	142.38	142.38	142.38	73.83	21.09	0
2014	0	5.27	5.27	105.47	168.75	158.2	268.95	226.76	295.31	258.4	0	10.55
2015	0	0	21.09	0	247.85	253.12	200.39	353.32	195.12	332.23	47.46	42.19
2016	0	0	21.09	47.46	406.05	200.39	411.33	332.23	437.7	353.32	0	0
2017	0	5.27	0	47.46	147.66	353.32	358.59	290.04	189.84	221.48	26.37	5.27
2018	0	0	26.37	5.27	226.76	142.38	221.48	210.94	121.29	232.03	10.55	5.27
2019	0	0	0	26.37	100.2	300.59	284.77	195.12	490.43	184.57	47.46	21.09
2020	0	0	15.82	73.83	300.59	321.68	374.41	316.41	311.13	337.5	10.55	10.55
2021	0	0	0	75.18	257.61	381.8	365.86	276.02	378.63	234.4	129.5	14.43
2022	29.86	0.6	2.79	75.6	154.3	350.24	340.78	259.34	277.99	218.1	2.09	6.23

Appendix: 2 Long-Term Temperatures of the Study Area in Assosa Station.

YEAR	Element	JAN	FEB	MAR	APR	MAY	JUN	JUL	AUG	SEP	OCT	NOV	DEC
2011	Max	28.7	31.0	29.0	30.0	28.4	11.9	24.8	23.1	24.5	25.2	26.9	28.3
	Min	11.5	12.5	13.1	133.9	15.7	16.8	15.9	15.4	15.7	14.3	11.6	10.1
2012	Max	30.3	33.3	45.9	31.6	28.1	12.5	23.6	24.5	25.1	26.0	26.6	28.7
	Min	12.1	12.1	10.3	15.6	16.2	15.9	16.1	16.3	15.7	13.0	11.6	12.1
2013	Max	30.5	31.7	32.5	32.0	27.7	12.7	23.3	23.5	24.9	25.5	27.1	29.3
	Min	12.3	12.6	13.3	14.2	17.2	16.7	16.3	16.1	15.7	14.2	11.6	11.5
2014	Max	31.0	30.7	31.3	30.3	26.3	11.8	24.6	23.8	25.0	26.0	27.0	29.0
	Min	11.4	13.2	16.0	16.7	15.6	16.1	16.9	15.7	16.1	14.0	11.6	11.5
2015	Max	29.8	31.6	31.8	30.7	27.1	12.3	24.9	25.2	26.2	26.1	27.7	26.1
	Min	11.9	12.3	15.8	15.1	16.5	16.4	15.8	16.3	16.3	15.4	11.6	15.4
	Max	30.0	33.0	33.2	31.1	26.4	16.8	24.1	24.3	25.1	26.2	28.6	29.9
	Min	16.2	13.0	16.2	16.3	17.4	16.2	16.3	16.0	16.0	15.3	11.6	13.5
2017	Max	31.6	30.0	32.8	30.9	27.3	12.7	23.9	23.8	24.7	29.9	30.7	29.5
	Min	12.3	14.5	15.3	17.6	17.0	16.5	16.2	16.0	15.8	13.6	11.6	11.8
2018	Max	29.2	31.0	30.8	29.9	28.1	14.1	23.9	24.7	25.8	25.7	28.1	29.4
	Min	13.7	14.2	13.2	15.3	17.0	16.2	16.3	15.9	15.6	15.1	11.6	14.6
2019	Max	31.5	30.9	32.8	30.5	26.9	14.5	24.0	24.7	25.7	27.6	28.5	29.4
	Min	14.0	15.0	16.7	15.9	17.3	16.4	16.3	16.2	15.8	14.9	11.6	14.7
2020	Max	31.1	30.8	29.0	31.6	26.8	14.9	24.0	24.9	25.8	27.9	28.8	29.5
	Min	14.5	15.1	14.1	16.4	17.5	16.7	16.2	16.4	15.9	14.7	11.6	15.2

2021	Max	31.2	30.6	43.1	30.8	26.7	15.3	24.0	25.0	25.9	28.2	29.1	29.6
	Min	14.8	14.7	14.6	16.5	17.3	16.4	16.2	16.1	15.9	15.1	11.6	15.6
2022	Max	29.4	30.2	32.2	29.2	27.6	13.9	23.8	25.1	25.5	28.5	29.4	29.7
	Min	13.5	14.4	15.1	16.6	17.0	16.0	16.1	15.8	16.0	15.3	11.6	16.1

Appendix: 3 Water Inventor Points.

NO,	Name of BH	coordination		depth	Yield during cons	functionality	Current discharge	remark
		x	y					
1	Abende mingda (Got 2)	34.507466	9.975321	93	7.5	fu	4.6	
2	Abende mingda (Gote 1)	34.506822	9.979541	86	6.5	fu	4.5	
3	Abrehamo (Gote 2)	34.51212	9.993915	110	5.5	no	-	Interference
4	Agusha (Got 10)	34.524295	10.107896	93	6.7	fu	4	
5	Agusha (Got 4)	34.52611	10.113656	58	19	fu	10	
6	Agusha (Got 7)	34.532545	10.108636	76	8.6	fu	4.8	
7	Amba 8 (Got 9)	34.538374	10.109124	98	7.5	fu	4	
8	Budir (Got 1)	34.400871	9.871494	87	3.7	fu	3	
9	Buldadini (Got 3)	34.399074	9.869199	98	3.3	no	-	dray
10	Qoshmengel (Got 2)	34.488119	10.165553	110	3	no	-	dray
11	Qushmegani (Gote 3)	34.366281	9.969435	86	5	fu	3.2	
12	Sherkole afundu (Got 4)	34.40915	10.01868	96	11	fu	6.7	
13	Sherkole afundu (Got 2)	34.403718	10.017436	82	26	fu	12.6	
14	Sherkole engine (Gote 2)	34.408226	10.022075	78	24	fu	10.7	
15	Tsetseadurnunu (Got 1(Abushendu))	34.514704	10.150502	76	8	On/off	5.5	problem of line
16	Tsetseadurnunu (Got 2)	34.524389	10.135154	110	7.5	fu	5	

Appendix: 4 Literature Review

No	Authors	Title	Influence Factors	Method
1	(Andualem & Demeke, 2019)	Groundwater potential assessment using GIS and remote sensing: A case study of Guna tana landscape, upper Blue Nile Basin, Ethiopia	Geology, Geomorphology, Slope, Soils, Land use/land cove, Lineament density, Drainage density	Remote sensing and GIS
2	(Anteneh et al., 2022a)	Appraising groundwater potential zones using geospatial and multi-criteria decision analysis (MCDA) techniques in Andasa-Tul watershed, Upper Blue Nile basin, Ethiopia	Lithology, Geomorphology, Soil, Rainfall, Groundwater Level, Lineament, Slope, Drainage network, Land use/Land Cover.	Geospatial and multi-criteria decision analysis Remote Sensing and GIS
3	(K. G. Berhanu & Hatiye, 2020)	Identification of Groundwater Potential Zones Using Proxy Data: Case study of Megech Watershed, Ethiopia	Rainfall, Elevation, Slope, Drainage density, Geomorphology, Geology, Lineament density, Land use/cover, Soil	RS and GIS, AHP.
4	(Bezabih & Bezabih Bashe, 2017)	Groundwater Potential Mapping using Remote Sensing and GIS in Rift Valley Lakes Basin, Weito Sub Basin, Ethiopia	Rainfall, Slope, Drainage Density, Lineament Density, Lithology, Land Cover, Soil, Geomorphology	Remote Sensing, GIS and AHP
5	(Bhowmick et al., 2023)	Delineation of Ground Water Prospect Zones of Mojo Watershed, Ethiopia, East Africa, Using GIS, Remote Sensing and Analytical Hierarchy Process	Geology/lithology, Slope, Lineament Density, Geomorphology, Drainage density, Soil, Land Cover, Rainfall	Remote Sensing, GIS and AHP
6	(Boru, 2007)	Delineation of groundwater potential zones of upper Tumet catchment, Menge area, western Ethiopia using remote sensing and GIS	Preamble, Lineament, Vegetation and Soil Moisture Anomaly, Land use/Land cover, Lithology, Drainage Density, Slope, Weathering.	Remote sensing and GIS.

7	(Dibaba et al., 2020)	Watershed Hydrological Response to Combined Land Use/Land Cover and Climate Change in Highland Ethiopia: Finchaa Catchment	Elevation, slope, Soil, LULCC, Climate Change.	Remote sensing and GIS.
8	(Diriba et al., 2024)	Delineation of Groundwater Potential Zonation Using Geoinformatics and AHP Techniques with Remote Sensing Data	lithology, lineament density, geomorphology, Slope, Drainage density, rainfall, Land use and land cover	Remote sensing and GIS-based
9	(Duguma, 2023)	RS and GIS analysis of the groundwater potential zones in the Upper Blue Nile River Basin, Ethiopia	geomorphology, geology, drainage, and structure, land use, infiltration rate, and rainfall	Remote sensing and GIS.
10	(Gebru et al., 2020)	Identification of Groundwater Potential Zones Using Analytical Hierarchy Process (AHP) and GIS-Remote Sensing Integration, the Case of Golina River Basin, Northern Ethiopia	Geology, Geomorphology, lineament density, Slope, Drainage density and streams, Soil texture, Land use/cover, Spatial distribution of precipitation, Normalized difference vegetation index, Topographic wetness index.	AHP and GIS-Remote Sensing Integration
11	(Haile et al., 2022)	Delineation of groundwater potential zones using geo-spatial and AHP techniques: Ambo area, Blue Nile Basin, Ethiopia	lithology, geomorphology, land use cover, lineaments, slope, soil, drainage density, precipitation and runoff.	geo-spatial and AHP
12	(Kitaro, 2021)	Groundwater potential evaluation of western Dabus River catchment, abay basin, Ethiopia	Rainfall, Temperature, Relative humidity, Wind speed, Sunshine, Evapotranspiration, Runoff, Recharge,	GIS, AHP, Geomatic,
13	(Moges et al., 2019)	Investigation of groundwater resources in highland Ethiopia using a geospatial technology	geomorphology, geology, lineament density, rainfall, drainage density, soil, slope, and land use.	Remote Sensing and GIS

14	(Tamiru & Wagari, 2022)	Comparison of ANN model and GIS tools for delineation of groundwater potential zones, Fincha Catchment, Abay Basin, Ethiopia	slope, geology, rainfall, geomorphological units, lineament density, lithology and soil.	ANN model, Remote Sensing, GIS, and AHP
15	(Teshome et al., 2021)	Fuzzy logic techniques and GIS-based delineation of groundwater potential zones: a case study of Anger River basin, Ethiopia	Slope gradient, Drainage density, Roughness, Curvature, topographic, Soil texture and soil types, Land use land cover changes	MCDM and GIS-based
16	(Tolcha Bekele & Daniel, 2019)	Groundwater Potential Zone delineation using GIS and Remote Sensing Techniques in Sululta and Surrounding Watershed, Ethiopia	Geomorphic units, Geology, Land use Land over, Drainage Density, Lineament Density, Slope, Soils, Rainfall.	Remote sensing and GIS.
17	(Tolche, 2021)	Groundwater potential mapping using geospatial techniques: a case study of Dhungeta-Ramis sub-basin, Ethiopia	Lithology, Land use land cover, Lineament density, slope, Rainfall	geospatial techniques
18	(Wakwoya et al., 2023)	Characterization and classification of soils of upper Hoha sub-watershed in Assosa District, Western Ethiopia	Climate and topography, Land use and farming system, Soils and geology.	Remote sensing and GIS.
19	(Yihunie & Halefom, 2020)	Investigation of groundwater potential zone using Geospatial Technology in Bahir Dar Zuria District, Amhara, Ethiopia	Lithology, Lineaments, Soil, Geomorphology, Land use land cover, Slope.	Remote sensing and GIS
20	(Gintamo, 2015)	Ground Water Potential Evaluation Based on Integrated GIS and Remote Sensing Techniques, in Bilate River Catchment: South Rift Valley of Ethiopia	Precipitation, Recharge and Discharge, Slope, Drainage density, Land use/ Land Cover, Soil, Geomorphology, Lithology, Lineament density	Remote sensing and GIS.

		Authors																				TOTAL
NO	**IF**	1	2	3	4	5	6	7	8	9	10	11	12	13	14	15	16	17	18	19	20	t=20
1	Geology																					17
2	Geomorphology																					15
3	Slope																					17
4	Soil																					17
5	D Density																					15
6	L Density																					16
7	LULC																					18
8	Rainfall																					15
9	Elevation																					2
10	Roughens																					1
11	Topography																					3
12	Runoff																					2
13	Temperature																					1
14	Humidity																					1
15	Wind speed																					1
16	ET																					1
17	Sunshine																					1
18	Structure																					1
19	Climate																					2
20	infiltration																					1
21	Weather																					1
22	**Method**																					
23	RS																					16
24	GIS																					18
25	AHP																					8
26	Geospatial																					2
27	MCDM																					1
28	ANNS																					1

The geographical location of the above research is as follows

Northern	10
Eastern	17
Southern	4,8, and 20
Western	6,11,12, and 18
N-W	1,2,3,7,9,14,15, and 19
Central	5 and 16

Note:

1	(Andualem & Demeke, 2019)	11	(Haile et al., 2022)
2	Anteneh et al., 2022)	12	(Kitaro, 2021)
3	(Berhanu & Hatiye, 2020)	13	(Moges et al., 2019)
4	(Bezabih & Bezabih Bashe, 2017)	14	(Tamiru & Wagari, 2022)
5	(Bhowmick et al., 2023)	15	(Teshome et al., 2021)
6	(Boru, 2007)	16	(Tolcha Bekele & Daniel, 2019)
7	(Dibaba et al., 2020)	17	(Tolche, 2021)
8	(Diriba et al., 2024)	18	(Wakwoya et al., 2023)
9	(Duguma, 2023)	19	(Yihunie & Halefom, 2020)
10	(Gebru et al., 2020)	20	(Gintamo, 2015)

PUBLICATION

Article Title: Identification of groundwater potential zones for sustainable groundwater resource management using an integrated approach in Sirkole watershed, Western Ethiopia.

Journal: Groundwater for Sustainable Development (Elsevier)

Impact factor: 4.9 (Q1)

Indexing Database: Scopus, Emerging Sources Citation Index (ESCI), SCImago Journal Rank (SJR), SNIP

Article link: https://doi.org/10.1016/j.gsd.2024.101328

Groundwater for Sustainable Development 27 (2024) 101328

Contents lists available at ScienceDirect

Groundwater for Sustainable Development

journal homepage: www.elsevier.com/locate/gsd

Research paper

Identification of groundwater potential zones for sustainable groundwater resource management using an integrated approach in Sirkole watershed, Western Ethiopia

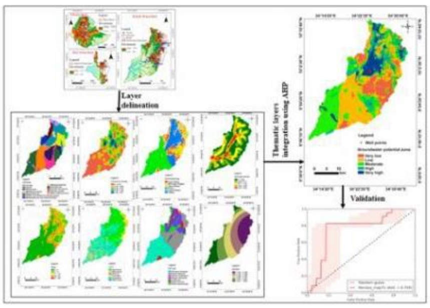
Wakgari Yadeta[a], Shankar Karuppannan[a,b,*], Dechasa Diriba[c], Hassen Shube[a]

[a] Department of Applied Geology, School of Applied Natural Science, Adama Science and Technology University, Adama, P.O. Box: 1888, Ethiopia
[b] Department of Research Analytics, Saveetha Dental College and Hospitals, Saveetha Institute of Medical and Technical Sciences (SIMATS), Saveetha University, Chennai, 600077, Tamil Nadu, India
[c] Department of Geology, College of Natural and Computational Science, Dilla University, P.O. Box: 419, Dilla, Ethiopia

HIGHLIGHTS

- Integrated GIS, Remote Sensing, and AHP approaches assess groundwater potential zones.
- Delineates GWPZ using eight thematic layers: lithology, slope, soil, GM, RF, DD, LULC, and LD.
- Results show that 22.8% of the study area has good groundwater potential.
- The research provides valuable insights for policymakers and water resource managers in Ethiopia.

GRAPHICAL ABSTRACT



ARTICLE INFO

Keywords:
Groundwater potential zones
AHP
GIS
RS
Sirkole watershed

ABSTRACT

The increasing population in the Sirkole watershed has led to a higher demand for groundwater resources essential for socio-economic development. To ensure sustainable groundwater management, accurate quantitative assessments are necessary, which can be achieved by utilizing scientific principles and modern techniques. This article discusses the use of RS and GIS techniques to evaluate Groundwater Potential Zones in a section of the Sirkole watershed in Western Ethiopia. The study analyzed various spatial data layers involving drainage density, land use, lineaments, slope, lithology, rainfall, geomorphology, and soil type to understand the factors influencing groundwater occurrence and movement. The eight thematic layers were weighted according to their significance. Additionally, a hierarchical ranking was performed using a pairwise comparison matrix (PCM)

* Corresponding author. Department of Applied Geology, School of Applied Natural Science, Adama Science and Technology University, Adama, P.O. Box: 1888, Ethiopia.
E-mail address: geoshankar1984@gmail.com (S. Karuppannan).

https://doi.org/10.1016/j.gsd.2024.101328
Received 14 July 2024; Received in revised form 16 August 2024; Accepted 2 September 2024
Available online 5 September 2024