Mapping Groundwater Potential Zones Using GIS-Based Analytical Hierarchy Processes Techniques in the Upper Dawa River Basin, Southern Ethiopia

Debisa Debela Dulecha

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 of Science in Applied Geology

Office of Graduate Studies

Adama Science and Technology University

March, 2025

Adama, Ethiopia

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Declaration

I declare that this master's thesis entitled "**Mapping Groundwater Potential Zones Using GIS-Based Analytical Hierarchy Processes Techniques in the Upper Dawa River Basin, Southern Ethiopia**" is my work, that it has not been submitted for any degree, diploma, or examination in any other university, and that all the sources I have used or quoted have been indicated and acknowledged by complete references.

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Name of the student	Signature	Date

Approval of Board of Reviewers

We, the undersigned, members of the Board of Reviewers of the master's thesis open defense by **Debisa Debela Dulecha** have read and evaluated the entitled **Mapping Groundwater Potential Zones Using GIS-based AHP techniques in the Upper Dawa River Basin, Southern Ethiopia,** and assessed the understanding of the candidate about the master's thesis. This is, therefore, to certify that the master's thesis is accepted and we recommend the implementation of the master's thesis.

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

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Recommendation

We, the advisors of this master's thesis, hereby certify that I/we have read the revised version of the thesis entitled "**Mapping Groundwater Potential Zones Using GIS-Based Analytical Hierarchy Processes Techniques in the Upper Dawa River Basin, Southern Ethiopia**" prepared under our guidance by **Debisa Debela** submitted in partial fulfillment of the requirements for the degree of masters of Science in Applied Geology (Hydrogeology). Therefore, we recommend the submission of the revised version of the thesis to the department following the applicable procedures.

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List of Acronyms and Abbreviations

AHP	Analytical Hierarchy Process
AMSL	Above mean sea level
ARC GIS	Aeronautical Reconnaissance Coverage Geographic Information System
AUC	Area under the curve
CI	Consistency Index
CR	Consistency ratio
DEM	Digital elevation model
ERDAS	Earth Resource Data Analysis system
GIE	Geological Institute of Ethiopia
GIS	Geographic Information System
GPS	Geographic Positioning System
GWPZ	Groundwater potential Zones
LULC	Land use land cover
MCDM	Multicriteria decision making
OLI	Operational Land Imagery
Qa	Quaternary Alluvial
Qe	Quaternary Elluvial
ROC	Receiver operating characteristics
SRTM	Shuttle Radar Topography Mission
WOA	Weighted Overlay Analysis

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Abstract

Groundwater is a vital freshwater resource and a critical water source to supply domestic, irrigation, and industrial demand. As the demand for drinking water increases globally, the need to evaluate the groundwater potential and aquifer productivity also increases. This study focused on mapping the groundwater potential zones in the upper Dawa Basin, Southern Ethiopia, using a Geographical Information System (GIS) based Analytical Hierarchy Process (AHP). This study considers seven factors influencing groundwater availability, recharge, and distribution: geology, lineament density, slope, land use/land cover, drainage density, soil types, and rainfall. The relative significance of each factor was determined using a pairwise comparison matrix, and the normalized weight of each factor was calculated based on the procedure used in the AHP approach. The weighted overlay analysis (WOA) tool in Arc GIS 10.8 was used to produce the final groundwater potential zones map. To validate the accuracy of groundwater potential zones relationship of well yield and the potential zones are assessed using the area under curve (AUC) approach. The study area is divided into five groundwater potential zones: very low, low, moderate, high, and very high, respectively, covering 0.26%, 45.9%, 8.8%, 16.34%, and 28.08% of the study area. The volcanic terrain in the north and northwest, the limestone terrain in the southeast, and small areas along streamlines in the basement terrain in the south are mapped as very high to high groundwater potential zones. On the other hand, a large portion of the basement terrain is marked by low to very low groundwater potential. To assess the accuracy of the prospective groundwater zones, the area under curve (AUC) approach was applied. AUC is equal to 0.834, signifying the reliability of the result and the strong predictive capability of the AHP method. The result of this study supports the efforts to provide sustainable water sources for vulnerable communities of the study area.

***Keywords**: Groundwater Potential Zones, GIS, Analytical hierarchy process, Weighted overlay, Dawa Basin,*

1. INTRODUCTION

1.1. Background of the Study

Groundwater is one of the most vital natural resources stored in the subsurface geological formations in the critical zones of the earth's crust and a dependable water source for drinking and household use because of its accessibility and availability (Andualem and Demeke, 2019b). Overall, 2.53 billion of the world's population live in areas severely water-stressed, and around 1.5 billion rely on groundwater (Das et al., 2021). As the demand for drinking water increases globally for human consumption and agricultural and industrial uses, the need to evaluate the groundwater potential and productivity of aquifers also increases (Faria et al., 2022). Region-specific hydrogeological and geological factors influence groundwater availability and distribution. Controlling factors such as lithology, soil properties, landforms, and lineaments influence groundwater movement and occurrence. Additionally, land use/land cover types, slope, rainfall amount and intensity, and infiltration rates contribute to groundwater occurrence and, to some extent, the volume of recharge (Abdul Athick and Shankar, 2019; Abdulkerim et al., 2022; Abdullahi et al., 2023; Genjula et al., 2023; Ndhlovu and Woyessa, 2021). In semi-arid drought-prone regions, mapping and effectively managing groundwater resources are essential to mitigate observable water shortages. Ineffective resource management and uncontrolled population expansion influence groundwater quantity and quality in developing nations like Ethiopia (Andualem and Demeke, 2019a; Fentahun et al., 2023; Kawo and Karuppannan, 2018). Furthermore, in Ethiopia, a complex litho-structural framework and diverse topography and climate results in significant hydrogeological heterogeneity, making predicting aquifer productivity much more difficult (Alemayehu and Bewket, 2016).

Mapping and identifying potential groundwater areas is essential to efficiently manage, develop, and allocate water resources for various sectors, including drinking, irrigation, industry, home usage, and conservation. Various techniques and technologies are applicable for mapping groundwater zones and associated characteristics. Recently, geographic information systems (GIS) and remote sensing (RS) combined with the Analytical Hierarchy Processes (AHPs) approach have been widely employed to determine potential groundwater zones. Remote sensing provides repeatable, affordable, temporal, and spectral data over large and remote locations (Andualem and Demeke, 2019a). The accuracy of GIS and RS-based AHP methods for groundwater potential zone mapping is generally considered high compared to other groundwater mapping techniques. This is because AHP integrates multiple factors and their weights in a systematic manner, which helps reduce the uncertainty associated with groundwater potential mapping (Arulbalaji et al., 2019a; Ngwijabagabo et al., 2023; Senapati and Das, 2022).

The study area, upper Dawa, experiences year-round water scarcity, particularly in its lower regions, due to uneven distribution of surface water, unpredictable rainfall patterns, and climatic variability. Even in its upper reaches, groundwater resources still need to be developed due to lack of a detailed knowledge regarding groundwater occurrence and distribution. Particularly in the lower half of the study area, there is a critical shortage of drinkable water for humans and cattle, which causes the latter to perish during the severe dry season (FAO, 2021). Women and children have been forced to travel several kilometers to get water for drinking and household purposes. Many negative consequences and humanitarian problems (such as diseases, economic loss, poverty, food insecurity, hunger, disrupted socioeconomic development, environmental instability, etc.) arise when people encounter water scarcity in the area. For example, approximately 68,000 animals have died, and over 1 million animals have been in poor condition due to the impact of consecutive droughts in the previous years (FAO, 2021). The poor outlook of the current rainfall will result in more loss of animals and livelihoods. Therefore, it is critical to carry out studies to investigate additional water resource reserves in the area.

In the basin, particularly in the lower part, people and animals largely rely on rainwater. However, the summer has lacked precipitation, and all surface water bodies remain dry. Moreover, most bore wells seem either dry, do not generate enough water to meet demand, or are not evenly distributed to be accessed by all. A map of potential groundwater zones is ideal for sustainably utilizing available water resources to address the problem of water shortage in the area. However, before the present study, the groundwater potential zone was not explicitly mapped in the upper Dawa River basin, in Southern Ethiopia. Literature assessment shows the study area is less investigated relative to the other parts of Ethiopia, likely due to its remote location.

Few regional hydrological and hydrogeological studies have been conducted in the area (MoWR, 2007; Woldemariyam and Ayenew, 2016) and these studies showed the basin's water resources potential and hydrology are governed by litho-structural framework and rainfall amount and distribution, with most rivers originating from highland areas. Further, Kassahun and Mohamed (2018) have characterized groundwater potential for the Genale-Dawa basin, where upper Dawa is located, using 3-D numerical modeling, estimating replenishable groundwater and hydrogeology based on hydraulic conductivity. The impact of land use/land cover change and climate change on water resources have been studied in the Awata watershed, which is one of the watersheds in the upper Dawa River basin (Shigute et al., 2022). These studies were regional type and not detailed enough to curb the significant challenges related to water scarcity and drought, highlighting the need for further research to better understand and manage its water resources.

This study aims to use a GIS-based AHP approach to map potential groundwater zones, a method never been applied in the study area. By incorporating various factors influencing groundwater recharge, occurrence, and movement, such as geology, lineament density, slope, land use/land cover, drainage density, soil types, and rainfall, this study hopes to provide a comprehensive understanding of the groundwater potential zonation in the area. The results of this study will not only contribute to the scientific community but also support efforts to provide sustainable water supply for the vulnerable communities of the study area, making a tangible difference in their lives.

1.2 Statements of the Problem

The Upper Dawa River basin, specifically the drought-prone areas in the Genale Dawa basin, is highly susceptible to drought events. In the study area particularly in the lower half, there is a lack of drinkable water, both for humans and livestock resulting in dying of livestock during extreme dry season. Many negative outcomes and humanitarian crises, (such as illnesses, economic loss, poverty, food insecurity, hunger, disrupted socioeconomic development, environmental instability, etc.) are inevitable when humans suffer water shortage. In the study area life of the population depends on water from erratic and unpredictable rainfall for both agricultural activities and livestock production. Consequently, the availability of water for domestic water supply has become scarce in the area, particularly, during drought periods. The lack of thorough understanding of the spatial distribution and variability of groundwater potential exacerbates the vulnerability of communities and ecosystems to drought impacts. In previous times, investigations have been undertaken in the area to identify the potential of water resources based on a numerical groundwater model approach (Kassahun and Mohamed, 2018). To use existing water resources sustainably to fulfill population demands, mapping groundwater potential zones is essential. Even though different regional/reconnaissance and patchy hydrogeological works, e.g., Gragn et al., 2019; Kassahun and Mohamed, 2018, were conducted in one way or another in the study area, However no assessment and detailed mapping of the groundwater potential zone has been made in the upper Dawa River basin using GIS-based analytic hierarchy process (AHP) techniques, do so far, However, there is a high need for groundwater development and exploitation in the study areas. Nonetheless, the groundwater potential in the study area is not well understood. Because of this scarcity of water, the communities themselves use surface water and hand-dug boreholes for the matter of existing in their life, while hand-dug boreholes can be a valuable resource in certain contexts, their limitations in-depth, susceptibility to contamination, sedimentation issues, seasonal variability, and maintenance challenges significantly hinder their effectiveness in hard rock and arid to semi-arid climates. Moreover, Groundwater systems have been considered to be the cost-effective technologies for population management in the area since no treatment of the water was required as that of surface water.

1.3 Research Question

This research work is expected to answer the following research questions:

- Where is the most promising area for groundwater development?
- What are the controlling factors that govern the occurrence and movements of groundwater?
- Which controlling factors highly contribute to groundwater potential in the study area and why?

1.4 Objectives

1.4.1 General Objectives

The main objective of this study is to identify and map groundwater potential zones to contribute to the effort of future groundwater development in the study area.

1.4.2 Specific Objectives

- To identify groundwater potential zones in the study basin.
- To identify controlling factors that govern the occurrence and movements of groundwater.
- To determine the extent/ degree to which determinant factors affect groundwater distribution and occurrence of the study areas, as well as how they relate to one another.

1.5 Significance of the Study

This study will be beneficial to the clarity and further research in the area:

- The study increases the success of water well drilling and identifies suitable sites for water well drilling in the study area.
- It is applicable in providing future groundwater potential information depending on that information, the water scarcity problem of communities in the area can be protected and the adverse effects of drought can be minimized.
- The study will serve as input for disaster management, planning, and related water scarcity problems.
- To provide systematic recommendation measures to overcome the prolonged drought.

1.6 Outcomes

The expected outcome for mapping groundwater potential zones using GIS-based analytical hierarchy processes (AHP) techniques in the upper Dawa River basin, Southern Ethiopia, is the identification of areas with high, moderate, low, and very low potential for groundwater recharge. This can be achieved by integrating various thematic layers, including geology, rainfall, slope, soil types, elevation, drainage density, land use land cover, and lineament density, and applying the AHP method to determine the weights of each layer. The GIS-based overlay analysis was then used to produce a map of the groundwater potential zones. Especially in areas that are prone to drought, this knowledge may be utilized to create sustainable groundwater management plans. It can also help in the planning of water supply systems, irrigation systems, and other water-related infrastructure projects.

1.7 Study Limitations and Challenges

The work is limited in its spatial and temporal scopes. The main obstacles for this study are:

- Since the study area is characterized by complex geological and structural setup and also limited data availability with harsh climatic conditions, Inaccessible and difficult to collect field data, but all efforts were made to conduct the research work.
- The lack of pre-existing data related to the present study is one of the limitations that may reduce the quality of the research.
- Geological mapping is done with a limited field observation supported by interpretations of satellite imageries and topographic maps.

1.8 Organization of the Thesis

The current thesis study was arranged as follows, with five major chapters: The statement of problem, goals, scope, significance, and introduction are all covered in the first chapter. This chapter reviewed, based on several types of literature, the current state of groundwater occurrence worldwide, in Ethiopia, and the research area. Furthermore, the problem that required the study was stated and was based on the issue that is present in theory, practice, and literature. The literature review is covered in chapter two. This chapter provides an overview of the literature that is relevant to the current research title and serves as a quick reference for the many theories supporting groundwater potential zones and groundwater potential mapping techniques. The location, physiography, climate, and geology of the study area are all covered in detail in the third chapter. While using geographic information systems (GIS), remote sensing, and integration of geographic information systems and remote sensing for groundwater potential mapping were discussed and the methods and materials, data source, data collection, data preparation, AHP techniques, and basic methodological processes are covered in the fourth chapter. The present study's data analysis methodology, the analysis's outcome, and its interpretation from the standpoint of a literature review or discussion section are all covered in the fifth chapter. This chapter introduced the thematic data layer maps and the data analysis process. The sixth chapter provides direction for future study as well as recommendations and discusses the work that has been completed. This chapter outlines the research, extra model, and data required for increased groundwater potential mapping.

2. LITERATURE REVIEW

2.1. General

Groundwater potential zones are regions around significant and commercially viable groundwater resources (Mandel and Shiftan, 2012). The presence of groundwater in rocks and soil is determined by the hydraulic conductivity of these materials, which is a result of the fluid's capacity to pass through the geologic formations and its porosity and permeability (Owolabi et al., 2020a). For groundwater development, it is therefore thought to be essential to identify the water-bearing structures and stratigraphic stratum with substantial hydraulic conductivity. The assessment of water resource reserves, zone budgeting, water quality protection, vulnerability mapping, and environmental management all depend on the mapping groundwater potential zones.

Advancements in technology have significantly enhanced groundwater exploration techniques. Recently, progress in geoscientific knowledge, along with improved data access and processing, has facilitated the regional exploration of groundwater potential areas. Because of the development of multi-criteria decision-making, in particular, the strong awareness obtained by geospatial technology for GWPZ mapping has enabled substantial improvement (MCDM) statistical classifier (Machiwal et al., 2011). Some of the statistical tools include the weight of evidence, evidential belief, weighted overlay (Anshul Sud, 2021) multi-influencing factors (Anbarasu et al., 2020), analytical hierarchical process, (Pourghasemi et al., 2020), logistic regression and frequency ratio (Benchelha et al., 2019). The analytical hierarchy process, or AHP, is one of the several techniques for assessing groundwater potential that has gained the most traction recently around the globe. The most effective multi-criteria decision-making technique has been determined to be the analytical hierarchical process (AHP), which makes mapping groundwater prospective regions with GIS-based AHP systematic and useful.

2.2 Techniques Used for Groundwater Potential Zone Mapping

2.2.1 Analytical Hierarchy Process (AHP) approach

Many researchers have used the analytical hierarchy process (AHP) method to identify groundwater potential zones and geohazards in hard rock and drought-prone locations. AHP is a multicriteria decision-making technique that ranks and evaluates different elements or criteria according to their relative relevance. Through AHP analyses, the weights and ranks of selected thematic and sub-thematic layers are calculated to establish their order of relevance. The weighted linear combination approach involves superimposing all chosen controlling elements to find possible groundwater zones. In AHP, the consistency ratio is defined as CR where $CR = CI/RI$, $CI = \lambda max – n / n -1$, Where CI stands for consistency index, λmax is the principal maximum eigenvalue, and n for the number of thematic layers, RI is the constant value depends on the number of selected parameters. Pieces of literature that provide information on groundwater potential are described below.

Dar et al., (2011), carried out research utilizing geospatial technologies to map GPZs in Southern India's hard rock terrain. By combining many layers of geospatial data, the study sought to pinpoint regions with significant groundwater potential. The study incorporated factors such as lithology, lineament density, slope, drainage density, and rainfall patterns. GIS was employed to superimpose and analyze these spatial data layers, enabling the identification of potential groundwater recharge zones. The research concluded that geospatial technology is effective in mapping GPZs and can support the management of groundwater resources in areas with hard rock. In the Kancheepuram district of Tamil Nadu, South India, hydro-geomorphological mapping employing remote sensing and GIS has been used to evaluate groundwater possibilities. According to Kamel and Hafez, (2021); Pande et al., (2021) GIS, Remote Sensing technology, and AHP play crucial roles in groundwater recharge planning, mapping, and sustainable watershed management and are primarily influenced by geologically linked characteristics. Kamel and Hafez, (2021); Pande et al., (2021) conducted a study on groundwater recharge planning using GIS, RS technology, and AHP. The study identifies the groundwater controlling factors, high potential areas, and validation techniques. They emphasized the importance of incorporating geological-related parameters into the mapping process. Their research highlighted the significance of lithology, soil type, land use land cover, and topography in understanding groundwater recharge dynamics. GIS and RS techniques were utilized to acquire and analyze spatial data, while AHP was used to assess the relative significance of various characteristics. The study concluded that integrating these technologies can enhance groundwater recharge planning and management. Kumar et al,. (2018), have mapped the possible groundwater zones in dry and semiarid areas using satellite data and GIS technologies. Another advantage of remote sensing and GIS information systems is their ability to integrate analog and digital data sets. Various thematic layers (i.e. Geology, lineament, lineament structure, drainage density, slope, rainfall distribution, land use classes, and soil types) were prepared using the remote sensing data along with the existing maps. Different classifications are distinguished based on the basin's groundwater availability (i.e., very good, good, moderate, poor) based on its hydrogeological conditions, finally recommended MCDA and GIS techniques as powerful methods in groundwater potential mapping in areas characterized by arid to semiarid climate and hard rock regions. Tolche et.al, (2021), stated that geospatial technology can be used to map groundwater potential. A study conducted in Ethiopia using Remote sensing and GIS techniques to assess groundwater potential mapping at Dhungeta Ramis sub-basin, the study used seven groundwater occurrence and movement controlling factors, including lithology, slope, LULC, rainfall, lineament, soil, and drainage density to map groundwater potential of the sub-basin. AHP models were utilized to apply weight to a thematic map, and the sub-basin's groundwater prospective was qualitatively categorized into five groups, namely very good, good, moderate, poor, and very poor. The map produced by this method might serve as a first guide for choosing appropriate locations for the exploitation of groundwater resources. The result also cross-validated using spring, hand-dug, and deep well data. Murthy and Mamo, (2009); Stated that the application of multi-criteria decision evaluation techniques in groundwater zone identification in the Moyale-Teltele sub-basin, South Ethiopia. The criteria considered include geological formations, hydrogeological characteristics, land use patterns, soil types, and topographic features. By assigning weights to each criterion by using AHP techniques based on their relative importance, researchers have generated thematic maps indicating groundwater potential zones. By combining various criteria such as hydrogeological parameters, land use land cover, soil characteristics, topography, and rainfall, researchers have successfully identified and mapped groundwater potential zones. The use of these techniques provides a systematic and objective approach to groundwater assessment, aiding in sustainable water resource management. Addressing challenges related to data availability, criteria weighting, and stakeholder involvement is crucial for the effective application of multi-criteria decision evaluation in groundwater zone identification. Further research and implementation of these techniques will contribute to improved groundwater management in the study area and beyond.

The reviewed studies highlight the effectiveness of integrating, GIS-based AHP techniques for mapping groundwater potential zones. These methodologies allowed for the assessment and integration of various factors influencing groundwater potential, resulting in the identification of areas with very good groundwater potential. The similarities among the studies demonstrate the consistency and reliability of these techniques for groundwater resource management. By utilizing GIS-based AHP, researchers and water resource managers can gain valuable insights into groundwater potential and make informed decisions related to groundwater planning and management.

2.2.2 Application of Remote Sensing and Geographic Information System (GIS) for Groundwater Potential Zone Mapping

In areas with little or inconsistent rainfall and a climate that is defined by an overall dry to semiarid region, remote sensing data and GIS techniques can be an effective way to map the groundwater potential zones. The most complicated aquifers are found in the Precambrian basement; they are divided and have comparatively low storage levels, which may be related to the complex geological past (Mézquita González et al., 2021). Thus, it takes a lot of time and money to explore groundwater using traditional methods. Some studies focused on accessing the groundwater potential of the Blue Nile (Melesse and Abtew, 2015). Groundwater resources in and surrounding portions of Ethiopia's southern area have been evaluated using GIS, as described by (Teka et al., 2020b). Andualem and Demeke, (2019b) evaluated the groundwater potential in the Guna Tana landscape of the upper Blue Nile basin by investigating and analyzing soil, geology, slope, drainage density, and lineament density.

2.2.3 Integration of GIS and Remote Sensing for Groundwater Potential Mapping

Many scientific fields, including environmental research, geohazard mapping, and groundwater exploration, use GIS and remote sensing techniques. Information on natural resources and changes that occur on Earth is timely and helpful when GIS, remote sensing, and GPS are integrated. Additionally, geospatial technology integrations may analyze and assess location-based data to identify possible areas. Through the evaluation, manipulation, and analysis of geospatial data, this approach is essential for mapping, detecting, and monitoring groundwater potential. Aerial pictures are frequently employed in groundwater potential mapping, according to a survey of a few studies on the subject employing RS data (Khalil et al., 2015). Several groundwater potential mapping, methods such as decision tree model, weighted overlay, AHP, and physically-based groundwater potential models are GIS and remote sensing-based models to map groundwater potential (Rehman et al., 2024; Tamiru et al., 2022). Studies that assess groundwater potential using GIS and RS methodologies varied greatly in the kind, quantity, and choice of thematic layers. Moreover, the majority of research has used subjective judgments to assess different themes and their attributes. Several studies have demonstrated that multi-criteria decision-making (MCDM), which offers structure, auditability, transparency, and rigorous judgment, can enhance the management of water resources (Kabir et al., 2014). AHP is a method for evaluating and prioritizing several difficult decisions and figuring out which elements are more or less important. This approach is well-known and suitable for complicated decision-making (Gebeyehu et al., 2023). The efficacy of these models was assessed using the available data. While other traditional methods work well and are dependable, they are expensive and require a lot of effort. Conversely, AHP is more economical, efficient, and cost-effective (Lozzi et al., 2020; Thengane et al., 2014).

2.3 Previous Work

A range of studies have explored the geology of Southern Ethiopia, particularly of the basement terrain, thanks to the anticipated mineral and petroleum potential in the region. The geology of the basement terrain of the study area is studied and mapped at the scale of 1:250,000 by the Geological Survey of Ethiopia (GSE) as well Tadesse et al., (2003). Individual investigators (Billay et al., 1997; Lewte, 2011; Waktola Merera, 2021; Yibas et al., 2002, 2003) have also examined the geology of a few locations in the study area's basement terrain.

The research area's volcanic rocks, which are a component of Ethiopia's trap series, were examined by (Berhe et al., 1987; Getaw and Fontijn, 2023; Philippon et al., 2014; WoldeGabriel et al., 2000). It has been determined that these geological investigations are crucial for understanding geological development and for creating the basin's geological map. On the other hand, only a few studies are available focusing on groundwater resources and related hydrogeology. Ayalew and Nigussie, 2023; Gragn et al., 2019; have investigated the hydrogeology of certain locations in southern Ethiopia, which encompass portions of the upper Dawa River basin; the wider regional work, the Genale-Dawa integrated River basin master plan study, covers the entirety of the study area (Integrated et al., 2007). These studies focused on evaluating groundwater potential using a qualitative assessment of rocks and characterizing water quality from the perspective of water consumption. The study area's volcanic rocks and basement complexes have subsequently been roughly categorized into zones with high to moderate and low groundwater potential, respectively. Gragn et al., (2019) assessed the influence of climate change on the water resources of the Awata River Watershed in the same basin.

Multiple studies have investigated the geology of Southern Ethiopia's basement terrain and volcanic rocks (part of the Ethiopian trap series) at a scale of 1:250,000, motivated by the area's mineral and petroleum potential. These geological investigations are crucial for understanding geological development and for creating the basin’s geological map. Studies focusing on groundwater resources and related hydrogeology are also available. These studies have assessed groundwater potential and water quality, categorizing volcanic rocks and basement complexes into zones with varying groundwater potential.

Recently, Woldemariyam and Ayenew, (2016), have characterized the groundwater flow system in the basin using isotope and hydrochemistry as a tool. Though these studies collectively provided valuable insights into the geology and hydrogeology of the study area the available hydrogeological knowledge of the study area is inadequate for a detailed understanding of groundwater occurrence and site-specific water resources development. There will likely be a greater need for groundwater as a result of future population expansion, the drilling of additional water wells, and the shift from a nomadic way of living to an agriculturally oriented economy, thus mapping groundwater potential zones in more detail is essential in this region.

2.4 Identification of Factors Influencing Groundwater Occurrence, Movements and Distribution

Based on existing literature, field investigation, and, expert knowledge about geological and hydrogeological characteristics of the study area, to some extent data availability, seven (7) groundwater potential impacting factors were chosen: geology, lineament density, land cover, slope, drainage density, soil texture, and rainfall. Groundwater potentiality was taken into consideration while creating and interpreting the maps of these thematic layers. The ArcGIS software version 10.8 was utilized to compile the necessary data, which was obtained from pertinent sources to create these thematic layers. The following section describes how the above-mentioned seven selected thematic layers control the groundwater occurrence and movement.

2.4.1 Lineament Density

The presence of groundwater in hard formations is primarily regulated by fractures and lineaments (Deyassa et al., 2014), while the presence of groundwater in sedimentary and volcanic formations is mainly regulated by porosity and permeability (Sruoga et al., 2004). Lineaments are naturally occurring fractures, joints, and faults that are easily seen from satellite pictures due to their generally linear alignments. Increased secondary porosity and permeability are the result of faulting and fracture zones, which are represented by lineaments (Rasool et al., 2020). As a direct or indirect representation of the groundwater moment, lineaments are naturally occurring permeable layers. It indicates that there is good groundwater potential if lineament is present.

In non-porous rocks, groundwater is concentrated in the crevices, cracks, and fractures. The depths are severely limited. There are distinct zones for groundwater flow, and well production varies greatly.

2.4.2 Drainage Density

The percolation of water from the precipitation into groundwater depends on the presence of streams. There is an inverse relationship between drainage density and groundwater potential (Ajay Kumar et al., 2020). The drainage pattern of the study area can be extracted from the Shuttle Radar Topography Mission (SRTM) Digital elevation model at a spatial resolution of 30 * 30 m spatial resolution using the Arc hydro spatial analysis tool. The drainage density map refers to the total length of rivers/streams per unit area.

2.4.3 Soil Texture

Soil types also affect groundwater potential, as the soil determines the rate at which water infiltrates the ground through the seepage of rain or snow, recharging the aquifer. Therefore, the preparation of the soil map is the main concern while assessing the area's possible groundwater zones. It also impacts groundwater potential, as soil dictates how quickly water infiltrates the ground through the seepage of rain or snow, replenishing the aquifer (Kormos et al., 2015). Nonetheless, the kind of groundwater circulation and occurrence in the region is determined by the existence of various soil types. The study area's observed soil type possesses distinct soil features and coverage. The hydrology of soil depends on the textures of rocks and the degree of fracturing and weathering.

2.4.4 Geology

Identifying the lithological types and characteristics is crucial for successfully selecting potential groundwater zones (Rajasekhar et al., 2018). The interplay between subsurface geology and surface features creates a complex system that governs groundwater availability. Effective management requires a comprehensive understanding of these factors to ensure sustainable use of this vital resource. By considering geological characteristics alongside hydrological dynamics, stakeholders can better address challenges related to water scarcity and quality in various regions. These geological features govern how groundwater is stored in aquifers. A geologic formation's porosity and permeability reveal how well it can hold and transfer water inside the aquifer. Geological materials with high permeability are indicative of groundwater recharge. The aquifer's interconnecting internal pores and fractures allow water to flow through it.

2.4.5 Slope

The slope is a critical factor that quantifies the degree of angle of inclination in a given region and is vital to understanding groundwater potential (Gebre et al., 2015). The slope offers crucial information on the features of the local geology and the geodynamic mechanisms controlling the occurrence and distribution of groundwater. The surface's slope greatly affects both the rate of infiltration and surface flow (Gebre et al., 2015). The slope of the land is a critical factor that land managers and hydrologists must account for when assessing and managing the partitioning of water between surface flow and subsurface infiltration. Understanding this relationship is key to effective water resource planning and soil conservation.

2.4.6 Land Use Land Cover

LULC affects surface and groundwater resources, due to rugged terrain and steep gradients, increases the rate of soil erosion and land degradation, and finally limits groundwater recharge. In a basin, LULC is one of the main variables affecting hydrologic features including runoff, evapotranspiration, and surface erosion. LULC regulates the quantity, timing, and volume of groundwater recharge. Additionally, it influences evapotranspiration and runoff (Guzha et al., 2018). The presence of impermeable structures prevents the infiltration of rainfall into grounds, and finally limits the recharges, Therefore Understanding this relationship is key to effective water resource planning and soil conservation.

2.4.7 Rainfall

Groundwater availability in a particular location is influenced by rainfall. Therefore, rainfall mapping is required to properly assess the possible groundwater zone. One of the various thematic levels used to identify possible zones for groundwater is rainfall. Indeed, it is the main source of naturally occurring groundwater recharge that aids in the growth of groundwater resources. The volume and timing of rainfall determine the rate at which groundwater recharge occurs (Teka et al., 2020a; Andualem and Demeke, 2019a). Long-duration, low-intensity rain produced a higher rate of groundwater recharge than runoff.

3. DESCRIPTION OF THE STUDY AREA

3.1 Location of Study Area

The Upper Dawa River basin is located in the Southern part of Ethiopia, bounded by latitudes 4.72–6.36° N and longitudes 38.52–39.524° E (Figure 1). It covers a total area of 29,905 km^2. It is bounded to the west and northwest by the Rift Valley and to the north by the Bale Highlands. The landscapes of the Northern parts of the study area were highland, whereas the landscapes of the Southern and eastern parts of the study area characterized were dominated by lowlands. The study basin is bounded by the Wabe Shebelle River basin in the eastern part.

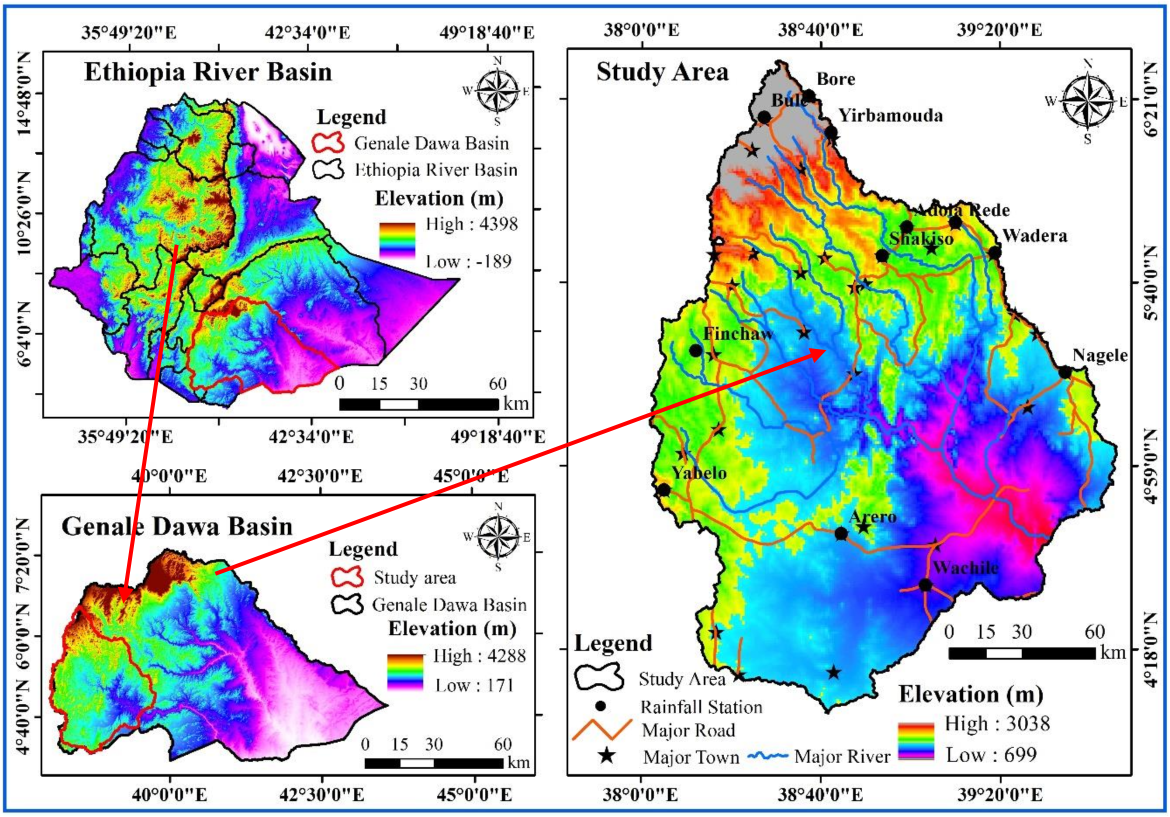
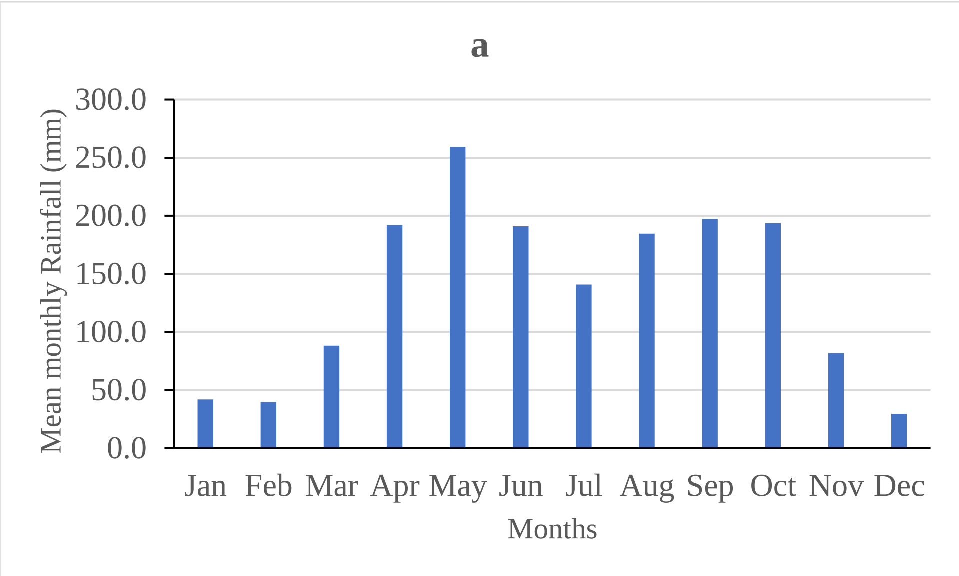


Figure 1: Location Map of Upper Dawa River Basin

3.2 Climatic Condition

The study area is divided into three regions: the north, center, and southeast have humid, semiarid, and arid climates, respectively. The lowlands are characterized predominantly by semi-arid while highland areas are characterized by humid climate conditions. The average yearly rainfall is around 1680 mm in the northern end and 490 mm in the southern end. With the highest and lowest rainfall peaks occurring in April to May and January to February, respectively, the rainfall displays a bimodal pattern (Figure 2). The presence of a bimodal rainfall pattern can vary depending on the specific location and climate conditions. The bimodality nature is increasing from highland to lowlands and clear bimodal nature is seen in lowland areas (Figure 2c) The long-term mean annual temperature is 15.5 °C above 2000 m.a.s.l and 28 °C above 600 m.a.s.l. Temperature ranges for the annual mean minimum and maximum are 6.9 to 16.2 °C and 18.9 to 27.7 °C, respectively. The basin is mostly characterized by humid, arid, and semi-arid climatic conditions, has irregular rainfall, and is prone to droughts. There are two distinct rainy seasons: April to May and September to October. These alternate with two dry seasons from January to February and from November to December, respectively, These are known as the short and long dry seasons.



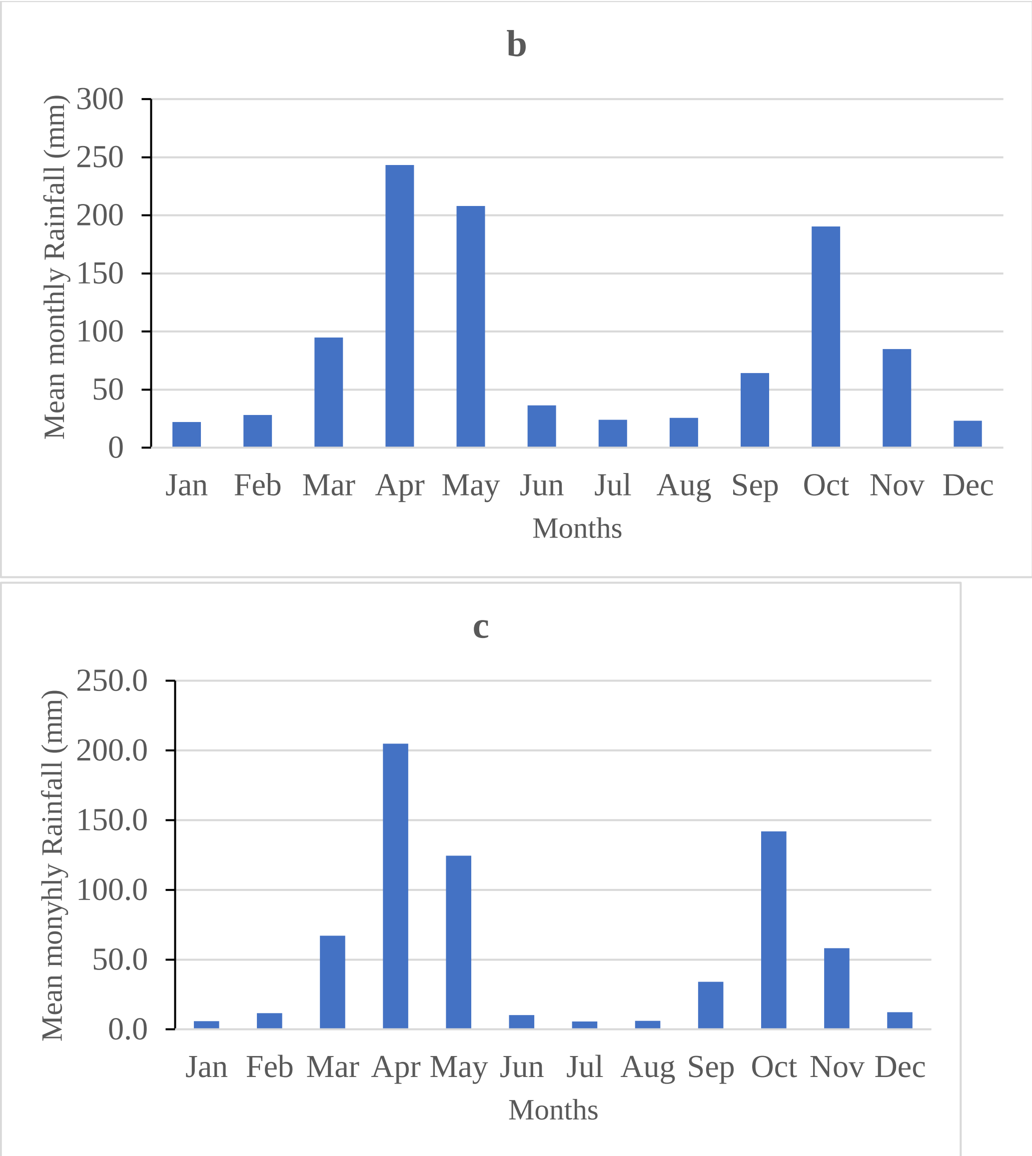


Figure 2: Bimodal Rainfall pattern (**a**) at Bore station, (**b**) at Shakiso station, (**c**) at Nagelle station

3.3 Soil Cover and Vegetation of the Study Area

The major soil type of the study area is sandy and sandy-loam textures (dark brown in color and reddish-brown soil) and its source is organic supplies and weathering products of rocks and plants. The vegetation of the study area is commonly characterized by; pasture (grass), medium trees with broad leaves, plant undergrowth, and small trees with thin leaves.

3.4 Physiography of the Study Area

The upper Dawa River basin is found in Ethiopia's southernmost region and is distinguished by a wide range of topographical features, including plains, steep gorges, plateaus with a flat top, and rocky, high mountains. The maximum elevation is 3038 m.a.s.l at the northwestern end and the minimum elevation is 702 m.a.s.l at the southeastern end (Figure 3). The basin can be defined in terms of lowlands with a gentle slope that is close to the floodplain and the base of the escarpments. The headwaters of the upper Dawa River are situated in the Sidamo highlands, which are progressively becoming lower in height to around 1500 meters above sea level near the western catchment border. The study area is a part of the highlands in Southern Ethiopia. In the southwest, south-central, and southeast, the topography is made up of leveled ground with sporadic hills, low-relief elongated valleys, and steep land next to the main river. In the northern and northwestern highlands, ridges and related gorges make up a large portion of the terrain.

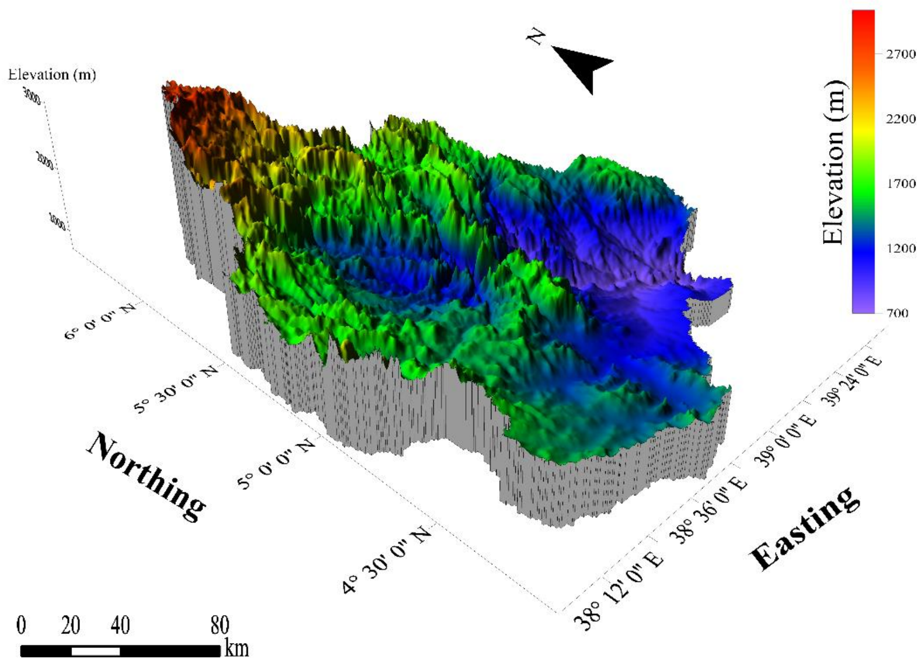


Figure 3: Three-dimensional physiographical map of the upper Dawa River Basin

3.5 Drainage Pattern of the Study Area

Dawa, Awata, Mormora, Welmel, and Dumal Rivers are major perennial rivers draining the area (Figure 4). Major rivers together with their tributaries form the upper Dawa drainage basin. Many of the streams, especially those in the dry and semiarid regions, provide water only during periods of intense precipitation because they rarely flood and the courses are primarily covered with alluvial deposits. Dawa, Awata, and Mormora are the three main tributaries that flow upstream from Melka Guba's main river gauging station.

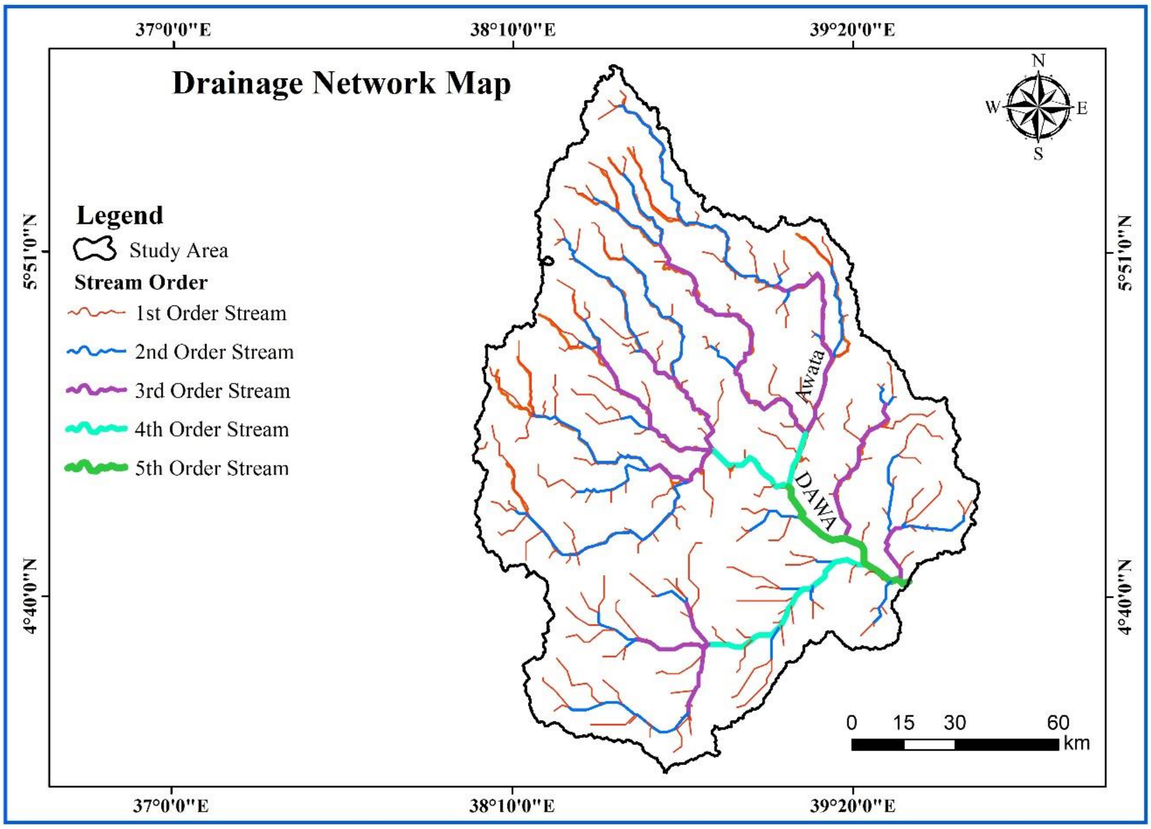


Figure 4: Drainage network map of upper Dawa River Basin

3.6 Regional Geology

3.6.1 Geological History and Stratigraphy

The upper Dawa River basin of Southern Ethiopia is distinguished by a complex geologic setting manifested via diverse lithology and structural framework, due to its location in the zone of numerous phases of volcano-tectonic processes (Woldehaimanot and Behrmann, 1995; Worku and Schandelmeier, 1996). During neo-proterozoic (870 Ma to 550 million years (Ma). Ocean closure, metamorphism, and consequent faulting and intrusion are the outcomes of the East Africa Orogeny, which was brought about by the collision of eastern and western Gondwana (Fritz et al., 2013; Stern et al., 2004). This geological event produced metamorphic complexes and associated plutonic rocks and structures in the basement terrain of the study region. The early breakup of east Gondwana resulted in a significant regional rifting event that began in the pre-Jurassic era. Ogaden Basin is formed in southern Ethiopia where the rift basin's branches meet during the breakup of Gondwana. The Mandera-Bodel rift is one branch of this rift system that crosses southern Ethiopia and enters northeast Kenya. The large-scale sinking of the whole Horn of Africa from the Triassic to Early Jurassic Period caused significant continental down-warping, and the Jurassic Sea gradually encroached upon the entire Horn of Africa. During the late Jurassic and early Cretaceous periods, the sea started to retreat. The Indian Ocean's transgression and regression are responsible for the large sedimentary rocks found in Southern Ethiopia.

The formation of the rift structure in East Africa, which has been linked to ongoing volcanic activity from the upper Oligocene to the present, is an important geological event that has greatly influenced the current geological structure of southern Ethiopia (Philippon et al., 2014). Volcanic rock distribution seems to be strongly associated with different stages of rift development, such as the doming and rift formation phases (Philippon et al., 2014). Similar to the continental flood basalts found elsewhere in the Ethiopian plateaus, the volcanic rocks of the southeast Ethiopian plateau are the product of pre-rift late Oligocene to mid-Miocene fissural eruptions (Philippon et al., 2014). The three main lithological terrains in the basin—volcanic, basement, and sedimentary—are exposed as a result of these geological events.

In terms of stratigraphy, the volcanic unit (basalt) unconformably overlies the basement units; this in effect facilitates the percolation of water downward to the base of the sequence. The presence of basement rocks at the base prevents further escape and enhances the accumulation of groundwater in volcanic aquifers. The contact between the two is usually marked by a variably thick paleo-weathering mantle that comprises a mix of sand, gravel, and silt. This can also considered potential aquifers if there is recharge.

3.6.2 Local Geology

3.6.2.1 Crystalline Basement Rocks and Plutonic Intrusive Rocks

The Central, Western, and Southwestern parts of the study basin are predominantly covered by crystalline basement rocks (Figure 5). These rocks, which date back to the Proterozoic era, encompass both high-grade and low-grade belts alongside pre-, post-, and syn-tectonic intrusives. The high-grade belt comprises gneisses, schists, and migmatite, occupying the lower litho-stratigraphic position. In contrast, the low-grade belts are primarily composed of meta-volcano-sedimentary rocks and mafic-ultramafic complexes.

Table 1: Summary of Precambrian rocks of upper Dawa River Basin (Zewdie and Sima, 2011)

Group	**Lithology**
Mormora Group	Quartz-graphite schist with intercalated marble and quartz-sericite schist (Pgs) Biotite-hornblende gneiss (pbhg) Quartz-biotite, quartz-sericite and garnet-staurolite-quartz-biotite schist (Pqbs)
Adola Group	Actinolite schist and actinolite-quartz-epidote schist (pcas) Talc, chlorite, tremolite-chlorite-talc, chlorite-actinolite and actinolite schists (Ptts)
Wadera Group	Quartzofeldspathic mylonite (pqfm)
Awata Group	Biotite-plagioclase-microcline-quartz mylonite (Pqkg)
Alghe Group	Biotite gneiss (pbg) Biotite-hornblende gneiss (pbhg)

3.6.2.2 Transitional to mildly alkaline and sub-alkaline Basalts and Rhyolites

This geological unit is exposed, in the study area's northernmost regions. It creates cliffs and exhibits fewer joints and cracks. Basaltic rock is found in the research region at high elevations, deposited on top of basement rocks. Because of its high elevation, the area's harsh topography, and its high transmissivity, the basaltic aquifer is distinguished by low storage characteristics. The olivine, pyroxene, and plagioclase make up its composition; the basalt is covered with rhyolites. A pink to light pink fresh hue is seen in the rhyolite due to its composition of little weathered quartz and k-feldspar exposed to cliff cuttings. This unit also contains trace amounts of trachyte and minor ignimbrites that cannot be mapped.

3.6.2.3 Aphyric and porphyritic basalt with lesser vesicular basalt, minor alkali trachyte flows, and tuffs.

This unit is exposed in the northwest of the study basin. Mostly dark and slightly weathered aphyric basalt that is visible on the hilltops makes up this material. The olivine-pyroxene phyric porphyritic basalt is fresh and dark gray, with little to medium weathering turning it into a light gray or light brown look. Cliffs are formed by the severely weathered, brown-colored smaller vesicular basalt. Pyroxene phyric basalt, olivine pyroxene plagioclase phyric basalt, aphyric basalt, and pyroxene phyric basalt are the components that make up this formation. Scattered trachyte outcrops are found in some areas, but they cannot be accurately mapped at this scale. There is an intercalation between aphyric and porphyritic basalt.

3.6.2.4 Biotite-quartz-oligoclase gneisses, amphibolites, and minor oligoclase-quartz microcline Gneisses

This unit is exposed in the western portion of the study basin. Well-banded amphiboles, quartz, feldspar, and less chlorite schist make up its composition. These rock units in the basin have different groundwater potentials depending on their porosity, permeability, fracture density, connectivity, and other geological properties that affect groundwater flow. The predominant rock type is leucocratic, predominantly fine-grained biotite-quartz-oligoclase gneiss, with a little coarse-grained variation. The main constituents are quartz, biotite, and oligoclase. Due to the presence of quartz and feldspar, this gneiss may have comparatively moderate to high porosity and permeability. As a result, it could be able to transfer and store groundwater. Amphibolite, which has fine to medium-grained crystals and generally occurs in bands, is another form of rock in this unit. These rocks typically have a dense and fine-grained texture, which may result in lower porosity and permeability compared to other rock types. However, the presence of fractures, veins, and other structural features within the amphibolites can enhance their permeability and provide pathways for groundwater movement (Gorbatsevich et al., 2010; Lachassagne, 2021).

3.6.2.5 Granite

The presence of these lithological units in the central part and small portions of the southeastern part of the study area can have implications for groundwater potential (Figure 5). Granite formations often exhibit low porosity and permeability, which means that they do not readily allow water to flow through them or be stored within their rock matrix (Boutt et al., 2010). However, fractures, joints, and other structural features commonly found in granitic and gneissic rocks can enhance their permeability and create pathways for groundwater movement. These fractures can act as conduits (Boutt et al., 2010), allowing water to flow through the rock mass and contribute to groundwater resources. The groundwater potential within the granite terrain in the study area would depend on factors such as the density and connectedness of fractures, the extent of rock weathering and alteration, and the topographic setting. Groundwater occurrence and availability in these formations are generally influenced by the interactions between the fractures and the surrounding hydrogeological conditions. Due to their poor porosity and permeability characteristics, the lower weight is allocated to the granite and gneisses units.

3.6.2.6 Melmel Limestone

Melmel limestone, which includes mudstone, pelletal oolitic grainstone, and alternating strata of wackestone, packstone, grainstone, and conglomerates, is found over a sizable portion of the eastern portions of the study basin (Figure 5). The main characteristic that distinguishes the Melmel succession is a clear angular unconformity. The primary textures are fossiliferous, dismicrite, and micrite. The alternating strata of grainstone, packstone, and wackstone are composed of yellowish-brown, massive, hard, fine-grained, horizontally bedded packstone to grainstone at the top, fine to medium-grained yellowish-white wackstone in the middle, and dull white to reddish-yellow packstone to grainstone at the bottom. The uppermost segment of the lower Melmel succession is distinguished by conglomeratic limestone that is strongly lithified, poorly sorted, reddish brown to pink, and has coarse to extremely coarse grains. It is fossiliferous, and the highly aligned fossils suggest a high-energy environment that may have been shallow marine. Moreover, the presence of angular interclasts of quartz silt further supports their proximity to the erosional surface.

3.6.2.7 Quaternary Sediments (Qa, Qe)

Quaternary sediments in the study area are predominantly found in flat terrains and along river channels such as Welmel, Genale, Dawa, Awata, and Mormora. These alluvial sediments range in size from fine sands to silty, clayey silty soils. Additionally, eluvial sediment, which originates mainly from the weathering of bedrock like limestone, forms residual deposits and they are not thick deposits. This unit is exposed in the southern end and small portions of the western part of the study area. The presence of alluvial deposits throughout the region suggests that there is a potential for groundwater occurrence within these deposits (Figure 5). The specific distribution, thickness, and connectivity of the different sediment types (clay, silt, and sand) within the alluvial deposits will influence the groundwater potential in the study area. From a hydrogeologic perspective, the quaternary alluvial deposit is a more transmissive and porous unit than the nearby rocks (Woldemariyam and Ayenew, 2016b), due to that reason we gave higher weight.

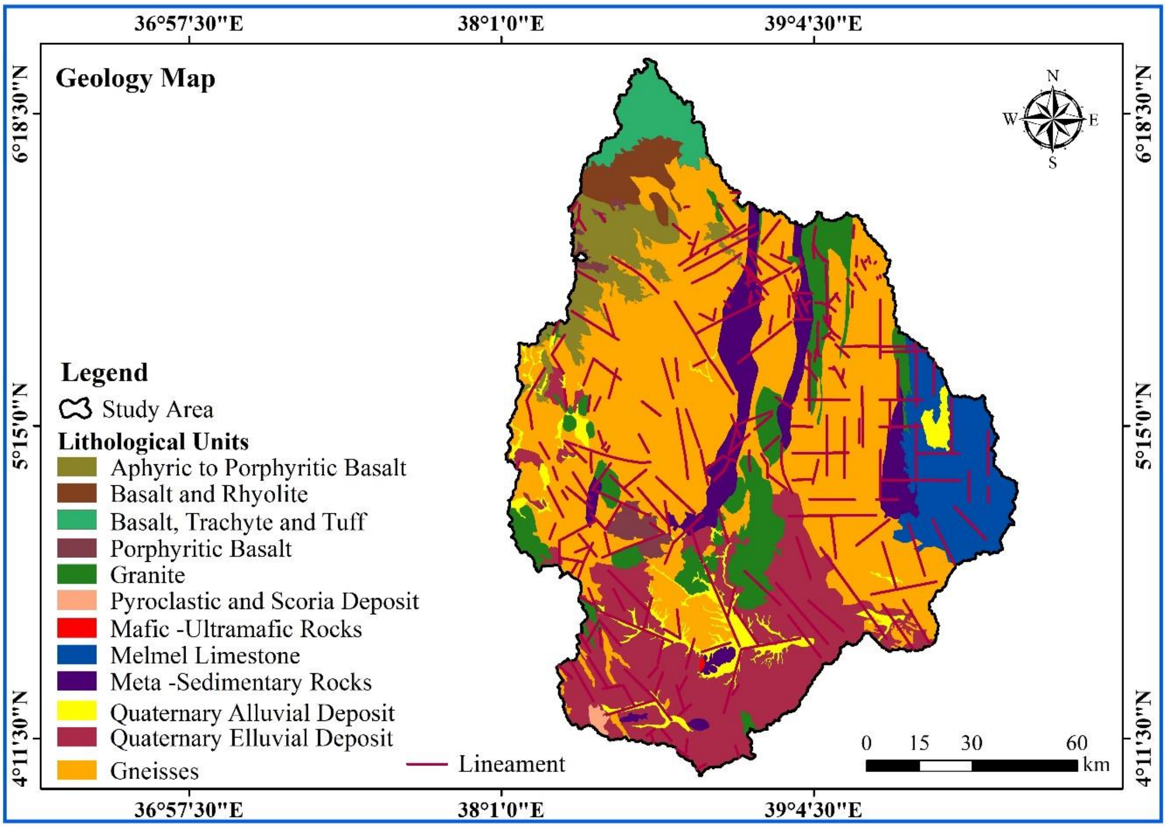


Figure 5: Geological map of the upper Dawa River Basin with structures

3.6.3 Geological Structures

The major structures that are visually interpreted and digitized from Genale Dawa's master plan study geological map are lineaments (Figure 5). These are structures that are shown up as linear arrangements of physiographic setup which are manifested as steep slopes or cliffs, elongated depressions, or valleys. These structures occur both on Precambrian rocks and volcanic rocks. Those structures in basement rocks may be associated with ductile-brittle deformation associated with metamorphism and deformation (Druguet et al., 2009). Those, found in volcanic (basalt) rocks however, are brittle deformations that have resulted in extensional structures such as faults and fractures. The lineaments have generally NW orientation with few in the SE direction and are relatively abundant on basement rocks. The various structures, such as folds, foliations, lineation, shear zones, faults, and lineaments, displayed in the uncovered crystalline basement area of the study area were developed throughout the progressive syn-orogenic (folding and thrusting) and post-orogenic (shearing) deformations. The variable size, shape, and orientation of these structures are attributed to the nature, style, and direction of deformations resulting, in the rheological character of the rocks subjected to deformation and crustal depth.

4. MATERIALS AND METHODS

4.1 Materials

Materials play a crucial role in conducting research to address various issues as they allow for the field collecting of data. The following resources were employed in this study: The essential field tools, including a sample bag, dip meter, GPS, Burton compass, topographic map, and geological hammer, and Microsoft Word and Excel, and also computer software programs such as ArcGIS software, IDRISI selva 17, ERDAS, and SPSS software are used. The used materials and their function are described in Table 3 below.

Table 2: Materials and Software used and their functions

Arc GIS 10.8	Integration of spatial and non-spatial data, thematic map generation, and layout preparation
IDRISI selva 17	To calculate pairwise comparison and weight for each thematic layer
Google Earth	Used as supplementary for accuracy of classification
GPS	For collecting of ground control points
MS Office	Documentation, statistical analysis
SPSS	Used for validation and visualization of result
Global mapper and Surfer	To prepare a 3D physiographic map

4.2 Methods

4.2.1 Data sources and descriptions

During this phase, various tasks essential for achieving the study's objectives were undertaken. Secondary materials and necessary information were collected from various institutions and sources. Below is a list of some of the things that were done during this time.

- Literature, articles, and websites related to groundwater and groundwater occurrences, both unpublished and published written materials, and maps were collected and studied to have a general background and a conceptual framework about the subject.

- Meteorological data was collected from the Ethiopian National Metrological Agency to acquire a good understanding about the climatic conditions of the study area.

- Geology data are acquired from the Geological Institute of Ethiopia (GIE) and used to generate lithology and lineament maps of the study area.

- A digital elevation model of the Space Shuttle Radar Topography Mission (SRTM-DEM) with a spatial resolution of 30 m was downloaded from the Earth Explorer website and subsequently used to generate elevation, slope, and drainage density, and a detailed literature review also part of the desk study.

- Soil properties like soil textures and soil types were acquired from the Ministry of Agriculture, Irrigation, and Energy of Ethiopia and used to generate a soil texture map for this study.

- Landsat 8 OLI/TIRS 2023 was downloaded from Earth Explorer (https://earthexplorer.usgs.gov/) for the classification of Land use land cover types.

- Rainfall data acquired from the National Meteorological Agency of Ethiopia was used to generate a rainfall map of the study area by using inverse distance weighting (IDW) techniques in ArcGIS.

Table 3: An overview of the data sources utilized in this study

Parameter	**Data source**
Precipitation	National Meteorological Agency of Ethiopia, Addis Ababa
Temperature	National Meteorological Agency of Ethiopia, Addis Ababa
Land use land cover	Landsat 8 OLI /TIRS (https://earthexplorer.usgs.gov/)
Soil properties	Minister of Agriculture, Irrigation, and Energy of Ethiopia
Well yield	Guji and Borena Zone Water Bureau
Drainage and Slope	From 30*30m resolution DEM
Wind speed, Relative Humidity, and sunshine hour	National Meteorological Agency of Ethiopia, Addis Ababa
Geological data 1:250,000 scale	From the Geological Institute of Ethiopia (Compiled from the existing work)

4.2.2 Field Investigation

The geology and hydrogeology of the study area were assessed using both qualitative and quantitative parameters. Important qualitative parameters were derived from physical observations and descriptions of the nature of geological materials, and degrees of weathering or fracturing. Field investigation was done to collect different kinds of primary data such as describing the nature of geological materials, structural information, and degree of weathering and confirm controlling factor maps made from secondary data sources. The following tasks were completed as part of field investigations:

- Geological materials of the study area were identified.
- Surface manifestations of groundwater (springs) were recorded and documented.

4.2.3 Data Interpretation and Analysis

The data were methodologically organized and evaluated utilizing existing techniques and computer programs after the collection of data from field observations and desk study. The results were validated using receiver operating characteristics and area under curve. In the present study, seven determinant factors like soil properties (soil texture and types), slope, lineament density, drainage density, Lithology, and LULC were selected based on their relative importance.

4.2.3.1 Geology

Identifying the lithological types and characteristics is crucial for successfully selecting groundwater potential zones (Rajasekhar et al., 2018). The subsurface and surface geology of a region determines the availability, flow, and distribution of groundwater. The geological map of the study area was digitized from Nagelle (NB 37- 11), Dilla (NB 37-6), Bule Hora (NB 37-10), Wachile (NB 37-11) and Yabello (NB 37-14) geological map sheet, thereby the geological map was prepared in ArcGIS, and transformed into significant lithological units by taking in to account their hydrogeological relevance and validation were performed during field works. There are different lithological types in the upper Dawa River basin. These lithological units were classified into different classes based on their hydrogeological properties.

The units like basalt and aphyric to porphyritic basalt and alluvial deposit were excellent and good, respectively, for assessing groundwater potential. In addition, melmel limestone, granite, and gneisses were categorized under moderate and low, respectively, while quaternary elluvial deposits, mafic to ultramafic rock, and metasedimentary were classified under very low groundwater potential zones.

4.2.3.2 Lineament

The presence of groundwater in hard formations is primarily regulated by fractures and lineaments and in pores of sedimentary formation (Deyassa et al., 2014). Lineaments are natural features such as faults, joints, and fractures, easily identifiable in satellite images due to their linear alignments. They indicate fractured and faulted regions that have more secondary porosity and permeability because they act as conduits/pipelines for groundwater movement (Rasool et al., 2020). The lineament of the study area was digitized from Nagelle (NB 37-11), Dilla (NB 37-6), Bule Hora (NB 37-10), Wachile (NB 37-11), and Yabello (NB 37-14) of geological map sheet acquired from the geological institute of Ethiopia. The line density tool in ArcGIS was used to create a lineament density map. Lineament density the study area was divided into five category zones, very low density (0 - 0.856 km/km^2), low density (0.0857- 0.171 km/km^2), moderate density (0.172- 0.257 km/km^2), high density (0.258-0.342 km/km^2), very high density (0.343-0.428 km/km^2). It indicates that there is good groundwater potential if lineament is present, It means that high lineament density was excellent for groundwater potential, whereas low lineament density was poor for groundwater potential. The whole length of all lineaments that have been recorded divided by the total area yields the lineament density, according to Equ (4.1).

$$L_d = \sum_{i=1}^{n} \frac{Li}{A} \qquad \text{Equation 4. 1}$$

where L_d lineament density km/km^2, L_i the cumulative length of lineaments in (km) A, the total area (km^2).

4.2.3.3 Rainfall

The amount, occurrence, and movement of groundwater in a particular location is also influenced by rainfall. Therefore, rainfall mapping is required to properly assess the possible groundwater zone. The spatial distribution of Ethiopia's hydrological and meteorological observation stations is characterized by an irregular and noticeably low density. The primary cause of the inadequate station distribution is that the majority of the nation's locations are inaccessible. Because rain gauges only provide a very tiny sample, it is never possible to pinpoint the actual average depth of precipitation. Three approaches to the area depth of precipitation estimation were used to solve this issue. Theissen polygons and Isohyetal map are useful tools for developing initial groundwater potential maps, especially when paired with other spatial data analysis approaches. The polygon methods and Isohyetal are used for this study, They enable spatial analysis of factors affecting groundwater potential, such as rainfall or infiltration rates. Overlaying these factors on Theissen polygons and Isohyetal methods allows estimation of how variations in them might impact groundwater recharge potential within each zone. This process helps identify areas with sparse data collection and areas with significant influence. Thiessen polygons and Isohyetal map can indicate regions requiring more data to enhance the accuracy of groundwater potential mapping, with influence zones represented by convex polygons and lines of equal precipitation respectively. This polygon is obtained by using a perpendicular bisector of segments that link each station to the closest neighboring stations (Figure 6A). These two methods are more accurate than simple arithmetic mean methods.

$$P_{avg} = P_1A_1 + P_2\,A_2 + P_3\,A_3 + \ldots P_n\ \ A_n / \textstyle\sum \mathrm{Ai} \qquad \text{Equ 3. 1}$$

Where P_1, P_2, and P_n are the mean annual rainfall recorded at each rainfall station, and A_1, A_2, and A_n are polygonal areas around each gauging station enclosed in the basin

Average rainfall = Total weighted rainfall divided by the total area of polygon

$$Pavg = \sum_{i=1}^{15} \frac{P}{A}$$

23551901664543.1/29905096202 = 52.5

The amount that high infiltration rates contribute to groundwater recharge depends on the length and intensity of the rainfall. It means that high rainfall was excellent for groundwater potential, whereas low rainfall was poor for groundwater potential. The area depth of precipitation provides a more representative measure of the actual precipitation over a larger area, as it takes into account the spatial variability of precipitation within the region. This information is crucial for various applications, such as water resource management, flood modeling, and agricultural planning.

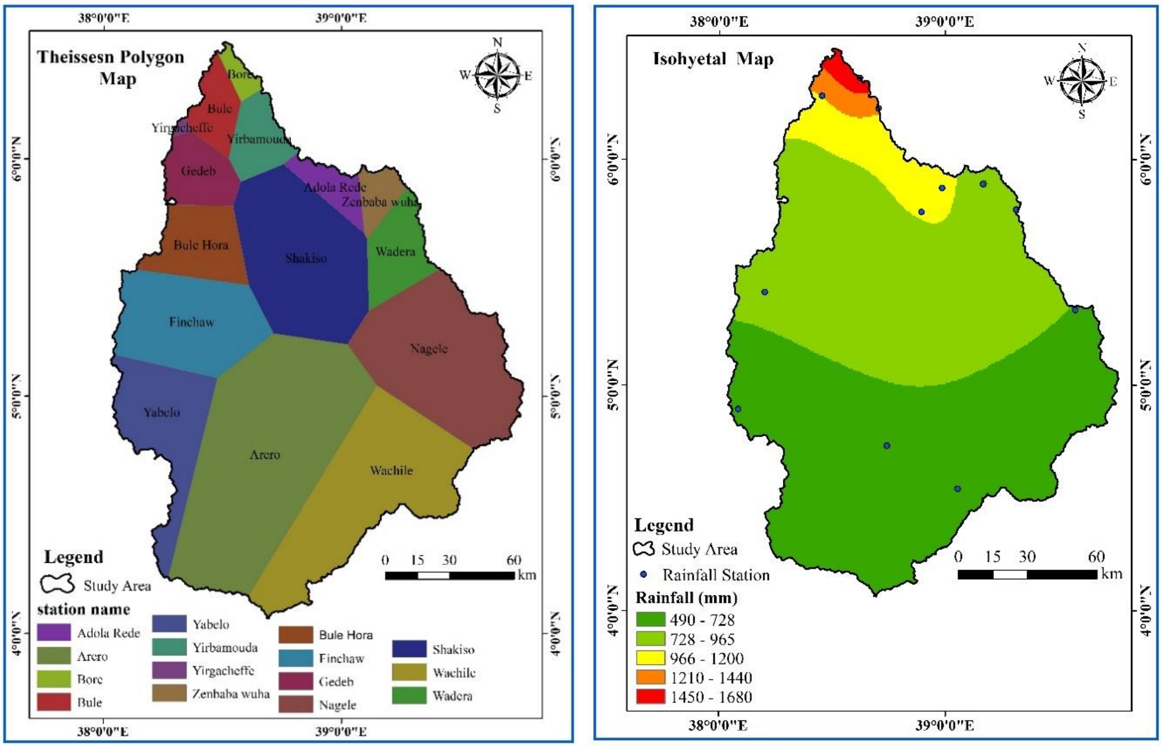


Figure 6: **A)** Theissen polygon **B)** Isohyetal map of the upper Dawa River Basin

4.2.3.4 Slope

The slope is a critical factor that quantifies the degree of angle of inclination in a given region and is vital to understanding groundwater potential (Gebre et al., 2015). The slope offers crucial information on the features of the local geology and the geodynamic mechanisms controlling the occurrence and distribution of groundwater. Thematic slope maps were created using the Shuttle Radar Topography Mission (SRTM) Digital Elevation Model (DEM) at 30 m resolution, which is an open-source product of the United States Geological Survey (USGS, 2021). First, the DEM was resampled to a cell size of 30 m after being gap-filled. For the present study area, the slope was, divided into five categories classes: 0-4º, 4-9º, 9-15º, 15-23º, and 23-73º. In this classification, 0 º to 4 º and 4 º to 9 º were excellent and good groundwater potential, respectively. In addition, 9 º -15 º and 15 º -23 º were classified as moderate and low groundwater potential, respectively, whereas 23-73º were classified as very low groundwater potential.

4.2.3.5 Soil Texture

Soil properties like soil textures and types impact groundwater potential, as soil dictates how quickly water infiltrates the ground through the seepage of rain or snow, replenishing the aquifer (Kormos et al., 2015). ArcGIS 10.8 was used to convert vector data of 1:250,000 scale soil maps acquired from the Ministry of Agriculture, Irrigation, and Energy of Ethiopia into raster format with a 30 m cell size resolution. There are five types of soil textures in the upper Dawa River basin. These are sandy loam, loam, sandy clay loam, sandy clay, and clay. According to the study by Badasa et al., 2023 soil textures of sandy loam and loam were excellent and had good groundwater potential, respectively. In addition, sandy clay loam and sandy clay were classified under moderate and low groundwater potential, respectively, while clay soil was characterized by very low groundwater potential.

4.2.3.6 Land Use Land Cover

LULC affects surface and groundwater resources, due to rugged terrain and steep gradients, increases the rate of soil erosion and land degradation, and finally limits groundwater recharge. LULC map of the study area was classified from Landsat 8 OLI/TIRS 2023 images using supervised classification with a maximum likelihood algorithm using ArcGIS 10.8. A raster data set of the land use land cover maps of the study area was used and converted into a 30 m cell size resolution in ArcGIS 10.8. In this study, the classified LULC types include built-up area, agricultural land, forest area, water body, woodland, grassland, and barren land. According to the study by Senapati and Das, 2022, water bodies and forest areas were categorized under excellent and good groundwater potential, respectively. In addition, grassland and agricultural land were categorized under moderate and low groundwater potential, respectively, whereas built-up and barren land were categorized under very low groundwater potential.

4.2.3.7 Drainage Density

The existence of streams affects how quickly precipitation-related water percolates into groundwater. There is an inverse relationship between drainage density and groundwater potential (Ajay Kumar et al., 2020). The drainage density map was created using a line density technique in ArcGIS 10.8 after the study area's drainage was initially obtained from a gap-filled DEM (30 m). The drainage density map of the upper Dawa River basin was generated according to Equation (4.2). The whole length of rivers/streams per unit area is shown on the drainage density map.

$$D_d = \sum_{i=1}^{n} \frac{Di}{A} \qquad \text{Equ 4. 2}$$

where D_d drainage density (km/km^2), D_i is the cumulative length of drains in each surface unit (km), and A the total area (km^2).

4.3 Analytical Hierarchy Process (AHP)

The Analytic hierarchy process (AHP) is a multicriteria technique used in ranking and determining the relative relevance of different aspects or criteria. AHP analyses were conducted to calculate the weights and ranks of the selected thematic and sub-thematic layers, establishing their order of relevance. Next, all chosen thematic layers were overlaid using the weighted linear combination approach, which also helped to locate possible groundwater zones. The accuracy of GIS-based AHP methods for groundwater potential zone mapping is generally considered to be high compared to other groundwater mapping techniques. This is because AHP integrates multiple factors and their weights in a systematic manner, which helps to reduce the uncertainty associated with groundwater potential mapping (Arulbalaji et al., 2019a; Ngwijabagabo et al., 2023; Senapati and Das, 2022). Establishing the decision's hierarchy is the first stage in the AHP analysis process. The problem is broken down hierarchically using AHP. One benefit of AHP is that it simplifies problem-solving by breaking down difficulties into more understandable parts. To guarantee that all criteria, regulating elements, and potential alternatives were used, it is also crucial to request the involvement of specialists (Mu and Pereyra-Rojas, 2017). To determine the importance of each factor, based on the relative relevance of the factors, a pairwise comparison matrix was developed (Equation 4.3). This matrix allowed the researchers to assign weights to each factor based on their relative importance. The scores of the sub-parameters within each factor were also assigned based on reviewing published literature and local knowledge of the geological and hydrogeological characteristics of the study area. The weighted overlay analysis (WOA) tool in ArcGIS 10.8 was used to integrate the factors and produce the final groundwater potential map.

GIS-based AHP methods accuracy is frequently contrasted with that of other approaches, such as artificial neural network model, Shannon's entropy, logistic regression, evidential belief function, certainty factor, decision tree, frequency ratio, multi-criteria decision analysis, weights-of-evidence, and machine learning approaches, like random forest and maximum entropy (Ngwijabagabo et al., 2023; Senapati and Das, 2022). Groundwater potential mapping has successfully employed the Analytical Hierarchy Process (AHP), a popular multi-criteria decision-making method. The integration of many hydrogeological, topographical, and environmental elements that impact the occurrence and transport of groundwater is made possible by this technique, especially in areas characterized by variable climatic conditions and prolonged drought-prone areas.

The flexibility of the AHP technique to combine both objective data and expert subjective assessments, as well as its capacity to manage both quantitative and qualitative data, are some of its advantages. Additionally, the transparent weighing procedure is another benefit. AHP has proven to be useful in identifying high-potential groundwater zones when paired with GIS approaches, which can improve groundwater resource planning and management. All things considered, the AHP-based groundwater potential mapping is a strong, methodical, and data-driven decision-support tool for sustainable groundwater development and management, especially in complicated hydrogeological contexts or situations with limited data. The consistency ratio in AHP is defined as CR, where CR = CI/RI, CI = $\lambda max - n$ / n -1, where n is the number of thematic layers, λmax is the eigenvalue, and RI is the constant value that varies according to the number of parameters used (Equation 4.5). Aguarón et al., (2021), the AHP analysis can proceed with a consistency ratio (CR) of 0.10 or below. It is essential to analyze and modify the decisions to determine and address the cause of the discrepancy if the consistency ratio rises over 0.10. Table 4: Random index (RI) value of different parameter sizes (Algarín et al., 2017)

N	1	2	3	4	5	6	7	8	9	10
RI	0.00	0.00	0.58	0.9	1.12	1.24	1.32	1.41	1.45	1.49

One to nine scales of parameter significance (Saaty, 2008).

Strength of significance	**Explanation**
1	Equal significance
3	Medium significance
5	Strong significance
7	Very strong significance
9	Maximum significance
2, 4, 6 and 8	Intermediate significance

$$B_1 = \begin{bmatrix} b_{11} & b_{21} & \cdots & b_{1n} \\ b_{21} & b_{22} & \cdots & b_{2n} \\ \vdots & \vdots & \ddots & \vdots \\ b_{n1} & b_{n2} & \cdots & b_{nn} \end{bmatrix}, \ b_{ij} = {b_{ij}}\Big/{\sum_j^n b_{ij}} \text{ for i, j = 1,2..} n \qquad \text{Equ 4. 3}$$

Where B_1 is normalized pairwise comparison matrix

$$W = \begin{bmatrix} w_1 \\ w_2 \\ \vdots \\ w_n \end{bmatrix} \ w_i = {\sum_1^n b_{ij}}\Big/{n} \text{ for i, j = 1,2.... n and } W' = \begin{bmatrix} w'_1 \\ w'_2 \\ \vdots \\ w'_n \end{bmatrix} \ldots \qquad \text{Equ 4. 4}$$

Where W and W' are eigenvector, and w_i and w_i' are eigenvalue of criterion i.

$$\lambda\text{max} = \frac{1}{n}\left[\frac{w'_1}{w_1} + \frac{w'_2}{w_2} + \ldots \frac{w'_n}{w_n}\right] \qquad \text{Equ 4. 5}$$

Where λmax is the average eigenvalue of the pair-wise comparison matrix.

4.4 Validation of Groundwater Potential Zones Map

Maps showing groundwater potential are useless without confirmation. Validation is an integral part of the groundwater potential mapping process. It ensures that the generated maps are reliable, and accurate, and can be confidently used for effective water resource management and decision-making. A training map was constructed using 70% of the groundwater yield data with the controlling factors, and 30% was used for validation of the result (Figure 7). There are several kinds of methods for validating maps of groundwater potential. In the current study, receiver operating characteristics (ROC) and area under the curve (AUC) were used to assess the accuracy of the groundwater potential map created using weighted overlay techniques.

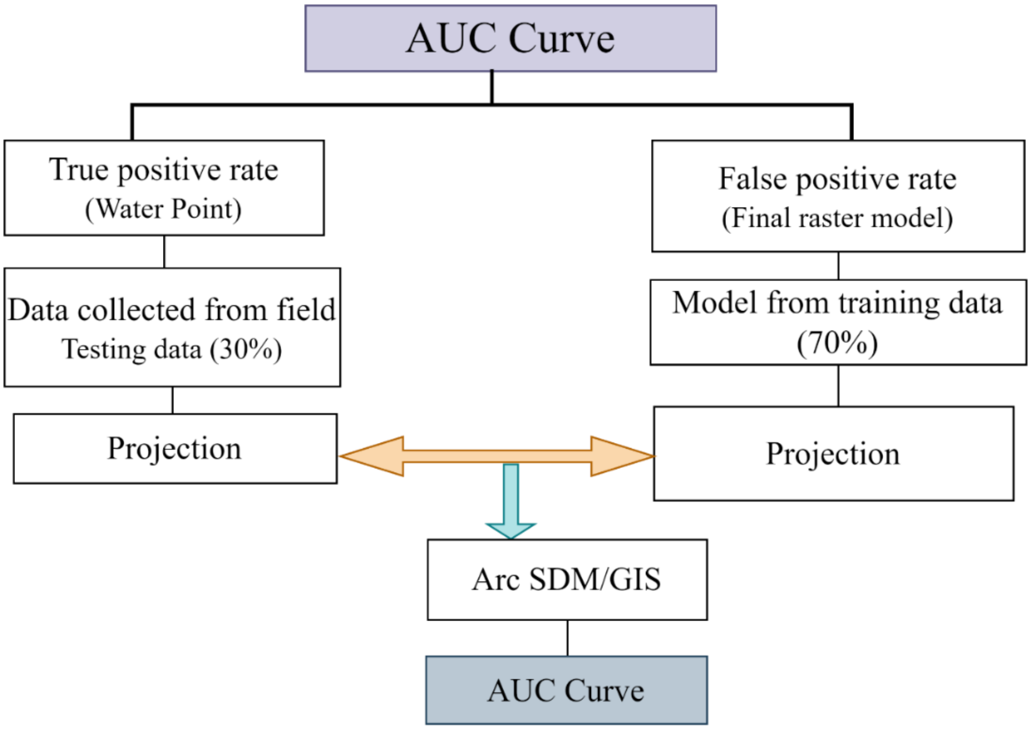


Figure 7: Area under the curve (AUC) flow chart

Area Under Curve	Test Quality
0.9 -1	Excellent
0.8-0.9	Very Good
0.7-0.8	Good
0.6-0.7	Satisfactory
0.5-0.6	Unsatisfactory

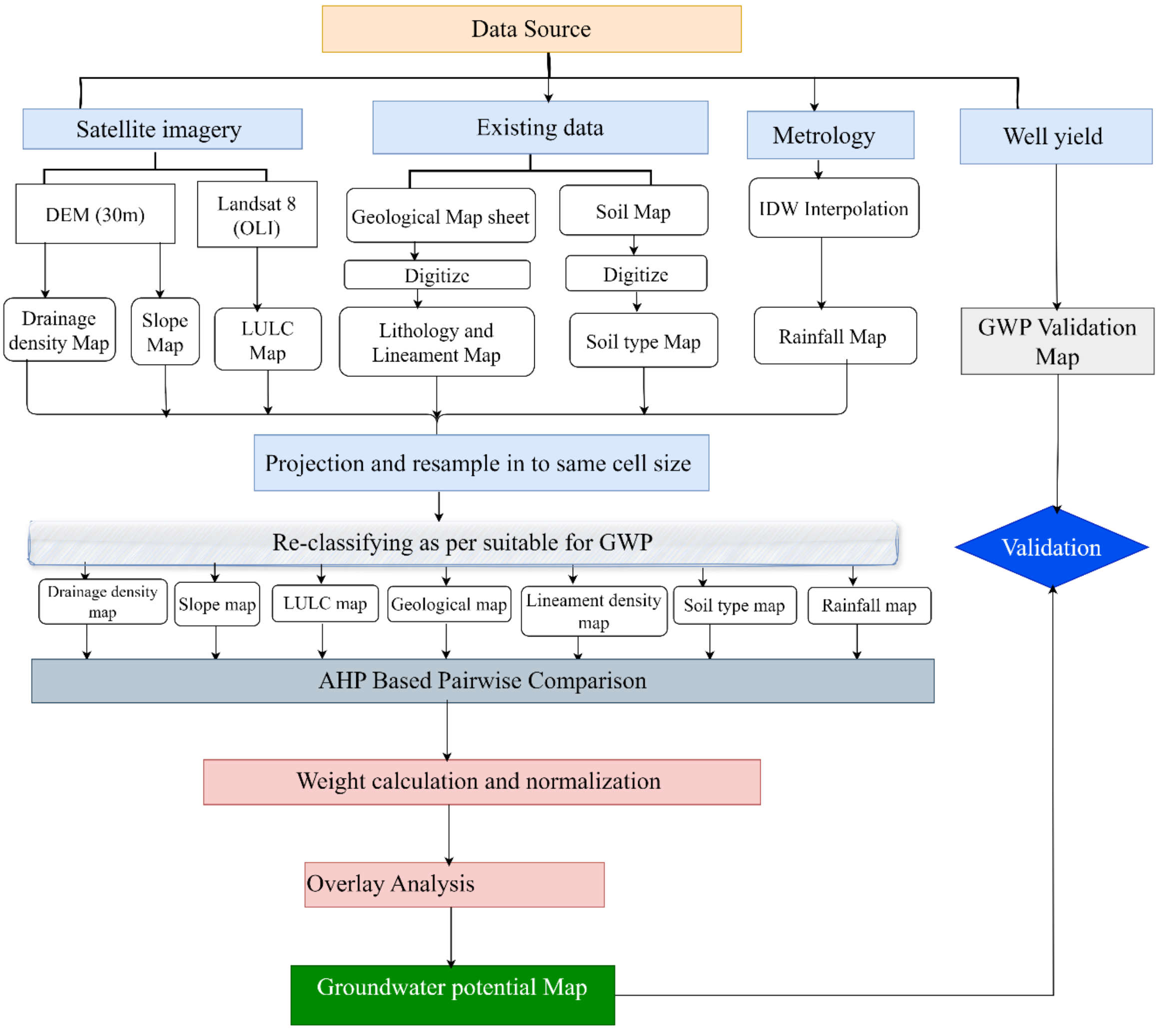


Figure 8: Methodology Flow Chart

5. RESULT AND DISCUSSION

5.1 The relation between controlling factors and groundwater occurrence, movements, and distribution

Various physical and climatological factors control groundwater occurrence and movement. In this study slope, geology, drainage density, lineament density, soil types, rainfall, and land use land cover are considered as main controlling factors. Similar factors are considered in different parts of the world by different scholars (Andualem and Demeke, 2019a; Arulbalaji et al., 2019b; Kumar et al., 2016; Magesh et al., 2012; Yeh et al., 2016) to map groundwater potential zone. Each factor's weight value has been determined by the use of the AHP approach, indicating its relative importance in influencing groundwater potential. Every parameter that controls groundwater potential can be implemented by applying the AHP technique to ascertain each weight's value. The derived weight value illustrates the spatial relationship between each class of groundwater regulating elements and groundwater potential. The following section describes the main controlling factors used in the present study and discusses their significance for groundwater occurrence and movement at a place.

5.1.1 Drainage Density

The existence of streams affects how quickly precipitation-related water percolates into groundwater. A reverse relationship exists between drainage density and groundwater potential (Arulbalaji et al., 2019b), leading to higher weights being assigned to lower drainage density classes. The central to the southeastern part of the study area is characterized by very high to high drainage density as indicated in (Figure 9). Based on the drainage density the area is divided into five category zones, very low density (0 – 18.1 km/km^2), low density (18.2- 36.3 km/km^2), moderate density (36.4-54.4 km/km^2), high density (54.5-72.6 km/km^2), very high density (72.7-90.7 km/km^2) (Figure 9). Most parts of the study area were characterized by very low to low drainage density. The information about infiltration, run-off rates, and permeability are acquired by quantifying drainage density (Manderso et al., 2023). Drainage density serves as a key indicator of how water moves through a basin, influencing both infiltration and runoff characteristics significantly.

From a hydrogeological point of view, more detailed investigations into the mechanisms controlling variation in drainage density have revealed that a wide range of variables, including topography, climate, soil infiltration capacity, vegetation, and geology, all affect stream density (Sangireddy et al., 2016).

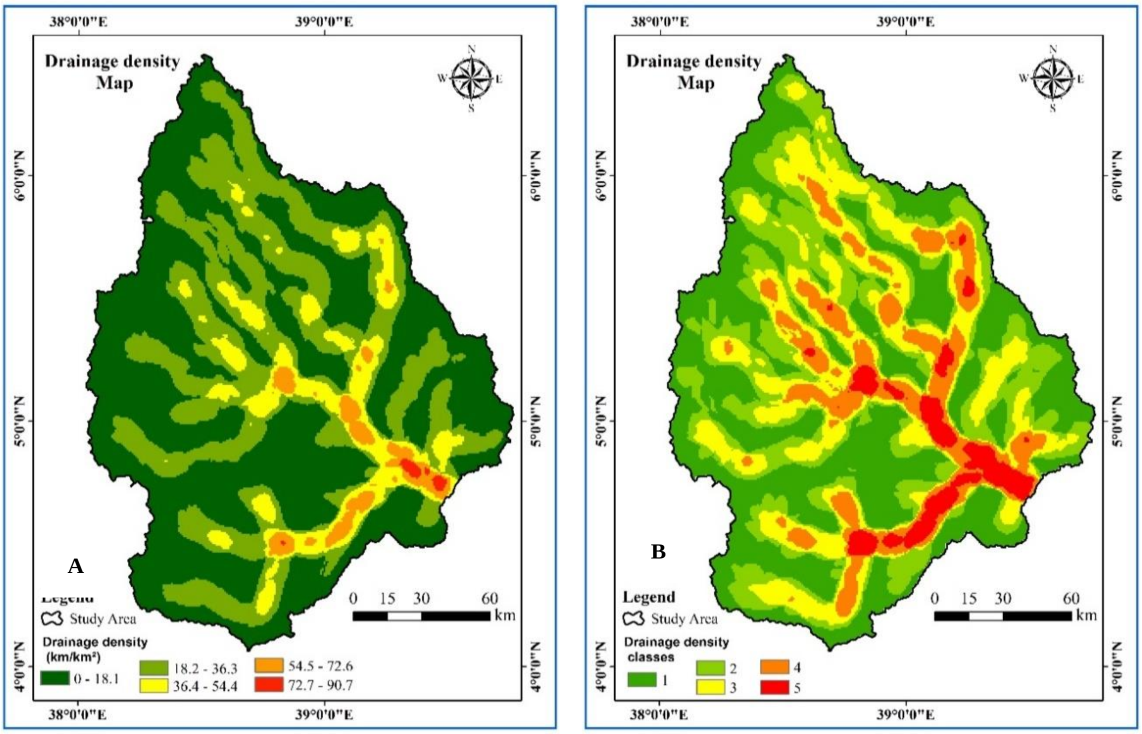


Figure 9: **A)** Drainage density map **B)** Reclassified drainage density map of upper Dawa River Basin

Table 5: Drainage density classes and suitability for GWP

Drainage density (km/km^2)	Drainage density classes	Rating	Area(km^2)	Percentage
0-18.1	Very low	5	11755	39.3
18.2-36.3	Low	4	7752.75	26
36.4-54.4	Moderate	3	5968.7	19.96
54.5-72.6	High	2	3164.5	10.6
72.7-90.7	Very high	1	1265.2	4.22
			29905	100

5.1.2 Lineament Density

The presence of groundwater in hard formations is primarily regulated by fractures and lineaments and in pores of sedimentary formation (Deyassa et al., 2014). Lineaments are natural features such as faults, joints, and fractures, easily identifiable in satellite images due to their linear alignments. They indicate fractured and faulted regions that have more secondary porosity and permeability (Rasool et al., 2020). Groundwater moment is directly represented by lineaments, which are the only type of naturally occurring permeable layer. It indicates that there is good groundwater potential if lineament is present. The higher weights are assigned for higher lineament density values due to a positive correlation between groundwater potential and lineament densities. The lineament density of the study area is highly concentrated in the northeastern and western areas of the basin (Figure 10). Based on the lineament density the area is divided into five category zones very low density (0 - 0.856 km/km^2), low density (0.0857- 0.171 km/km^2), moderate density (0.172- 0.257 km/km^2), high density (0.258-0.342 km/km^2), very high density (0.343-0.428 km/km^2) (Figure 10).

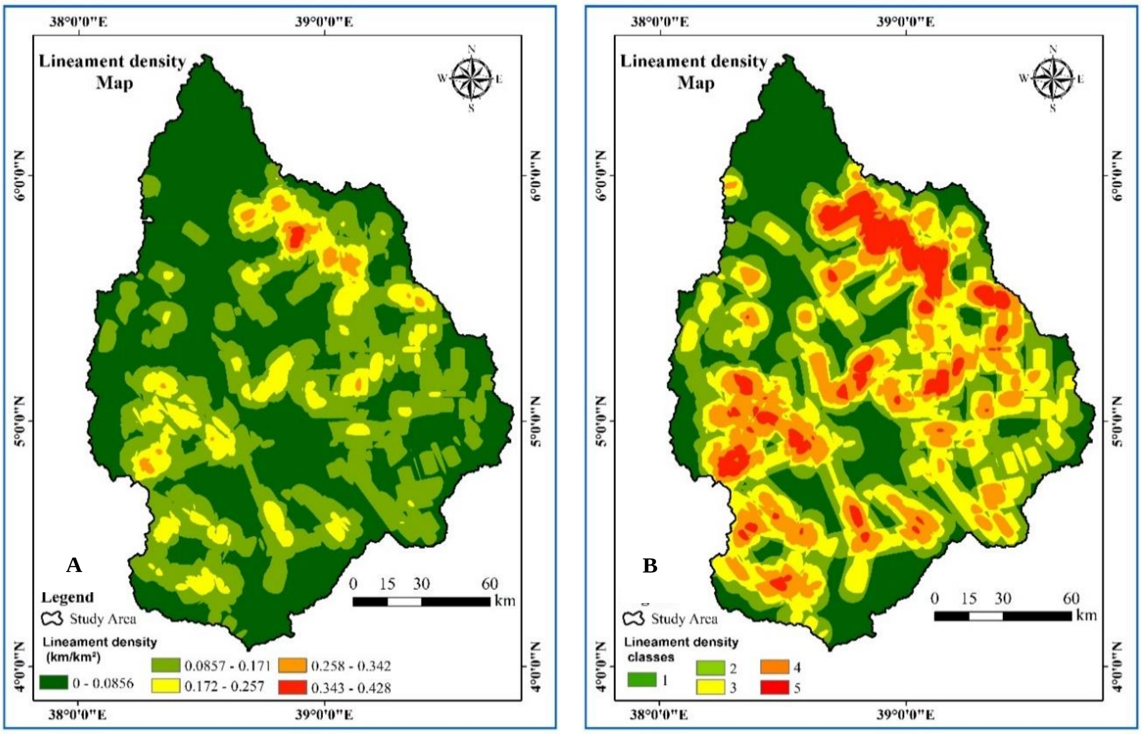


Figure 10: A) Lineament density map B) Reclassified lineament density map of upper Dawa River Basin.

Table 6: Lineament density class and suitability for GWP

Lineament density (km/km^2)	Lineament density classes	Rating	Area(km^2)	Percentage
0-0.856	Very low	1	8123.6	27
0.857-0.171	Low	2	7684.73	26
0.172-0.257	Moderate	3	7308.3	24.43
0.258-0.342	High	4	4975.8	16.63
0.343-0.428	Very high	5	1812.5	6
			29905	100

5.1.3 Slope

The slope plays a vital role in determining the occurrence and movement of groundwater. The slope angle is a key component of the groundwater influencing factor set, indicating the steepness and gentleness of the ground surface. Groundwater occurrence and flow through porosity and permeability are not usually solely determined by surface processes. These topographic characteristics affect the presence, distribution, rate of recharge, and discharge of groundwater. Higher elevations and steeper slopes, for instance, enhance surface runoff, whereas the presence of depressions aims to maximize infiltration rates and groundwater recharge potential. Gentle slopes are anticipated to exhibit a high frequency of groundwater occurrence due to their lower runoff and higher rates of infiltration (Hussein et al., 2017). Steep slopes are found in the study area's northern and central regions. For the present study area, the slope was, divided into five categories classes: (0-4º), (4-9º), (9-15º), (15-23º), and 23-73º (Figure 11). The slope (degree) varies from 0 -73º and most parts of the study area have slope values between 0-4º (44%). The higher weight is assigned for gentle/ flat areas, due to the negative correlation between slope and groundwater potential. The occurrence and movement of groundwater within a basin are greatly influenced by the existence of steep scarps, cliffs, sharp ridges, rugged slope faces, deep gorges, and valleys as indicated in (Figure 11). The complex topography can create variations in groundwater levels and flow paths. Steep slopes can act as recharge zones for groundwater, while valleys may serve as areas of groundwater discharge. Understanding these patterns is crucial for sustainable water resource management and groundwater extraction. The impacts of physiography on geohydrology and water resources are interconnected and can vary depending on factors such as climate, land use, and geology. Therefore, a comprehensive understanding of the physiography and its interactions with other environmental factors is crucial for effective water resource management in the basin.

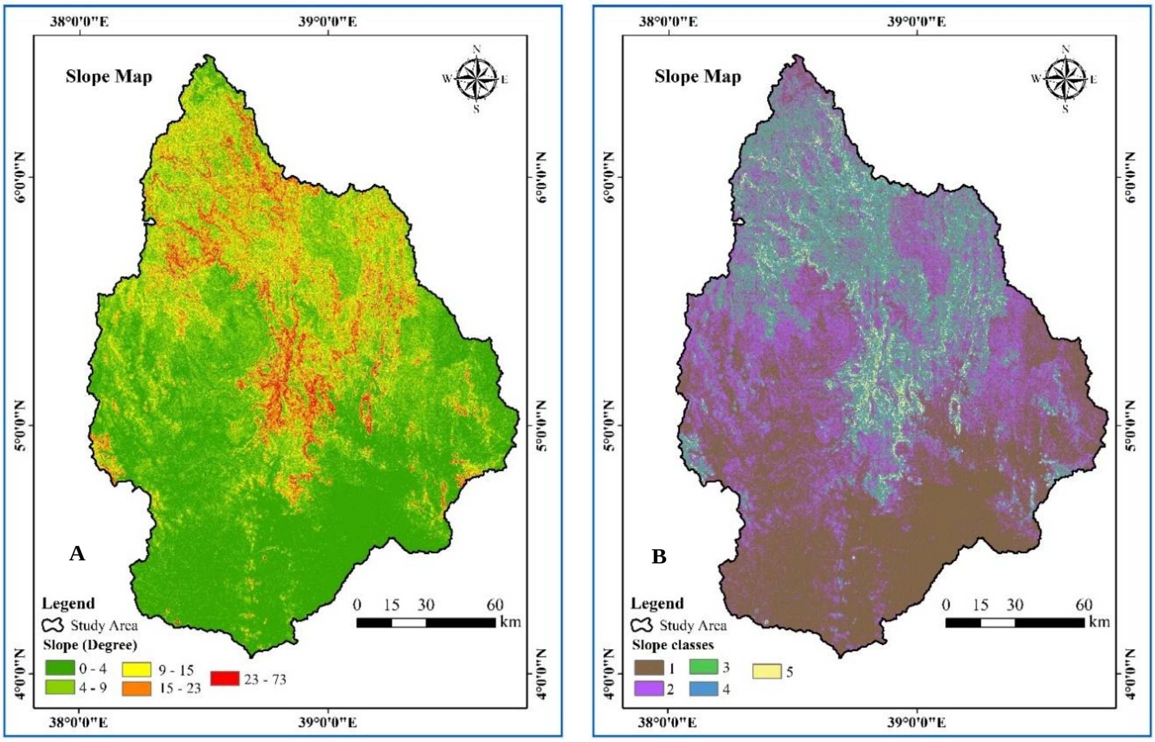


Figure 11: A) Slope map B) Reclassified slope map of upper Dawa River Basin

Table 7: Slope class and suitability for GWP

Slope (Degree)	Slope classes	Rating	Area(km^2)	Percentage
$0-4^{o}$	Flat	5	16245.25	44
$4-9^{o}$	Gentle	4	8822.24	26.2
$9-15^{o}$	Sloping	3	1536.3	4
$15-23^{o}$	Moderately steep	2	2405.23	15
$23-73^{o}$	Very steep	1	896.3	2.5
			29905	100

5.1.4 Land Use Land Cover

LULC affects surface and groundwater resources, due to rugged terrain and steep gradients, increases the rate of soil erosion and land degradation, and finally limits groundwater recharge and infiltration rate of geological materials (Fashae et al., 2014). They have a great function for the recharge of groundwater through roots. The amount of reaching was largely dependent on the rainfall, rivers, and streams of nature, which have highly recharging groundwater. Within a river basin, surface erosion, evapotranspiration, and runoff are all influenced by land use and land cover. LULC changes can alter groundwater recharge rates, with increased impervious surfaces leading to lower recharge and increased runoff. The distribution of the LULC is expected to enhance the groundwater recharge depending on the underlying soil and geologic conditions (Fashae et al., 2014). According to the Lulc categorization of the upper Dawa River basin, water bodies, and barren lands occupy extremely minor regions of the basin, with forest and woodland covering the majority of the western, northern, and eastern parts, respectively (Figure 12). Each land use type has a distinct impact on groundwater potential (Fashae et al., 2014). Agricultural land use can both increase and decrease recharge, while also contaminating groundwater through fertilizer and pesticide runoff. Urban land use reduces recharge due to impervious surfaces and pollutes groundwater through stormwater runoff and industrial waste. Forest land use contributes to recharge through transpiration and evapotranspiration. Grasslands contribute to recharge through infiltration and evapotranspiration. Water bodies also contribute to recharge and maintain quality by filtering out pollutants. Built-up areas reduce recharge due to impervious surfaces and pollute groundwater through stormwater runoff and industrial waste.

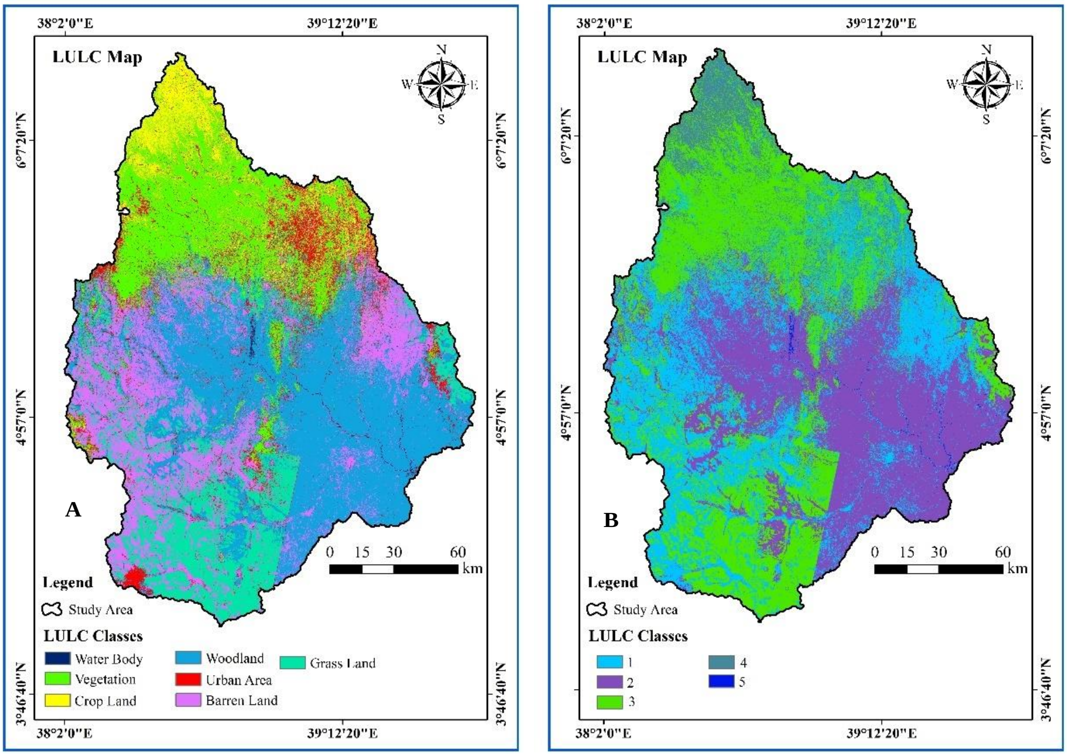


Figure 12: **A)** Land use land cover map **B)** Reclassified land use land cover map of upper Dawa River Basin.

Table 8: Land use land cover class and suitability for GWP

Lulc types	**Lulc classes**	**Rating**	**Area(km^2)**	**Percentage**
Built-up area	Very low	1	8482.3	28.3
Agricultural land	Low	2	1943	6.5
Grassland	Moderate	3	14415	48
Forest	High	4	4967	16.6
water body	Very high	5	97.2	0.32
			29905	100

5.1.5 Rainfall

Rainfall has a major influence on surface runoff and infiltration as a crucial part of the hydrological cycle. The primary source of groundwater recharge through infiltration is rainfall (Ahmad et al., 2020a; Andualem and Demeke, 2019c). Therefore, rainfall mapping is essential for effectively evaluating potential groundwater zones. The amount that high infiltration rates contribute to groundwater recharge depends on the length and intensity of the rainfall. They have a great function for the recharge of groundwater through roots. The amount of reaching was largely dependent on the rainfall, rivers, and streams of nature, which have highly recharging groundwater. The northern part of the study basin receives a high amount of rainfall while the southern part receives low rainfall throughout the year (Figure 13). The range of the annual average rainfall is 490 mm to 1680 mm. Higher annual rainfall means more water is available for infiltration into soils and aquifers, Due to that reason higher weights are given to the high annual rainfall. Rainfall directly affects the availability of groundwater in a given area.

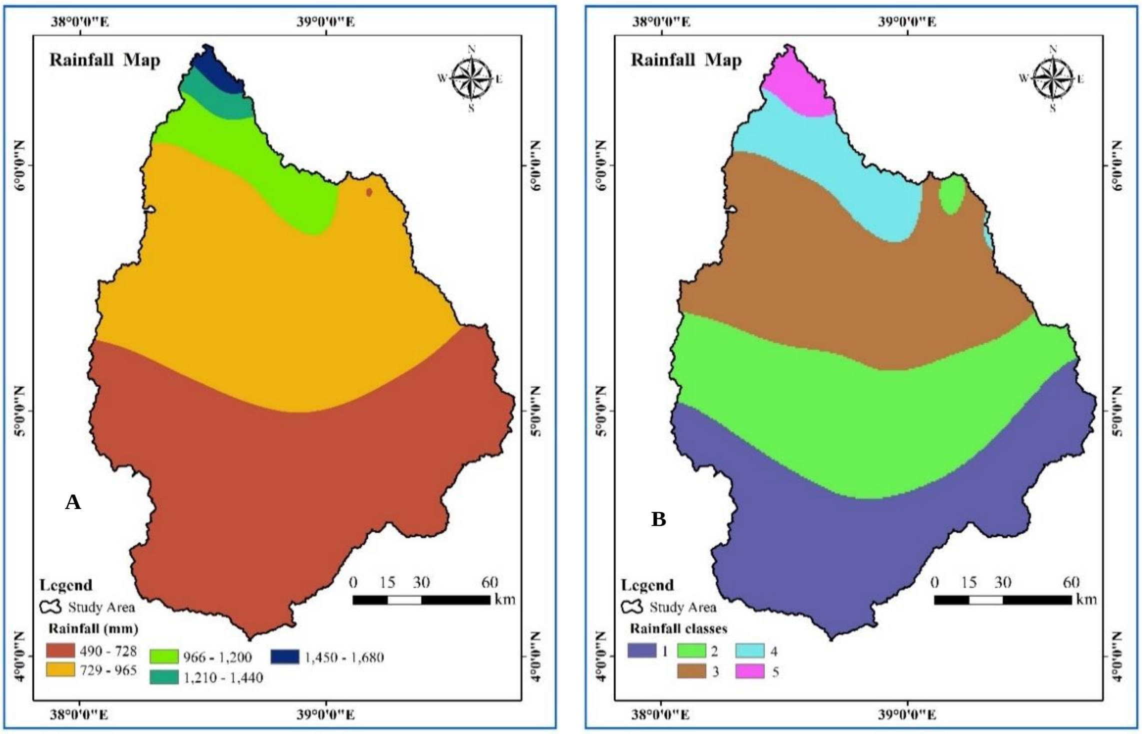


Figure 13: **A)** Annual rainfall map **B)** Reclassified annual rainfall map of upper Dawa River Basin

Table 9: Annual rainfall(mm) class and suitability for GWP

Annual rainfall	Annual rainfall classes	Rating	Area(km^2)	Percentage(%)
613-812	Very low	1	11085.6	37
813-1010	Low	2	9441.5	32
1020-1210	Moderate	3	6543.2	22
1220-1410	High	4	2403.7	8
1420-1610	Very high	5	431.1	1.44
			29905	100

5.1.6 Geology

5.1.6.1 Crystalline Basement Rocks and Plutonic Intrusive Rocks

Plutonic intrusive igneous rocks (granite, diorite) and metamorphic rocks (gneisses, quartzite) are characterized by insignificant primary intergranular porosity and permeability (Deyassa et al., 2014). The basement rocks are considered to be regional aquicludes with localized aquifers along their fractured and weathered zones. Some areas where a relatively higher degree of fracturing occurs are considered to have better potential for groundwater. Due to its inherent poor permeability, basement rocks are generally known to be non-aquifers (Deyassa et al., 2014). Groundwater occurrence and availability in these formations are generally influenced by the interactions between the fractures and the surrounding hydrogeological conditions. Due to their poor porosity and permeability characteristics, the lower weight is allocated to these units.

5.1.6.2 Basalt (Transitional to mildly alkaline and sub-alkaline basalts and aphyric to porphyritic basalt)

Hydrogeologically, transitional to mildly alkaline/ aphyric to porphyritic basalts can exhibit high porosity and permeability, due to the presence of vesicles, joints, and faults. The primary porosity and fracturing in basalts allow for greater groundwater storage and yield (Faria et al., 2022). This makes basaltic aquifers more favorable for groundwater development. The volcanic rocks mostly located in the headwater areas, have a moderate to high productivity.

The overall hydrogeological configuration of the study area is mainly controlled by the geomorphological, structural setup, and lithological formations. The variations in the aquifer distributions and the groundwater flow system are the result of structural and lithological differences over the study area. The volcanic rocks are the regional aquifers with variable hydraulic capacities. The porous and permeable media forming aquifer in the study area is the weathered and fractured basaltic unit. The hydrogeological importance of rocks is considered here for assigning weight. The characteristics such as rock types, origin, occurrence, and degree of weathering are given due importance while assigning weight. Depending on the rock characteristics such as highly fractured and weathering properties, the high weight was assigned for this unit.

5.1.6.3 Melmel Limestone

The uppermost segment of the lower Melmel succession is distinguished by conglomeratic limestone that is strongly lithified, poorly sorted, reddish brown to pink, and has coarse to extremely coarse grains. The Hamanlei series limestones have a relatively high productivity, but the depth to groundwater is high. The Hamanlei formation has organogenic and oolitic limestones with shale and sandstone. The well-jointed nature of limestones, along with their moderate to high permeability and porosity, makes them vital for groundwater systems. Understanding these properties is essential for managing water resources effectively, especially in areas dependent on limestone aquifers. Its permeability is relatively high, making it a significant aquifer, but yield from the well is not significantly high, due to that reason moderate weights are assigned for these units.

5.1.6.4 Quaternary Sediments (Qa, Qe)

Alluvial and eluvial sediments range in size from fine sands to silty, clayey silty soils and coarse sand. Eluvial sediments grouped under this system have fine sand and clay content which makes them possess poor permeability and have no hydrogeological significance. Additionally, elluvial sediment which originates mainly from the weathering of bedrock like limestone, forms residual deposits and is mainly characterized by significantly poor porosity and permeability. Elluvial sediment occurs extensively in the metamorphic area. This elluvial sediment in the metamorphic areas consists of clay, silt, and fine sand, but it has dominantly silt and fine sand. The presence of alluvial deposits throughout the region suggests that there is a potential for groundwater occurrence within these deposits. The specific distribution, thickness, and connectivity of the different sediment types (clay, silt, and sand) within the alluvial deposits will influence the groundwater potential in the study area. Gradation of the deposit from clay and silt to coarse sand and gravel at their bottoms gives it to possess moderate to good permeability. However, the unit forms localized aquifers only when it rests over the basement unit. From a hydrogeologic perspective, a quaternary alluvial deposit is a more transmissive and porous unit than the nearby rocks (Woldemariyam and Ayenew, 2016b), due to that reason we gave higher weight. Tuff and ignimbrite have undergone intensive weathering. According to Alapján (2016), pyroclastic volcanic rocks and ash weathering produce low permeability but high porosity.

Table 10: Lithological units and suitability for GWP

Lithological Units	Lithological classes	Rating	Area (km^2)	Percentage(%)
Eluvial, MA and meta-sediment	Very low	1	7387	24.6
Granite and Gneisses	Low	2	16123	54
Melmel Limestone	Moderate	3	2169	7.3
Alluvial Sediment, BT	High	4	1429.4	4.8
Basalt, APB	Very high	5	2796.6	9.34
			29905	100

MA: mafic to ultramafic, ML: Melmel limestone, BT: Basalt, trachyte and Tuff, APB: Aphyric to porphyritic Basalt

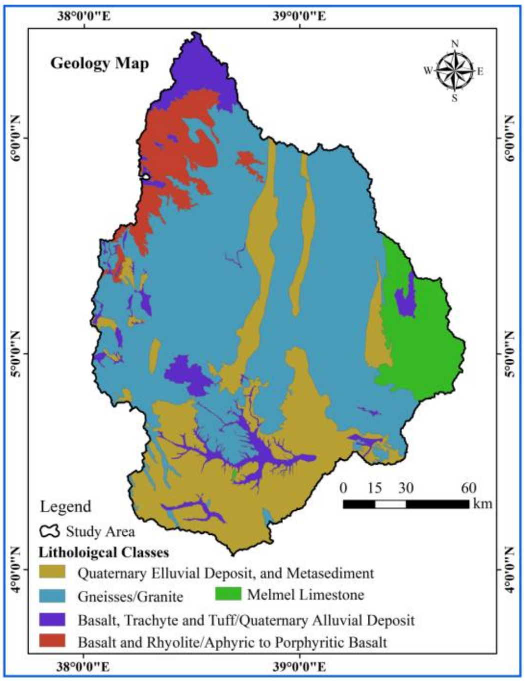


Figure 14: Reclassified geological map of upper Dawa River Basin

5.1.7 Soil Textures

Soil texture significantly impacts the presence and flow of groundwater. Soils that are deep, well-drained, and have a coarse texture are ideal for stormwater infiltration. In the study basin, loam and sandy loam soils are deep, well-drained, and fertile soils that have a high capacity for water infiltration, and porous and permeable nature and storage, making them favorable for groundwater recharge. The clay soils are characterized by high clay content, which can restrict water infiltration and reduce groundwater recharge. Because fine-grained soils have a low permeability, water cannot easily permeate lower weight was assigned for this soil texture, while coarse-grained soils have a high permeability due to that reason higher weight was assigned (Fashae et al., 2014; Olutoyin and Flowerday, 2016). There are five types of soil textures in the upper Dawa River basin. These are sandy loam, loam, sandy clay loam, sandy clay, and clay (Figure 15). As shown in Figure 15, sandy clay is the dominant soil texture covering an extensive area of the study basin.

The sandy loam soil texture was assigned a larger weighting factor due to its higher sand content, water-holding capacity, and high permeability, in comparison to regions covered by huge, unfractured rocks and clayey soil, which were assigned a lower weightage.

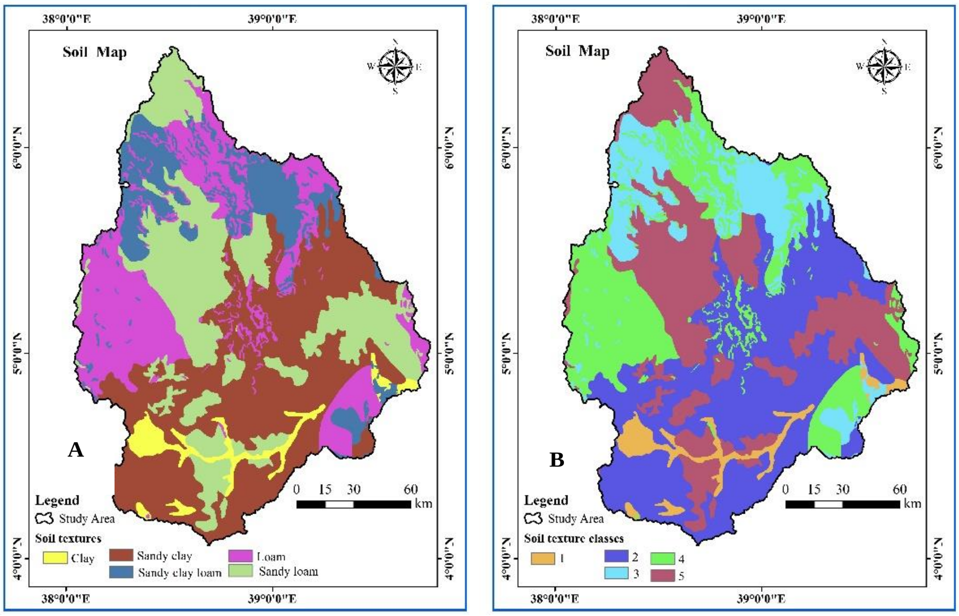


Figure 15: **A)** Soil texture map **B)** Reclassified soil texture map of upper Dawa River Basin

Table 11: Soil textures and suitability for GWP

Soil types	**Soil texture**	**Rating**	**Area(km^2)**	**Percentage(%)**
Eutric vertisols	Clay	1	1083	3.6
Orthic solonchaks	Sandy clay	2	3727	12.5
Chromic cambisols	Sandy clay loam	3	10513.7	35
Eutric nitosols	Loam	4	6693.7	22.4
Eutric cambisols	Sandy loam	5	7887.6	26.4
			29905	100

5.2 Weight assignment to groundwater contributing factors

Weights were allocated to parameters that contribute to groundwater, such as geology, slope, drainage density, land use and land cover, rainfall, lineament density, and soil types (Arshad et al., 2020; Magesh et al., 2012), to map the groundwater prospective zones of the upper Dawa basin. The weights of the chosen criteria were allocated according to how they affected the occurrence, distribution, and movements of groundwater. These distributions were decided by consulting experts in the field and looking over previous research and also depending on local geological and hydrogeological characteristics of the area (Andualem and Demeke, 2019a; Arulbalaji et al., 2019b; Kumar et al., 2016; Magesh et al., 2012; Yeh et al., 2016). Each element's weight indicates the proportion of that element's impact on locating possible groundwater potentials. The consistency ratio (CR) of the below matrix is 0.04, which indicates an acceptable limit as Saaty's AHP approach. The primary influencing factors were assigned a higher weight. To illustrate, geology has the most weight (35.3%), followed by lineament density, slope, rainfall, soil texture, land use land cover, and drainage density, 23.4%, 13.7%, 10.1%, 5.4%, 6.2%, and 5.9%, in that order (Table 12). Table 12: Normalized weights and pair-wise comparison matrix of the seven thematic layers

Factors	**Geology**	**Lineament density**	**Slope**	**Rainfall**	**Soil texture**	**LULC**	**Drainage density**	**Eigen normalized Weight**
Geology	**1**	1	5	5	5	5	5	35.3%
Lineament density	1	**1**	2	2	5	3	3	23.4%
Slope	1/5	1/2	**1**	2	3	2	3	13.7%
Rainfall	1/5	1/2	1/2	**1**	2	2	2	10.1%
Soil texture	1/5	1/5	1/3	1/2	**1**	1	1	5.4%
LULC	1/5	1/3	1/2	1/2	1	**1**	1	6.2%
Drainage density	1/5	1/3	1/3	1/2	1	1	**1**	5.9%
Sum								100%

Table 13: Assigned and normalized weights of the seven thematic layers for groundwater potential zone mapping.

Parameters	Assigned rank	Normalized weight
Geology	7	35.3
Lineament density	7	23.4
Slope	5	13.7
Rainfall	5	10.1
Soil texture	3	5.4
LULC	2	6.2
Drainage density	1	5.9

The elements influencing the occurrence and flow of groundwater have been given weights based on their relative importance. GIS-based weighted overlay analysis was utilized to generate the groundwater potential map. A weighted linear combination technique was used to construct the groundwater potential zones map (Equations 5.5 and 5.6).

$$\mathrm{GWPZ} = \mathrm{GrGw} + \mathrm{SlrSlw} + \mathrm{LurLuw} + \mathrm{RfrRfw} + \mathrm{DdrDdw} + \mathrm{LdrLdw} + \mathrm{StrStw}$$

Equ 5.6

Where; GWPZ is the groundwater potential zones, G is geology, Sl is Slope, Lulc is land use, Rf is rainfall, Dd is drainage density, Ld is Lineament density, St is soil texture, the suffixes r and w represent the rank and weight of each layer respectively. Further Eq. (5.6) can be simplified as;

$$\mathrm{GWPZ} = \sum_{w=1}^{m} \sum_{i=1}^{7} (\mathrm{Xij} * \mathrm{Wij})$$

Equ 5. 7

where; Xi is the normalized weight of the ith feature of the thematic layer, Wj is the normalized weight of the jth thematic layer, m is the total number of thematic layers, and n is the total number of features of a given theme.

5.3. Identification of Groundwater Potential Zones

The combined weighted values of the seven important thematic layers were utilized to generate a groundwater potential map for the upper Dawa River basin employing the weighted overlay method. Every contributing element's data was gathered from many sources and assessed with the ArcGIS 10.8.2 environment. Following the assessment of the criteria and their sub-features using a specific process, appropriate weights and ranks were allocated to each class. The AHP approach was employed to ascertain the rankings and weights for each parameter. The groundwater potential zones were mapped using a weighted overlay analysis technique, Equation (5.7) was utilized in determining these groundwater potential zones. Consequently, the index value was utilized to classify the obtained groundwater potential zones into five categories: very good, good, moderate, poor, and very poor.

Table 14: Groundwater potential zones class and area coverage

SN№	**GWP Classes**	**Area (km^2)**	**Percentage (%)**
1	Very low	77.75	0.26
2	Low	13722.76	45.9
3	Moderate	2631.64	8.8
4	High	4588.6	16.34
5	Very high	8098.27	28.08

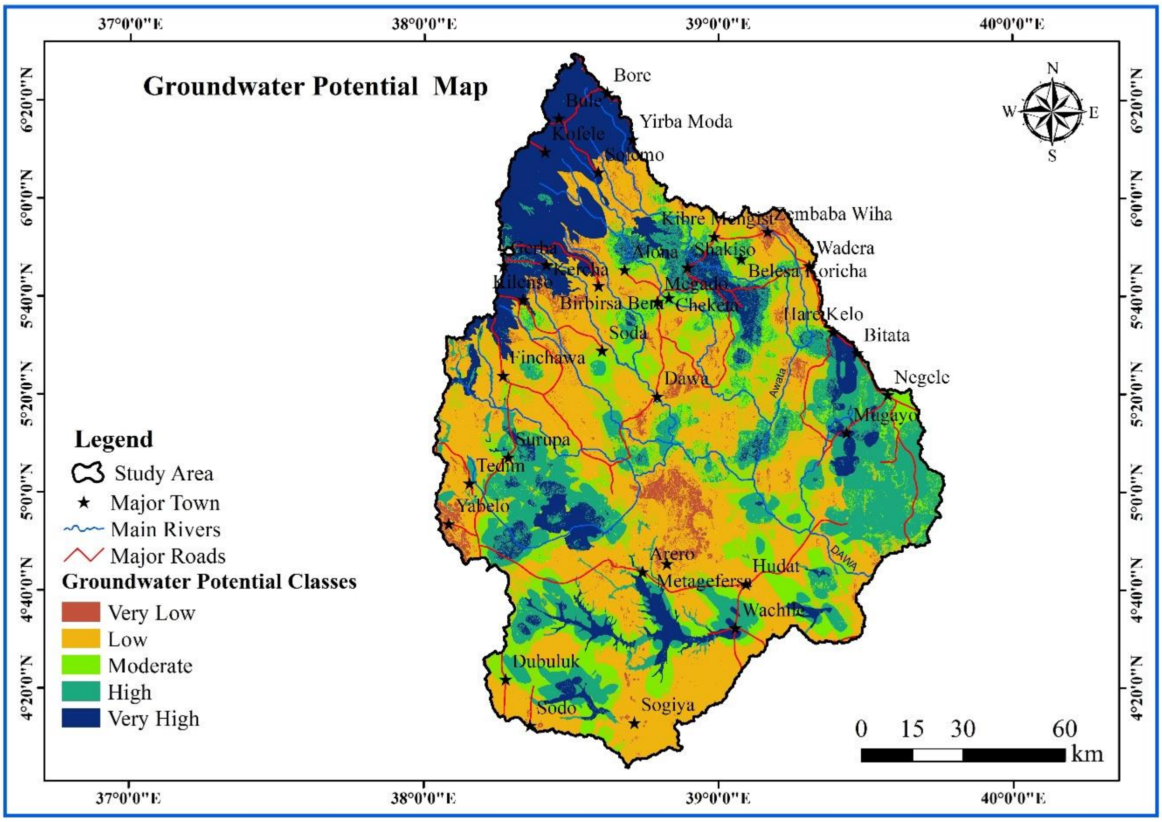


Figure 16: Groundwater potential zones map of upper Dawa River Basin

The Northern and Northwestern parts of the basin, along with some areas in the South, showed good to very good groundwater potential (Figure 16). This was due to the porous and permeable nature of geological materials, flat terrain, and higher rainfall. An area with very high groundwater potential made up about 28.08% of the total region. The majority of the central part covering 8.8% of the area, were classified as having moderate groundwater potential. This classification was based on factors such as rainfall amount, infiltration capacity, nature of geological materials, and land use types. Conversely, approximately 0.26% and 45.9% of the basin were categorized as having very poor and poor groundwater potential, respectively, due to the impermeable and nonporous nature of geological materials, steep slopes, semiarid climatic condition, and relatively low rainfall amount in the area (Figure 16). Areas underlain by metamorphic basement rocks, in the Central, Southwestern, and Southeastern parts of the basin, form steep slope terrain with relatively low to very low rainfall, high to very high drainage densities, and impermeable and nonporous geological materials. These characteristics indicate very low to low potential for groundwater potential.

Other studies across the country have also employed a GIS-Based Analytical Hierarchical Process approach for mapping groundwater potential zones. For instance, Andualem and Demeke, (2019) used this methodology to map the groundwater potential of the Guna Tana landscape in Ethiopia and discovered that approximately 23.8% of the area had excellent prospects, while 13.4% had very good prospects. Similarly, Teka et al., (2020), used a GIS-Based Analytical Hierarchical Process approach to assess the groundwater potential of the Wonbera basin in Ethiopia, finding that about 48.01% of the area exhibited good groundwater potential. The groundwater potential map developed through this innovative GIS-AHP approach should be actively utilized by local water resource managers and policymakers in the upper Dawa River basin. The identified high and moderate groundwater potential zones represent priority areas for targeted groundwater exploration, well-drilling, and sustainable development initiatives. Investing resources into these high-potential zones will help to enhance access to reliable groundwater supplies to support domestic, agricultural, and industrial water needs in the region. Additionally, the low-potential zones highlighted on the map should be managed carefully to prevent overexploitation. Overall, this study contributes important knowledge on groundwater resources in a data-scarce region and showcases the utility of GIS-AHP approaches for hydrogeological investigations.

5.4 Validation of the Groundwater Potential Zones Map

The GWPZ map's accuracy was assessed by overlaying yield data from 76 boreholes in the study area. The yields from these boreholes ranged from 8 l/s to 12 l/s, averaging 10 l/s, 5 to 8 l/s, averaging 6 l/s, and from 3.1 l/s to 5 l/s, averaging 4 l/s, corresponding to very high, high, and moderate potential zones, respectively. Conversely, well yields ranging from 1 to 3 l/s averaging 2 l/s fall within low potential zones, while yields below 1 l/s are categorized as very low groundwater potential zones. Wells with high yields (≥ 8 l/s) are mostly found in the upper Dawa basaltic rock units and associated alluvial sediments due to the presence of permeable and porous lithological units. In contrast, wells situated in the metamorphic basement and quaternary eluvial deposits generally have low yields (1–3 l/s) or very low yields (≤1 l/s) due to their impermeable and nonporous nature. The well yield distribution effectively validates (83.4 %) the GWPZ map of the Basin, demonstrating the success of the integrated GIS-based analytical hierarchical process technique in mapping groundwater potential zones in the upper Dawa River basin. This modern approach proves valuable for investigating groundwater resources in data-limited areas like the upper Dawa River basin. A training map was created using 70% of the groundwater yield data along with the controlling factors, while the remaining 30% was used to validate the results. Various techniques exist for validating groundwater potential maps. In this work, the area under the curve (AUC) and receiver operating characteristics (ROC) were used to evaluate the accuracy of the groundwater potential map created using weighted overlay techniques. The validation of groundwater prospect maps against existing wells yield is indicated by the AUC curve and AUC of 0.834, this value signifies the strong predictive capability of the AHP method in mapping groundwater potential (Figure 17). Therefore, development activities targeting these high groundwater prospect zones can be pursued to boost productivity for supplementary irrigation and domestic purposes.

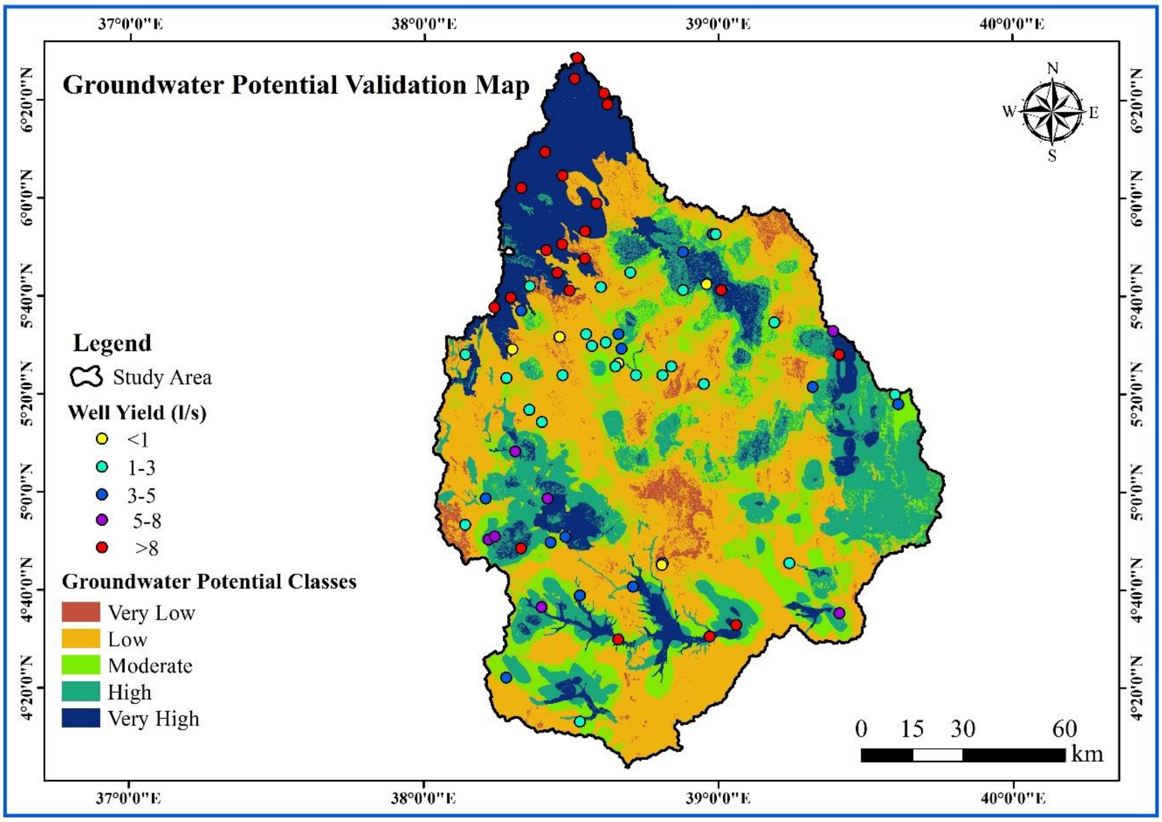


Figure 17: Groundwater potential Validation map of Upper Dawa River Basin

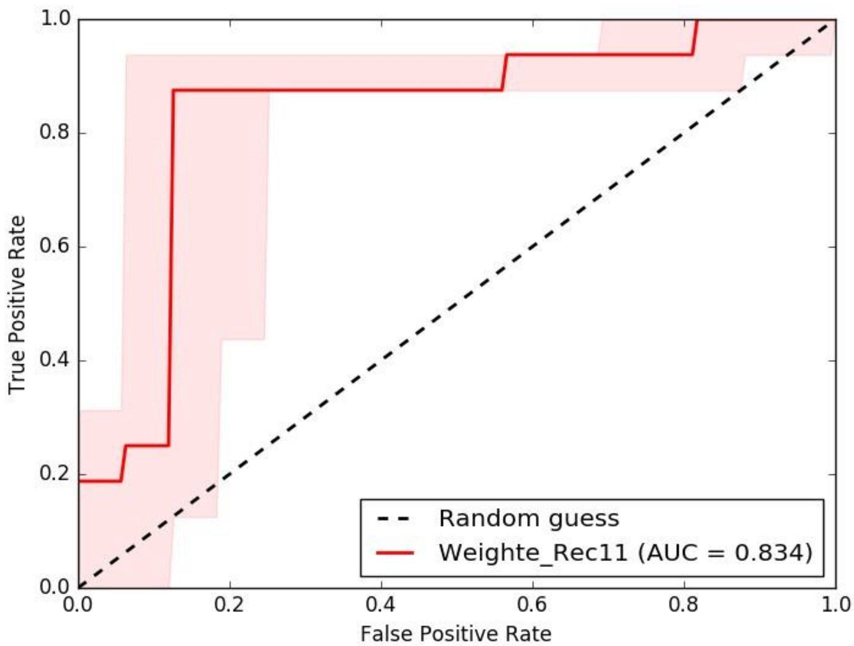


Figure 18: Area under the curve (AUC) and Receiver operating characteristics (ROC) curve

6. CONCLUSION AND RECOMMENDATIONS

6.1 Conclusion

Precambrian basement rocks, Mesozoic sedimentary formations, tertiary volcanic rocks, and quaternary alluvial and eluvial deposits are all present in the upper Dawa River basin. Groundwater is a vital freshwater resource and a critical water source to supply domestic, irrigation, and industrial demand. As the demand for drinking water increases globally, the need to evaluate the groundwater potential and aquifer productivity also increases. This study focused on mapping the groundwater potential zones in the upper Dawa basin, Southern Ethiopia, using a Geographical Information System (GIS) based Analytical Hierarchy Process (AHP). The study area is divided into five groundwater potential zones: very low, low, moderate, high, and very high, respectively, covering 0.26%, 45.9%, 8.8%, 16.34%, and 28.08% of the study area. The volcanic terrain in the north and northwest, the limestone terrain in the southeast, and small areas along streamlines in the basement terrain in the south are mapped as very high to high groundwater potential zones. On the other hand, a large portion of the basement terrain is marked by low to very low groundwater potential. The study findings revealed that very high to high groundwater potential occurrences in the northern and southern ends were mainly due to the influence of the porous and permeable nature of geological materials while those of the Northeastern was mainly due to the influence of lineament. The identified high and moderate groundwater potential zones represent priority areas for targeted groundwater exploration, well-drilling, and sustainable development initiatives. Investing resources into these high-potential zones will help to enhance access to reliable groundwater supplies to support domestic, agricultural, and industrial water needs in the region. The well yield distribution effectively validates (83.4 %) the GWPZ map of the basin, demonstrating the success of the integrated GIS-based analytical hierarchical process technique in mapping groundwater potential zones in the upper Dawa River basin. Overall, this study contributes important knowledge on groundwater resources in a data-scarce region and showcases the utility of GIS-AHP approaches for hydrogeological investigations.

6.2 Recommendation

This research will offer valuable insights into the creation and management strategies for sustainable groundwater in the basin. As a result, it is advised that future research install and recode data at test wells to conduct a quantitative examination of groundwater recharge, hydro-chemistry, and its appropriateness for irrigation and residential use. The basin under study is difficult, isolated, and has a complicated geology. The task was completed in an environment with little data. Based on the results of this study the following has been recommended:

- Since the groundwater flow system in the upper Dawa River basin is mostly local in character, groundwater development, and management strategies should be implemented at the basin scale.
- Improve the quality and completeness of the input data layers.
- Conduct rigorous field validation and ground-truthing.
- Employ more advanced modeling techniques, such as numerical groundwater flow models, to complement the GIS-based AHP approach.
- Regularly update and refine the groundwater potential assessment as new data and information become available.
- The present study reveals that the integration of various factors was responsible for controlling groundwater potential in the study area. Consequently, in addition to preparing a groundwater potential map of the area; suggesting the necessary preventive measures on high and very high potential zones of the mapped area are essential to reduce the impact of water scarcity in the future.
- The groundwater potential map produced in this work highlights information about groundwater potential areas; however, further works with additional methods are recommended.

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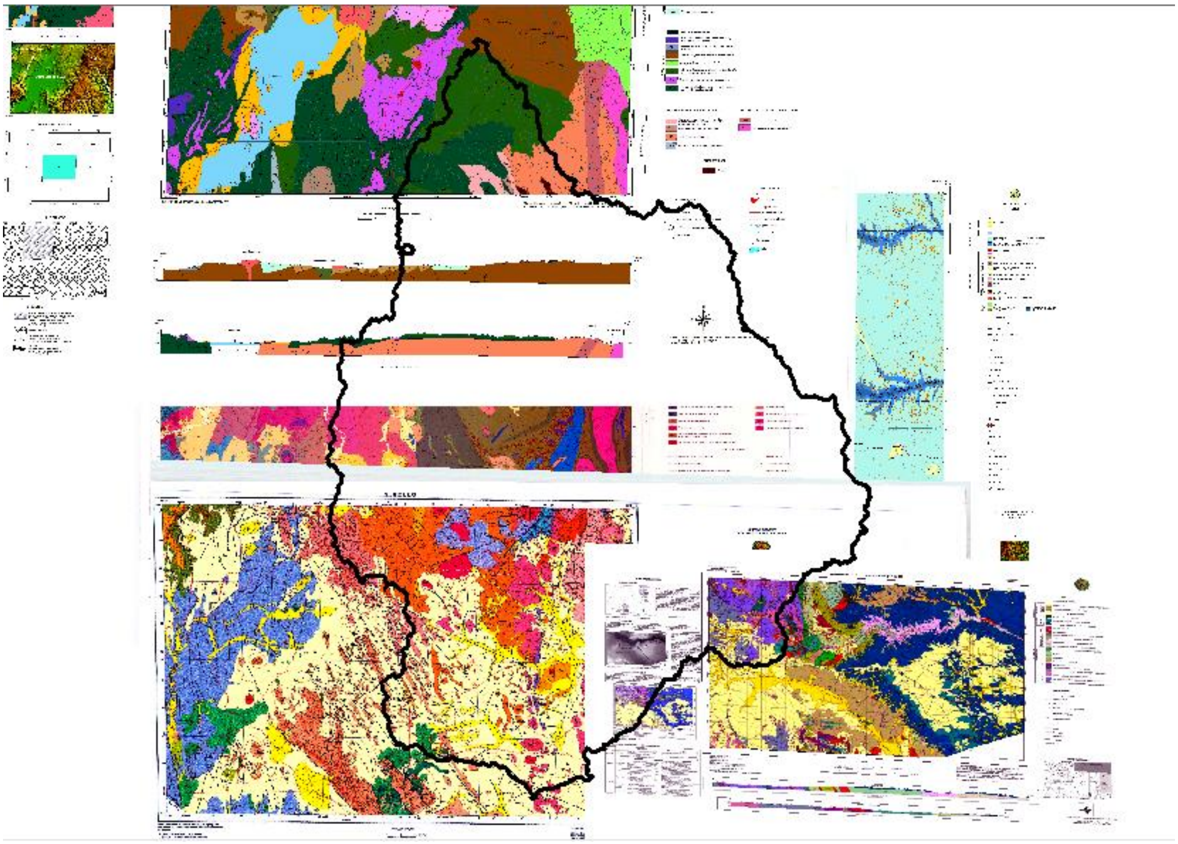
Appendices

Appendix 1: Well yield data of upper Dawa River Basin

Station no	Shape	Well ID	Site name	X	Y	Q
1	Point ZM	BH	Alona	38.7	5.75	3
2	Point ZM	BH	Amiko	39.41	4.59	5
3	Point ZM	BH	Badakessa	38.88	5.82	3.5
4	Point ZM	BH	Bake	38.21	4.98	4
5	Point ZM	BH	Balambal	39.32	5.36	5
6	Point ZM	BH	Baya Gundi	38.617	5.512	1.5
7	Point ZM	BH	Bubuka	38.96	5.71	5
8	Point ZM	BH	BuriKaro	38.84	5.43	1
9	Point ZM	BH	Chabiti	38.66	5.44	0.9
10	Point ZM	BH	Cheme	38.4	5.24	3
11	Point ZM	BH	Dambala Saden	38.43	4.83	4
12	Point ZM	BH	Dida Yabelo	38.22	4.84	6.2
13	Point ZM	BH	Didola	38.96	5.71	0.78
14	Point ZM	BH	Dubluk	38.28	4.37	3.5
15	Point ZM	BH	Dureti	38.81	4.76	0.95
16	Point ZM	BH	Ela Dima	38.6	5.7	3
17	Point ZM	BH	Ela Korcha	38.65	5.43	2.5
18	Point ZM	BH	Figa Bike	39.19	5.58	3
19	Point ZM	BH	Finchawa town	38.28	5.39	2.5
20	Point ZM	BH	Funana Birressa	38.71	4.68	3.5
21	Point ZM	BH	Gada	38.48	4.85	3.1
22	Point ZM	BH	Galo Bokola	38.67	5.49	4
23	Point ZM	BH	Gayu	38.53	4.22	1
24	Point ZM	BH	Hadha gora	38.72	5.4	3
25	Point ZM	BH	Harakelo	39.39	5.55	8
26	Point ZM	BH	Haro Gari	38.95	5.37	1.5
27	Point ZM	BH	Haro Xixita	38.55	5.54	1.5
28	Point ZM	BH	Hema Kisho	38.14	5.47	2.5
29	Point ZM	BH	Kadale	38.24	4.85	5
30	Point ZM	BH	Kalkaltu	38.33	5.62	4.7
31	Point ZM	BH	Kibremengist	38.98	5.88	4.7
32	Point ZM	BH	Kibremengist	38.99	5.88	2
33	Point ZM	BH	Laga Bursano	38.57	5.5	2.5
34	Point ZM	BH	Melka Baya	38.47	5.4	1.5
35	Point ZM	BH	Melka Baya_2	38.46	5.53	0.8
36	Point ZM	BH	Metagefersa	38.808	4.754	0.9
37	Point ZM	BH	Nurahumba	39.41	5.47	6
38	Point ZM	BH	Oda	38.357	5.282	1

39	Point ZM	BH	Orbati	38.42	4.98	5
40	Point ZM	BH	Qa gofa	38.4	4.61	5
41	Point ZM	BH	Qawa	38.53	4.65	3
42	Point ZM	BH	Rippessa	39.01	5.69	8.6
43	Point ZM	BH	Siminto#2	39.611	5.301	3
44	Point ZM	BH	Surupa	38.31	5.14	5.2
45	Point ZM	BH	Udet	39.24	4.76	1.5
46	Point ZM	BH	Wachile 2	39.06	4.55	9
47	Point ZM	BH	Wacho Dima	38.81	5.4	1.7
48	Point ZM	BH	Webe 1	38.66	4.5	8.2
49	Point ZM	BH	Welesu	38.97	4.51	9.2
50	Point ZM	BH	Wolena	38.88	5.69	2
51	Point ZM	BH	Yabelo	38.33	4.81	10
52	Point ZM	BH	Yabelo town	38.14	4.89	3
53	Point ZM	BH	Ageremariam	38.239	5.631	8.4
54	Point ZM	BH	Badessa	38.494	5.688	9
55	Point ZM	BH	Banko michicha	38.415	5.825	15
56	Point ZM	BH	Bilida Kojoa	38.468	5.846	10
57	Point ZM	BH	Bore#2	38.61	6.36	9.3
58	Point ZM	BH	Bore#3	38.622	6.322	8.3
59	Point ZM	BH	Chemeri_Kercha	38.294	5.664	8.8
60	Point ZM	BH	Chorso Golja	38.329	6.038	8.3
61	Point ZM	BH	Danaba#2	38.51	6.41	10.4
62	Point ZM	BH	Darikidame	38.547	5.89	10
63	Point ZM	BH	Darsa Sake	38.546	5.797	10
64	Point ZM	BH	Dhak bor	38.47	6.08	8.6
65	Point ZM	BH	Guracho Jaldo	38.452	5.749	10
66	Point ZM	BH	Hagereselam	38.52	6.48	8.5
67	Point ZM	BH	Haro Borena	38.41	6.16	9.6
68	Point ZM	BH	Hartume Lama	38.359	5.703	2.5
69	Point ZM	BH	Kilenso	38.299	5.488	0.9
70	Point ZM	BH	Yabitu Koba	38.585	5.985	8.1
71	Point ZM	BH	Negele Army base	39.6	5.333	5
72	Point ZM	BH	Negele Army base	39.6	5.333	1.1
73	Point ZM	BH	Negele Army base	39.6	5.333	1.5
74	Point ZM	BH	Siminto#1	39.61	5.302	1
75	Point ZM	BH	Siminto#2	39.611	5.301	3.7

Appendix 2: Geological Map Sheet



Appendix 3: Rain gauge Station of Upper Dawa River Basin

Station	**Mean annual Rain (mm)**	**Shape area (Km^2)**	**Area_m²**	**Weighted Rainfall**
Yabello	613	2196.629	2196629253	1346533731833.38
Arero	668	6711.169	6711168863	4483060800222.81
Bule Hora	950	1313.629	1313629214	1247947753534.65
Wachile	618	4397.035	4397034656	2717367417516.77
Nagelle	716	4008.717	4008716576	2870241068314.33
Gedeb	823	933.466	933466192.2	768242676217.635
Bule	1209	691.718	691718287.3	836287409292.504
Finchawa	790	2723.082	2723081888	2151234691512.89
Shakiso	992	3796.934	3796934185	3766558711158.91
Yirbamuda	1250	803.171	803170950.4	1003963687956.25
Yirga chaffe	1408	44.671	44671011.8	62896784612
Wadera	948	1069.109	1069109391	1013515702377.91
Bore	1610	238.09	238090421.4	383325578479.76
Adola Rede	1083	536.064	536064383	580557726742.431
Zembaba	725	441.611	441610930.7	320167924771.275
Total			29905096202	23551901664543.1