GROUNDWATER POTENTIAL MAPPING BY USING GIS AND REMOTE SENSING TECHNIQUES IN WELMEL WATERSHED,

GENALE DAWA RIVER BASIN, SOUTHEAST, ETHIOPIA

MSc. THESIS

HAILEYESUS HIFAMO HILLO

HAWASSA UNIVERSITY, HAWASSA, ETHIOPIA

MARCH, 2023

GROUNDWATER POTENTIAL MAPPING USING GIS AND REMOTE SENSING: A CASE STUDY IN WELMEL WATERSHEDE, GENALE-DAWA RIVER BASIN, SOUTHEAST ETHIOPIA

HAILEYESUS HIFAMO HILLO

A THESIS SUBMITTED TO THE

DEPARTMENT OF HYDRAULIC AND WATER RESOURCES ENGINEERING, HAWASSA INSTITUTE OF TECHNOLOGY, SCHOOL OF

GRADUATE STUDIES, HAWASSA UNIVERSITY

HAWASSA, ETHIOPIA

IN PARTIAL FULFILLMENT OF THE

REQUIREMENTS OF THE

DEGREE OF

MASTERS OF SCIENCE IN (HYDRAULIC ENGINEERING)

MARCH, 2023

SCHOOL OF GRADUATE STUDIES

HAWASSA UNIVERSITY ADVISORS' APPROVAL SHEET

This is to certify that the thesis entitled " **Groundwater Potential Mapping Using GIS and Remote Sensing." A Case Study in Welmel Water Shade ,Genale Dawa River Basin , South East ,Ethiopia**" has been submitted in the partial fulfilment of the requirement for the degree of **Master of Science** in **Hydraulic Engineering**, the graduate program of the department of Hydraulic and Water Resources Engineering has been carried out by **Haileyesus Hifamo Hillo** Id.No. (**GPHydrW/0006/12**).Therefore, we recommend that the student has fulfilled the requirements and hence hereby can submit the thesis to the department.

Tewodros Tesfaye (Ph.D.)	---------------------------	---------------------------
Major advisor	Signature	Date
Ashenafi Wondimu (MSc.)	---------------------------	---------------------------
Co-advisor	Signature	Date

SCHOOL OF GRADUATE STUDIES

HAWASSA UNIVERSITY EXAMINERS' APPROVAL SHEET

We, the undersigned, members of the Board of Examiners of the final open defence by **Haileyesus Hifamo Hillo** have read and evaluated his thesis entitled ''**Groundwater Potential Mapping using GIS and Remote Sensing: A case study in Welmel Catchment , Genale-Dawa River basin, Southeast Ethiopia''**, and examined the candidate. This is, therefore, to certify that the thesis has been accepted in partial fulfilment of the requirements for the degree.

Tewodros Tesfaye (Ph.D.)	____________________	____________________
Name of the Major Advisor	Signature	Date
____________________	____________________	____________________
Name of the Internal Examiner-I	Signature	Date
____________________	____________________	____________________
Name of the Internal Examiner-II	Signature	Date
____________________	____________________	____________________
Name of the External Examiner	Signature	Date
____________________	____________________	____________________
SGS Approval	Signature	Date

ACKNOWLEDGEMENTS

First of all, I would like to thank my Almighty God who gave me all the opportunities and strength that have been showered on me to bring my hope into reality. Without His support and blessing, it could not have been possible to complete my work.

Next, my deepest feeling of gratitude goes to my advisor Tewodros Tesfaye. (Ph.D.) for his strong advice, work quality, professional guidance and constant encouragement starting from thesis proposal writing up to the completion of this thesis work. Also, I would like to present my heartfelt gratitude to my Co-advisor Ashenafi Wondimu (MSc.) for encouragement during the research period till the completion of my work successfully.

I would like to appreciate the following institution that supports my work on obtaining data: Ministry of Water, Irrigation, and Energy, Ethiopian Institute of Geologic Survey, Ethiopian National Meteorological Agency and Bale Zone Water Resources Development and Energy.

I wish to thank my parents for their love and encouragement, without whom I would never have enjoyed so many opportunities. Especially my brother Wondimagegn Hifamo , I never forget his genuine financial support . It would not be possible to finish this thesis without support from them.

Finally, I wish to thank all of my friends who were ever with me, Last but not least, I would like to thank all my best friends and classmates as well as Biruk Tamiru and Abdulgefar Muhidin who helped and contribute their best during this study.

TABLE OF CONTENTS

LIST OF TABLE

LIST OF FIGURE

DECLARATION

I undersigned and declared that this M.Sc. thesis entitled "Groundwater Potential Mapping using GIS and Remote sensing : A case study in Welmel Catchment, Genale Dawa River basin .south East, Ethiopia'' is my original work and has not been presented for a degree in any other university, and all sources of material used for this thesis have been duly acknowledged.

Name: Haileyesus Hifamo

Signature: ______________

This M.Sc. thesis has been submitted for examination with my approval as thesis advisor.

Name: ___________________________________

Signature: __________________________________

Place and Date of Submission: ______________

ABSTRACT

*To fulfil the demand of a rapidly growing population in drought-prone areas with high rate of urbanization, identification and management of groundwater resources are required. In the welmel catchment, a search for an alternative source of water has been always a major issue. The current practice of groundwater potential zone (GWPZ) identification is time-consuming and uneconomical. This study applied integration of GIS-Remote Sensing (RS) and Analytical Hierarchy Process (AHP) for mapping the GWPZ of welmel catchment , Southeast Ethiopia. This technique is a fast, accurate, and feasible technique. Groundwater potential zone influencing parameters were derived from Operational Land Imager 8, digital elevation model(DEM) 20*20 resolution and secondary sources were utilized in this research. These were geomorphology, lineament density , lithology, rainfall, drainage density , slope , elevation , LULC, and soil texture were prepared . Borehole data were used for results validation. All thematic layers were reclassified based knowledge based analysis that was reviewed from different kinds of literature. Then the weight for each factor was assigned according to their relative importance as per suitable based on Saatty's scale of AHP. The important factors result show that geomorphology and lineament density have a higher weight and soil texture has the lowest weight for identifying groundwater potential zone . For weights allocated to each parameter, the consistency ratio obtained was 0.061, which is less than 0.1, showing the weight allocated to each parameter is acceptable. The resulting GWPZ of the study area indicates four zones representing Very Low, Low, Moderate and High . The areal extent of high and moderate GWPZ is 350 km^2 and 2256 km^2, respectively. low and very low GWPZ covers 10356 km^2 and 1547km^2 areas. The particular direction of groundwater flow is towards the NE and SE, coinciding with the direction of surface water flow. The validation result of 82.08% confirms the very good agreement among the groundwater record data and groundwater potential classes delineated. Thus, the identification of GWPZ by using GIS and RS through AHP is reliable for conducting similar studies.*

***Key word**: AHP, GIS, Groundwater Flow Direction, Groundwater Potential, and, Welmel Watershed*

LISTS OF ACRONYMS AND ABBREVATIONS

AHP	Analytic Hierarchy Process
BCK	Billion Cubic Kilo meter
BCM	Billion Cubic Meter
CI	Consistency Index
CR	Consistency Ratio
CW	Criteria weight
DEM	Digital elevations model
ERDAS	Earth Resource Data Analysis System
FAO	Food Association Organization
GIS	Geographic Information System
GWP	Groundwater Potential
GWPZ	Groundwater potential zones
IDW	Inverse Distance Weighted
LU/LC	Land-use/land-cover
MCDA	Multi-Criteria Decision Analysis
MoWIE	Ministry of Water, Irrigation and Energy
SAGA	System For Automated Geoscientific Analysis GIS
RS	Remote sensing
TM	Thematic map
TPI	Topographic Position Index
USGS	United States Geological Survey
UTM	Universal Transverse Mercator

1. INTRODUCTION

1.1. Back ground

Groundwater is the water that is located in the subsurface and saturates the rocks and soil beneath the ground surface. It has been estimated that 20% of all freshwater used by humans comes from subsurface groundwater resources (Hope, 2020). With separate usage rates continuing to increase, there is a growing need for sustainable and reliable sources of groundwater. To meet this demand, research suggests increased potential for harvesting usable groundwater from readily available subsurface aquifers across the globe (Kamstra et al., 2021)

Among many substances that are necessary to life on the earth, water is the most important for life.Water is abundant, yet frequently scarce and characterized by uneven spatial and temporal distribution. Also water is a finite resource and must be managed in sustainable way to meet human as well as environmental needs.Groundwater is a precious resource of a limited extent.To ensure its judicious use, proper evaluation is required (Rwanga, 2013) .

In Ethiopia,the occurrence and movement of groundwater is mainly influenced by geophysical and climatic conditions of the area. The geology of the country provides good transmission of rainfall to recharge aquifers, which produce springs and feed perennial Rivers (Alemayehu, 2006; Gintamo, 2015). The difficulty in obtaining productive aquifers is the wide heterogeneity of geology, topography and environmental conditions. In many parts of the country, groundwater is an important source of domestic and industrial water use especially in rural areas and towns (Alemayehu, 2006). Hence, the groundwater provides over 90% of the improved rural water supply. About 8.4% of the urban and 56.8% of the rural population of Ethiopia utilize groundwater sources for potable water consumption (Yasin, 2017).

Groundwater is an important natural resource and major contributor to the water supply system in Ethiopia, providing the majority of domestic, agricultural, industrial and hydropower supplies. Ethiopia has a large potential for groundwater resources and many studies have found that Ethiopia holds estimated ground water reserves of 33.2 million cubic meters in its rivers, aquifers and springs. In addition to this, groundwater provides nearly 60% of all renewable freshwater resources within the country (Tesfaye et al., 2018). Consequently, groundwater is found to underpin much of Ethiopia's rural livelihoods and has been referred to as the "lifeblood" of subsistence farmers (Amann et al., 2018). Groundwater is an important source of water in Ethiopia, with much of the available resources confined to the northern lowlands. Despite this, groundwater potential in Ethiopia is generally lower than desired for development due to limited availability and high levels of depletion throughout the country. The average groundwater potential recognized in Ethiopia ranges from $7m^3/s$ to $50m^3/s$, which is far below the global average of 600–1000 m^3/s (Nedaa et al., 2020). Groundwater availability varies widely across different regions, further complicating resource management efforts. For example, some key aquifers such as the Awash Basin and Bilate Sore display a highly productive potential while others such as the Omo-Gibe appear to be mostly unexploited or unexplorable (Yirga et al., 2018)

Ground water is one of Ethiopia's most important natural resources and has the potential to support vital agricultural, industrial and domestic activities. Groundwater potential maps generated by geophysical surveys have estimated that a huge amount of groundwater exists in the western parts and some parts of eastern Ethiopia. Of this, approximately 80 million m3/year can be economically exploitable for irrigation and 10 million m3/day for municipal supply (Gebremariam et al., 2004). Furthermore, nearly 6 billion cubic meters of usable groundwater is found at more then 200 well-defined aquifers in the country (USAID, 2012). Recent studies suggest that several sedimentary hydrogeological basin throughout Ethiopia hold unexploited underground water reserves which needs to be tapped for economic development of the country (Hinnell and Schumann, 2015).. Therefore investments in exploration technologies should be made to fully understand these groundwater stores.

Surface waters are seasonal in their availability and respond immediately to climate change (Fiedler, 1992;Louks and Beek, 2005;Whitehead et al., 2009). A tremendous increase in the demand for groundwater due to an increase in population, advanced irrigation practices and industrial usages need a reliable source of water supply (Jha et al., 2010).Hence the largest and reliable source of freshwater lies under the earth's surface, there is a tendency to think of groundwater as being the primary source of water (Todd, 2005).Assessment of groundwater resources is critically needed to help for mitigation of the effects of drought and reduce the risks of overexploitation (MoWR, 2002).

In developing countries like Ethiopia, most of the hydrogeological investigations have been done by using conventional techniques like ground-based surveys and exploratory drilling. The conventional approaches for groundwater investigation are understood to be time-consuming and uneconomical (Mamo, 2007) .Besides, these methods do not cover inaccessible areas and may not be highly reliable due to the assessment of diverse factors affecting groundwater potential (Doyo, 2020)

Recently, with the help of Geographic Information System (GIS) and Remote sensing, to address a large number of spatial data for quicker and cheaper processing are becoming more useful and mandatory for detection of potential groundwater areas.(Nagarajan and Singh, 2009 Zeinolabedini and Esmaeily, 2015).

Groundwater usually flows from points of higher hydraulic heads to the points of lower hydraulic heads in the direction of maximum change in elevation (Doyo, 2020). Even though the flow of groundwater in the aquifer may not always reflect the surface water flows, it flows either towards or away from streams, rivers, lakes, ponds and boreholes (Amah and Agbebia, 2015). Since the groundwater occurs out of our sight, deep in the subsurface, there is no direct method to facilitate observation of water below the surface. Its presence or absence can only be inferred indirectly by studying the groundwater occurrence and distribution controlling parameters Thus, in order to ensure wise use of groundwater, a systematic evaluation of groundwater is required.

Several researchers have been successfully utilized GIS and Remote sensing techniques for the identification of GWPZ around the world and in Ethiopia.The approach of GIS and Remote sensing techniques for groundwater potential identification indicates an acceptable result.In the present study GIS and Remote sensing multi criteria decision analysis technique is used for mapping the GWPZ of Welmel catchment.

1.2. Statement of Problem

In the world scenario, the availability of groundwater is reduced gradually due to over exploitation, and the lack of groundwater management. Ethiopia has suffered from repeated drought scenarios in the past; especially the peripheries of the country like Genale-Dawa basin are more prone to drought than the interior highlands including this study area. Genale-Dawa River Basin is one of the largest and most drought-prone regions in Ethiopia (Kassahun and Mohamed, 2018).As a result, a search for an alternative source of water has been always a major issue in the region. The study area of welmel watershed at driest seasons even major surface water sources dry up, as a result the available large areas of suitable irrigation land are left uncultivated and in times, standard domestic water supply become scarce.In fact, the exponential growth of urban population, insufficient surface water due to irregular rain season and agricultural-led industrial development have resulted in greater attention to groundwater identification (Dessalegn, 2018). Instead of GIS and remote sensing techniques Groundwater development was done based on traditional field studies (using existing water source site as guideline) is also the main problem. So because of these sequential problems; the communities are exposed to the problem of accessing safe drinking water at acceptable distance. Therefore the primary problems of all these listed things are due to the gap of proper Groundwater potential zone site identification.

1. 3.Objective of the Study

1.3.1. General Objective

The general objective of this study was to map out Groundwater potential zone using GIS and Remote sensing method in welmel water shed Genale Dawa river basin ,South east Ethiopia

1.3.2. Specific Objective

- To prepare thematic maps for groundwater potential affecting parameters.
- To delineate groundwater potential occurrence zone
- To identify the groundwater flow direction of welmel watershed

1.3.3. Research Questions

1. What are the major parameters which affect the occurrence and movement of groundwater of study area ?
2. How to delineate groundwater potential zone using GIS and Remote sensing ?
3. What does the predominant groundwater flow direction of study area look like?

1.4. Significance of the study

This study expected to improve the different water shortage related problems occurring in welmel watershed such study will have a paramount importance to understand the better picture of Groundwater potential zone, Groundwater flow directions and improving the problem of adequate and safe water. In addition to this, any professional interested to work on related issues in this area will be use this Groundwater potential zone identification report as a reference to a detailed study

1.5. Scope of the study

This study is geographically limited to the South Eastern part of Ethiopia which is limited between 5°000” N–7°4500” N latitude and 39°000” E–41°1500”E longitude. In addition to geographically scope of the area, This study specifically focuses on mapping the groundwater potential zone of welmel watershed. As it was a qualitative study the recharge and groundwater storage was not quantified. Since the time and resources are limited the study does not include the analysis of groundwater water quality and the structural design of groundwater conveyance structures.

1.6. Scope and limitation of the Study

This study specifically focuses on mapping the groundwater potential zone of welmel catchment. As it was a qualitative study the recharge and groundwater storage was not quantified. Since the time and resources are limited the study does not include the analysis of groundwater water quality and the structural design of groundwater conveyance structures (borehole/dug well depth, cross-section etc.), rather than mapping suitable groundwater potential zones of catchment . The effect of LU/LC change on groundwater recharge/potential and the suitability of the identified GWPZ for irrigation, water supply and other water resources development projects were not assessed.

2. LITERATURE REVIEWS

2.1. Groundwater Potential Investigation

Water is the most significant natural resource supporting human health, economic development, and ecological diversity. Groundwater is part of the water cycle, and which is stored in the saturated zones underneath the land surface and moves slowly through geologic formations called aquifers. Water could remain in an aquifer for hundreds or thousands of years. The existence and flow of groundwater is controlled by factors such as geological formations, soil type, lineament density, slope, drainage density, rainfall form, morphology, land-use/land-cover characteristics, and the interrelation between them. Most groundwater originates from precipitation that percolates through the rock strata. Groundwater replenished, or recharged, by rain and snow melt that seep down in to the cracks and crevices beneath the land's surface. In different areas of the world, people face solemn water scarcities because groundwater discharge for use is faster than its natural replenishment (recharge).(Negewo & Sarma, 2021)

All water beneath the land surface is referred to as Groundwater (or subsurface water).The equivalent term for water on the land surface is surface water. The potential of Groundwater is depending on the Groundwater recharge amount. Groundwater recharge is the process by which water percolates down the soil and reaches the water table either by natural or artificial methods to replenish the aquifer with water from the land surface (Yongxin, 2003; cited as Aschalew Gurmu, 2019).Groundwater is the most valuable global resource, comprising 96% of the earth's unfrozen freshwater, as well as being the main water source in many water-scarce areas (Kidanu, 2018). It is the only underground water that is available to supply wells and springs, supports wetlands, and maintains land surface stability.About 70% of the world's population depends on groundwater for basic domestic water services. The spatial distribution of GWPZ showed regional patterns related to geologic, physiographic and hydrologic characteristics of the area (Mamo, 2007). Groundwater potential and its flow directions of a given catchment were mapped based on different indicators such as; topography, Groundwater flow pattern and static Groundwater levels. Topography is a major factor which has to be considered for delineating the recharge and discharge zone; high land areas are an indicator of recharge areas (Afewerk, 2011).Identifying Groundwater potential zone using geographic information system(GIS) and remote sensing(RS) is done by considering a nine parameters ; such as drainage density, elevation, geology, geomorphology, land use and land cover, lineaments, rainfall pattern, slope gradient and soil texture. The selected parameters have been prepared and classified using analytical Hierarchical process, then weighted overlay analysis in ArcGIS used to find out the result. The result of the study has been compared with collected sample data to assess the accuracy of the result (Bane Lammesa, 2017; Ramu, 2014; Jha et al., 2010).

2.1.1. Groundwater Potential of Ethiopia

Ethiopia is often referred to as the "rooftop of Africa" because its extensive highlands capture a major portion of the precipitation that falls on the continent (Mamo, 2007).The geology and environmental condition of the country which shaped by complex geological formations, diversity of the topography, climate and soil causes spatial variability of GWPZ. The geology of the country provides usable groundwater resources. In many parts of the country, groundwater is an important source of domestic and industrial water use (Alemayehu, 2006). Groundwater resource in Ethiopia was estimated by different researchers and organizations. However, the estimated values differ from each other.

The MoWR water sector development program main report volume II (2002) estimated the country groundwater resource of 2.6 BCM.A previous study by Makombe et al. (2011) estimated 2.86 BCM of groundwater potential. Later revised by Seleshi et al. (2007), it to be about 28 BCM and other study have estimated it to be above 28 BCM (Seifu, 2012).At present, detailed groundwater assessments in several areas indicate that the estimated groundwater potential of 2.6 BCM by MoWR or 2.86 BCM by Makombe et al. (2011) was underestimated, and it needs to be revised. Best guesses in this respect range between 12 and 30 BCM, or even more if all aquifers in the lowlands are assessed (MoWR and GWMATE, 2011).

The study conducted by Belete et al. (2014) reviews the surface and groundwater resources potential of Ethiopia.The study estimates the country’s groundwater potential of about 30 BCM, With the understanding of the nature of the distribution of rocks and the recharge classification of the country, Alemayehu (2006) estimated the total groundwater reserve of the country as 185 BCM.It was distributed over an area of 924,140 km^2 made of sedimentary, volcanic and quaternary rocks and sediments, including the highlands and the Rift valley. The groundwater potential of the Genale-Dawa River basin alone is estimated to have a groundwater reserve of 2.78 BCM (Kassahun and Mohamed, 2018)

2.1.2. Remote Sensing (RS)

RS is the non-contact recording of information about the earth surface, from the ultraviolet, visible, infrared and microwave regions of the electromagnetic spectrum, by means of instruments such as scanners and cameras, located on mobile platforms such as aircraft or spacecraft followed by the analysis of acquired information by means of photograph interpretation techniques, image interpretation and image processing. The contact between the remote sensor and the target is through electromagnetic energy such as visible, thermal and infrared radiation, force fields that are gravity magnetic (Kibrit, 2018).

2.1.3. Groundwater Potential Mapping Using GIS and Remote Sensing

Before the incorporation of RS techniques, groundwater potential study was only done by using the data from field observations. In developing countries like Ethiopia, most of the hydrogeological investigations have been done using conventional techniques. The conventional approaches for groundwater investigation like ground-based surveys and exploratory drilling are understood to be time-consuming, uneconomical and able to cover small areas of land (Mamo, 2007; Marghany et al., 2009).

Several researchers have successfully utilized GIS and RS technologies in the identification of GWPZ around the world.RS in the form of aerial photography, satellite imagery and geophysics evolved as solutions with larger coverage, lesser collection period and access to physically inaccessible areas. The study conducted by Gebrie et al. (2019) delineates the GWPZ of the Guna tana landscape, upper Blue Nile basin of Ethiopia by using GIS and RS. MCDA techniques were used to develop the GWPZ by integrating different groundwater contributing thematic layers. The study approach involves integration of thematic layers based on the weights assignment and normalization concerning the relative contribution of the themes to groundwater occurrence using Saaty's AHP. The GWPZ were classified as low, moderate and high zone. Validation of the result with existing water point yield data highlights the efficiency of the integrated RS and GIS methods for GWPZ mapping.

Generally, a various study conducted by several researchers on the worldwide, continent and in Ethiopia shows the efficiency of the integrated RS and GIS methods for GWPZ.The approach provides a proper groundwater resources evaluation, quick guides of perspective groundwater exploration and exploitation (Arshad et al., 2020; Berhanu and Hatiye, 2020; Çelik, 2019)

2.2. Factors That Affects Groundwater Potential

The occurrence of groundwater potential is mainly influenced by the geophysical and climatic conditions of the area. The difficulty in obtaining productive aquifers is a peculiar feature of Ethiopia, which is characterized by the wide heterogeneity of geology, topography and environmental conditions (Alemayehu, 2006). An integrated approach of RS and GIS was adopted to assess the groundwater potential in the Southern lowland of Ethiopia, Moyale-teltele Sub-basin of Genale-Dawa River basin. The lithology, geologic structure, geomorphology, slope, LU/LC and drainage density were considered for mapping groundwater potential zone (Mamo, 2007).

The latest study of groundwater potential assessment using a similar technique were conducted by Andualem and Demeke (2019); Gebrie et al. (2019); Berhanu and Hatiye, (2020) and Gebru et al., (2020). The studies consider several factors including; lithology, geological structures, soil, lineament features, slope, drainage pattern, geomorphology, LU/LC, normalized difference vegetation index (NDVI) and topographic wetness index (TWI) to identify the occurrence and movement of groundwater.

Even though the degree of influence will vary depending on the hydrologic, hydro-geologic and topographic or physiographic factors almost all the considered factor influences the GWPZ. Therefore, in order to obtain more accurate information about the occurrence and distribution of groundwater increasing the number of parameters is mandatory. To bound the factors in Saaty's random consistency index (RI) which computed for $n \leq 10$ and minimize the complexity of finding the plausible random index for $n > 10$ some factors which is possible to describe by dominant factor (major factors encompassing the minors) are merged together.

2.2.1. Elevation

Elevations also lead to better environmental conditions, including better soil permeability and increased infiltrated surface water runoff (Fissaha et al., 2020; Wang et al., 2020). In addition, high elevations allow for favourable weather conditions, resulting in higher precipitation amounts which may be beneficial for recharge of groundwater resources (Tefera et al., 2019). As such, these regions tend to contain good quality sources of drinking water and can provide valuable sources for regional water use (Meki et al., 2018). The identification and monitoring of potential groundwater sites at any specific site relies heavily on understanding the effects of elevation (Drammeh et al., 2016)

Elevation is one of the main inputs parameters of delineation Groundwater potential zone. It is known that water tends to store at lower topography rather than at the higher topography (Ramu et.al. 2010). To prepare the elevation, slope and drainage map, either the SRTM or ASTER DEM 20m data could be used. In this study, SRTM DEM 20m was selected since it is more accurate both in its vertical and horizontal accuracy than ASTER DEM (Odutola et al., 2012; cited in Kibrit, 2018).Hence elevation should be considered in the factors affecting groundwater potential of an area. Naturally topographical high lands can generally be considered recharge areas and topographically low areas can be considered discharge areas (Kiflu et al., 2009).

2.2.2. Geomorphology

Geomorphology plays an important role in understanding the groundwater potential mapping in Ethiopia. Different geomorphic surface features, such as slope, soil type, and landform relief, affect extents of groundwater recharge, store groundwater and thus determine local water availability (Maru et al., 2019)

The study of landforms is an important branch of earth science that can be used for the prediction of watershed characteristics (Mokarram et al., 2018).The ability to classify the continuous terrain surface into meaningful and discrete features provides a way to describe, analyze and quantify the characteristics of landscape (Blaszczynski, 1997). A study conducted by Gebru et al. (2020) identifies the GWPZ of the Golina River Basin, Northern Ethiopia. The geomorphological landforms of the areas classified by topographic position index (TPI) techniques using SAGA GIS software from the DEM. Accordingly, the geomorphological landforms of the area are classified into the plain, valley, open slope, upper slope, mid-slope drainage, stream, upland drainage, local ridge, mid-slope ridge, and high ridges.

The normalized weight value of plain and valley landforms is higher than the others for groundwater potential.While ridges are lower for groundwater potential (Gebru et al., 2020). Analysis of landform using TPI shows more logical and realistic landform interpretation associated with the landform classes (Alemayehu et al., 2019).The results of the TPI approach derive accurate results for all selected input datasets in comparison to ground-truth data from a geomorphological field survey (Kramm et al., 2017). Several studies assign the highest weight for the geomorphological landforms (Doyo, 2020; Waikar & Nilawar, 2014).

2.2.3. Soil Texture

A recent study on the effect of soil texture on groundwater potential mapping in Ethiopia was conducted by Tadesse et al. (2018). The authors used the geographic information system (GIS) and remote sensing technology to examine the influence of different soil types on groundwater resources in the Amhara region of Ethiopia. The results showed that soil texture was an important factor determining regional aquifer recharge potential. Specifically, areas with high clay content (such as red clay soils) had lower groundwater storage capacity and more seasonal water stress, while those with sandy soils had higher overall recharge potential and greater seasonal stability. Additionally, this study identified areas ideal for well construction based on local hydrogeological features, such as hydraulic parameters, hydraulic conductivity and water-bearing formations. Thus, the findings from this paper provide essential guidance for sustainable groundwater management in Ethiopia.

The type and texture of the soil have an important role on the amount of water that can be infiltrated into the subsurface formation.Soil store rainwater in their pores before it infiltrates to greater depths and recharges the aquifer system.The water stored at the upper layers was evaporated easily, it negatively affects Groundwater potential (Habtamu, 2014).The major soil in catchment are eutric cambisols, chromic cambisols, leptosols (formerly lithosols), rendzic leptosols, developed from limestone (formerly rendzinas), chromic luvisols, pellic vertisols and chromic vertisols (Yared et al. 2020). It comprised the major soil texture of clay, clay loam and loam.

2.2.4. Land Use Land Cover (LU/LC)

Ethiopia, recent studies on the impacts of land use and land cover (LULC) on groundwater potential mapping have indicated a strong association between LULC and aquifer properties. These studies suggest that increases in urbanization and increasing soil erosion from land degradation have had negative impacts on groundwater potential. Surface water runoff has also been identified as an important influencing factor when assessing aquifer potential. One study found that changes in vegetation cover due to conversion of forested lands to agricultural fields led to an increased infiltration rate of surface runoff into groundwater aquifers, leading to decreasing groundwater storage potential in unconfined aquifers (Mathavan, et al., 2019).

Additionally, a recent study utilized remote sensing data to analyzed the influence of LULC change and its effect on groundwater recharge in Ethiopia (Ogbazghi et al., 2020).

The study indicates that forests, woodlands and areas with low built-up area are more conducive for high levels of groundwater recharge than other LULC categories such as bare rock surfaces or barren lands. The research suggests that increasing land conversion can act as a barrier for recharging shallow aquifers, thus leading to lower long term water security and lower productivity within localized areas.

Groundwater potential was affected by different classes of LULC. Forests and agricultural lands increases the Groundwater potential by trapping and holding the water in root of plants, whereas the built and rocky land affect the recharge of Groundwater by increasing runoff during rainfall.

Information on the rate of changes in land resources is essential for proper planning, management and regulating the use of land resources

2.2.5. Drainage Density

Drainage Density is the measure of the total length of the stream segment of all orders per unit area, which is inversely proportional to permeability (Magesh, 2012).Drainage in an area depends on the topography, slope and sub-surface characteristics (Elango, 2017).). The term drainage density of the basin first introduced by Horton(1932) which is defined as the ratio of total (cumulative) line length of stream network to the basin area(the area of consideration) which describe the closeness of the spacing of the stream channel and river. It can be calculated by using the following formula:

$$\text{Drainage Density (Dd)} = \frac{Total\ length\ of\ the\ straem\ network}{Total\ basin\ area} = \sum_{i=1}^{n} \left(\frac{Si}{A}\right), \frac{km}{km2}$$

Where, Si denotes the total length of stream network (drainage, km), and A denotes the total basin unit area (km^2).

- High drainage is the resultant of weak or impermeable surface (fine texture soil type). Sparse vegetation and mountain relief which have high runoff and low infiltration result. While low drainage density is the result of high permeable subsoil (course texture soil type) and low relief which have less runoff and high infiltration.
- High drainage density indicate high runoff and less infiltration which results in less occurrence of groundwater and reverse are true, low drainage density has less runoff

and high infiltration results in high contribution of groundwater potential and recharge (Waikar and Nilawar, 2014). .

2.2.6. Rainfall Distribution

Recent research suggests that groundwater potential mapping in Ethiopia is highly affected by rainfall distribution. In particular, a study published in 2019 states that changes in the spatial and temporal patterns of rainfall in the country have increased vulnerability of groundwater resources due to an inadequate hydrological balance (Feleke et al.,2019). Additionally, another article from 2021 finds that the accuracy and precision of mapping groundwater recharge zones for different parts of Ethiopia relies largely on understanding the seasonal variations of precipitation, surface runoff, evapo-transpiration and other factors (Tadesse et al., 2021).

Rainfall is an important factor for the formation of groundwater potential (Kidanu, 2018). The spatial distribution of rainfall in Ethiopia is significantly influenced by the topographical variability of the country (Camberlin, 1996). Rainfall is the major source of recharge Ethiopia; that determine the amount of water would be to percolate into the Groundwater system (Genet Mathewos, 2017). Ethiopia, seasons are classified based on rainfall pattern, Indicates that there are three major seasons; kiremt (main rain season from June to September), Belg (small rain season from February to may) and bega (dry seasons from October to January (Birhanu, 2009).Due to an even distribution of Topography the climate condition of welmel water shade are characterized by The northern part of the watershed has a bimodal rainfall distribution, as in most parts of south eastern Ethiopia: from February to May (the "short rains"), with a peak in April, and; from June to September (the "long rains"), with a peak in August (Degefu et al. 2017).

2.2.7. Slope

A number of recent studies have been conducted to examine the influence of slope on groundwater potential mapping in Ethiopia. For example, an assessment of the impacts of topographic and textural parameters (slope, lithologic composition) on the groundwater potential (GWPs) was conducted at the system level in Southern Oromia, Ethiopia (Gebre et al., 2020). Results indicated that soil properties and slope appear to be important parameters for GWPs estimation. On a regional scale, Tesfaye et al. (2019) found that significant correlations were observed between slope and groundwater recharge and availability

Slope is an important factor for the identification of Groundwater potential zones, higher degree of the slope results in rapid runoff and increase erosion rate which decreases recharge (Magesh, 2012). This so indicate high slope regions have high runoff and low infiltration rate that are not suitable for groundwater recharge, because of water cannot get enough time to infiltrate to the ground and vice versa. The slope map of the area is extracted from digital elevation model (DEM) using surface-spatial analysis tools in ArcGIS.

2.2.8. Lineaments

Recent studies have identified lineament as one of the most important hydro-geological features for groundwater potential mapping in Ethiopia. The recognition of lineaments has helped to better understand how faults and fractures can affect the distribution of groundwater resources beneath the surface and enhance subsurface exploration programs. A study by Konde et al. (2020) used GIS-based lineament density analysis to map sub-surface structural conditions in order to identify suitable zones for shallow aquifer development in the Dawuro zone, Southern Ethiopia. Their results demonstrated that areas with high lineament densities indicate areas with higher potentials for groundwater development than other parts of the area with lower lineament densities.

Lineaments like joints, fractures and faults are hydro geologically very important and may provide the pathways for groundwater movement. The lineament density is generated by extracting the lineament from DEM using the Arc toolbox and drainage network is created using ArcGIS

Lineament density (Ld.), defined by (Murasingh and Jha, 2013; Das and Pardeshi, 2018) is the total length of all the lineaments demarcated divided by the total study area expressed in (km/km^2), as:

$$Ld = \frac{Total\ length\ of\ all\ lineament}{Total\ area} = \sum_{i=1}^{n} \left(\frac{Li}{A}\right)$$

❖ Where, Li = the total length of lineament (km), and A= the unit area (km^2).

Areas with high lineament density are good for groundwater potential whereas the areas with low lineament density are poor in groundwater potential. Therefore, as lineament density of the area increases, the potentiality of groundwater of the area increases.

2.2.9. Geology/Lithology

Lithology/Geology is one of the most important factors which play a significant role in the distribution and occurrence of groundwater as well as the quantity and quality of the groundwater in the given area. It determines the aquifer characteristics and underlain rock porosity which govern the percolation/infiltration and permeability of water flow. It affects ground potential, by controlling the infiltration of water flow in subsurface aquifer. Porosity of the rock determines the storage capacity of rock formations. Sedimentary rocks were considered as having a high potential for groundwater due to their high porosity and permeability relative to igneous and metamorphic rocks. Relatively among other factor, geology is the 3rd dominant factor influencing groundwater and recharge which assigned the highest weight among all factor (Thapa and Gupta, 2017)

2.3. AHP and its Application in Groundwater Potential Zone Mapping

The Analytic Hierarchy Process (AHP), introduced by Thomas Saaty (1980), is an effective tool and internationally acceptable for dealing with complex decision making, and may aid the decision maker to set priorities and make the best-fit decision. It can be used in many fields of studies which attempted to identify groundwater potential zones that the important factors which affect the occurrences of groundwater are slope, drainage density, lithology, geomorphology, land use/cover , lineament density , soil type and rainfall(Aneesh and Paresh Deka, 2015; Ramu *et al.*, 2014; Sajikumar and Gigo, 2013). So depending upon the suitability and the type of region of study, all the nine parameters or any few relevant parameters have been chosen and weighted by AHP to generate groundwater potential zones (Rajkamal *et.al.*,2014; Guptaa and Srivastava, 2009; Rambabu *et al.*, 2015). In the studies done to identify groundwater potential zones in Bengaluru and Mysuru (Aneesh and Deka, 2015; Ramu *et al.*, 2014), all the above mentioned criteria have been used and thematic maps have been made and given proper weight based on the importance to groundwater occurrences and movements.

2.4. Geographic Information System (GIS) and Remote Sensing (RS)

GIS and RS techniques is the most advanced technology for scientific application of groundwater exploration and water-level fluctuation trend assessment (Amah and Agbebia, 2015; Senanayake et al., 2016). It allow to access large data at the same time which are impossible to reach such as cliff, mountains and gorges (Solomon, 2003). GIS and RS techniques can be used to easily characterize groundwater potential and recharge zone (Senanayake et al., 2016). RS provides information with regard to spatial distribution of vegetation type and land use in less time and low cost in comparison to conventional data (Waikar and Nilawar, 2014).

Comparing GIS and RS applications of groundwater delineation with other methods such as geospatial, numerical modelling and geophysical methods, those methods are very expensive, laborious, time-consuming and destructive (Salwa, 2015). Generally, a number of works done on the role of GIS and RS for GWPZ delineation shows its efficiency, time and cost effectiveness of the technology.

2.5. System for Automated Geoscientific Analysis (SAGA) GIS

SAGA is a free Geographical Information System with support for vector and specially raster data (Olaya, 2004). SAGA GIS software, which was developed by a team of geospatialists at the Department of Physical Geography, University of Gottingen, Germany, facilitates faster geomorphometrical calculations and terrain computations.

This particular software has been designed for easy and effective implementation of spatial algorithms (Zawawi et al., 2014). It simplifies the analysis of raster data, particularly of DEM, which have been used to predict terrain-controlled process dynamics (Conrad et al., 2015). Whilst there are a number of sophisticated free open source raster analysis packages available, SAGA GIS was chosen as it provides the simple process for sophisticated hydrological and terrain modelling, easily comprehensible interface similar to other GIS packages and works seamlessly with all standard GIS data formats. SAGA GIS software was effectively used in process of terrain attributes computation that characterized the landform (Zawawi et al., 2014). Considering the above advantages application of SAGA GIS was employed by various researchers. The TPI based landforms of Golina River Basin, Northern Ethiopia was prepared using SAGA GIS software from the digital elevation model (DEM). .

2.6. Surfer 13

Surfer is a powerful contouring, gridding and surface mapping package that interpolates irregularly spaced XYZ data into a regularly spaced grid. The grid is used to produce different types of maps including contour, color relief, cross-sectional profiles and 3D surfaces. The program allow users to produce easy and quick publication quality maps, by adding multiple map layers and objects, customizing the map display and annotating with text to create attractive and informative maps map that best represents data.

3. MATERIAL AND METHODES

3.1. Description of Study Area

3.1.1. Location of Study Area

Welmel watershed found in South eastern part of Ethiopia, in Oromia regional state, Bale Zone at about 423 km of Addis Ababa. The catchment situated in Genale-Dawa basin at the uppermost portions of the Web Sub-watershed, which is one of the Sub-watersheds of Genale-Dawa Basin. It is located between 5˚0′0″ N–7˚45′0″ N latitude and 39˚0′0″ E–41˚15′0″ E. The mean annual precipitation experienced in the area is 810 mm, and the distribution of rainfall in the watershed ranges from 300 to 1,303 mm per year. The monthly temperature ranges from 14.5°C to 24.6°C, with an average of 19.5°C. The maximum and minimum elevation of the area is 4238 and 362 to m ASL, respectively .Its watershed covers an area of 14,512 km^2. It crosses the Adaba, Berberi, Dinsho,Goba, Goro,Delomana, Gura-Damelo ,Harena Buluk, Madawalabu ,Mena, Sinana and administrative districts of Oromia regional state,south-eastern Ethiopia Figure (3.1).The land cover of the watershed encompasses dense forest in the northern part and open forest in the middle of the watershed however ,the lower altitude southern part of the study area is characterized shrub land, grassland ,degraded bare ground land

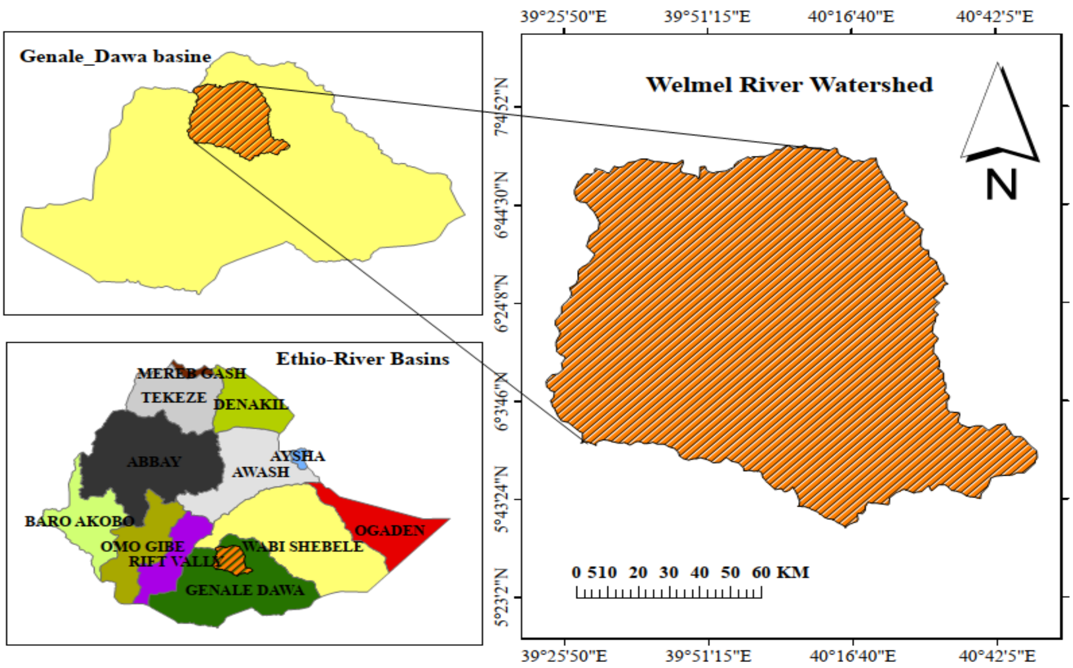

Figure3.1.Location map of the study area

3.1.2. Climate

The climate change impact on the hydraulic cycle is one of the major challenges in the context of water resource management (Messene, 2017). Due to the wide range of altitudinal extent, the seasonal variation of welmel watershed recognized, the northern part of the watershed has a bimodal rainfall distribution ,as in most part of south-eastern Ethiopia : from February to May (short rain) with peak in April and from June to September (the long rain)with peak in august (Degefu et al 2017).

Due to the great variation in altitude and the great bulk of the mountain massif itself, the climatic condition of welmel watershed shows a considerable variation (Gobena et al., 1997).Thus, the area comprehends four climatic regions of Alpine (Wurch), Temperate (Dega), Sub-tropical (Weynadega) and Tropical (Kola).Area of elevation above 3300m a.m.s.l. and a temperature less than 10°c are classified under Alpine climate region (Kiflu et al., 2009). This includes parts of Bale Mountain National Park, Dinsho-Gassy plain and Sanate plain highlands. The temperate climatic condition includes the area within the elevation range of 2300-3300m a.m.s.l. and temperature varies from 10 to 15˚c. This includes most of the plateau area up to the mid-slope mountain peaks.

The steep slope of Bale mountain high land along the Goba-Meliyou area and Sheneka Plain are classified under zone of temperate climatic conditions. The area within the elevation range of 1500-200 meter and temperature of 15 to 20 °c is classified under Sub-tropical climate region. The tropical zone occurs between altitudes 500-1500 m and temperature of about 30°c.This includes the Eastern lowlands of study area with hot to very hot temperatures. Tropical and sub-tropical climatic regions are not extensive. Alpine and temperate are the principal climatic regions to represent the study area.

The Rainfall of study area is mainly caused by orographic and direction of moisture-bearing seasonal air currents. These are the main factors accounting for the seasonal distribution of rainfall in the area. Though the duration, amount and spatial distribution of the rainfall varies in the plateaus and low lands, a bimodal type of rainfall regime is generally observed (Mulugeta and Tafa, 2010)

The bimodal pattern of rainfall divides the year into two main seasons: a main rainy season from July to October and a minor rainy season from March to May (Kassahun and

Mohamed, 2018).The dry season spans from November to February.The annual mean rainfall in the lowlands and highlands varies between 546 – 1352 mm. The annual mean areal rainfall of the study area is 918.7mm /yr. The mean annual maximum and minimum temperature of the study area is 29.10°C and 15.6°C, respectively.

a) Estimation of Missed Data

The studies of water resources development and management depend heavily on hydro meteorological data.These data should be stationary, consistent, and homogeneous when they are used to compute a hydrological system. If it does not fulfil one of the above criteria, its result wills in a big problem that contradicts the actual situation. The missing data can be estimated by using the data of neighbouring stations (Subramanya, 2008).A number of methods have been proposed for estimation of rainfall missing data. The normal-ratio method is preferable. Normal ratio method is a method that recommended estimating missing data in a region where unevenly (non-uniform) rain gauge network over the study area and the annual rain fall among stations differ by more than 10%. %. Because of such problem the study area's meteorological stations are distributed unevenly so due to this problem Normal ratio method was preferable and calculate as

$P_{X=}\frac{1}{n}\,[p_{1*}\frac{Nx}{N1}+p_{2*}\frac{Nx}{N2})+p_{3*}\frac{Nx}{N3}\ldots\ldots\ldots.+pn*\frac{Nx}{Nn}]$,where

P_x and N_x the corresponding values for the missing station X

P_1, P_2, P_3…....P_n are the annual precipitations data

n is the number of stations

N_1, N_2…….N_n, the normal annual rainfall

3.1.4. Land Use and Land Cover (LU/LC)

Land use describes human operations such as land related agriculture, settlement, and industry, while as the land cover relates to features such as lakes, mountains, vegetation, and rocks on the surface of . The land cover of the watershed encompasses dense forest in the northern part and open forest in the middle of the watershed; however, the lower altitude southern part of the study area is characterized by shrub lands, grasslands and degraded bare grounds (Hurni et al. 2016).

The lower area is dominantly characterized by agriculture (agriculture/settlement).The types of crops grown in the area include; maize, teff, sorghum and sesame among annual crops and coffee and fruits among perennial crops (Teketay, 2001; IBC, 2005; MoWR; 2007; Mulugeta and Tadesse, 2010).Agricultural land is covers from the middle to downstream parts of the river watershed. It is the land cover under the crop cultivation of annual crops. The downstream and south eastern part of the watershed area is largely characterized by cultivation land use and woodland. The middle part of the catchments is dominantly characterized by forest following by cultivation land. Crops like sorghum, maize, sesame and teff are grown by two rain-fed seasons March to June and September to December. Cultivation intensity increases gradually from the canter and goes to the south, south eastern, north eastern and north western parts of the command area.

3.1.5. Geology and Geomorphology

Geomorphology of the area is represented by denuding hills, which are structurally controlled with or without complex folding and faulting, residual hills, plateaus, valley fill, pediments, and buried pediments, pedi-plains, and alluvial plains. Pediments are gently sloping smooth surface of erosional bedrock with thin detritus. Alluvial plains land surface produced by extensive deposition of alluvium, usually adjacent to a river that periodically overflows its banks. The major part of the area is characterized by an undulating topography with in numerable local depressions (Welmel Irrigation project 2006). Table 3 Hydraulic conductivity values of different geologic medium on welmel catchment (Geologic coding is presented in appendix 3 and is consistent with fig 4)

Table 3.1: Hydraulic conductivity values of different geologic medium on welmel catchment. Source.(Nebiyou kassahun2015)

Geologic class code	Hydraulic Conductivity			
	Kx(m/s)	Ky(m/s)	Kz(m/s)	Keq
Ja	8.64E-05	8.64E-05	8.64E-05	8.03E-07
Jg	1.30E-05	1.30E-05	8.64E-05	1.20E-07
Jh1	8.64E-05	8.64E-05	8.64E-05	8.03E-07
Jh2	1.73E-05	1.73E-05	2.16E-04	2.54E-07
Ka	8.64E-05	8.64E-05	8.64E-05	8.03E-07
NMt	8.64E-04	8.64E-05	8.64E-05	2.54E-06
Nn	8.64E-04	8.64E-05	1.73E-04	3.59E-06
Ntr2	8.64E-04	8.64E-05	8.64E-05	2.54E-06
Ntr3	8.64E-05	8.64E-05	8.64E-05	8.03E-07

Pcgb1	5.18E-04	5.18E-05	1.30E-04	1.87E-06
Pcgn2	8.64E-08	8.64E-08	4.32E-07	5.68E-11
Pcgn3	8.64E-08	8.64E-08	8.64E-08	2.54E-11
Pcgn4	8.64E-08	8.64E-08	8.64E-08	2.54E-11
Pcgt2	4.32E-07	4.32E-07	2.16E-07	2.01E-10
PNb1	1.73E-04	1.73E-05	1.73E-05	2.27E-07
PNb2	8.64E-05	8.64E-05	8.64E-05	8.03E-07
PNtr1	8.64E-08	8.64E-08	8.64E-07	8.03E-11
Q	2.16E-03	2.16E-03	2.16E-03	1.00E-04
Qa	4.34E-03	4.34E-03	4.34E-03	2.86E-04
Qv	4.34E-04	4.34E-04	4.34E-04	9.03E-06
Tsy	1.30E-04	8.64E-04	1.30E-04	3.81E-06

The geologic table 3.1. of the catchment shows the configuration of individual geology classes that are listed in the table above. The Welmel watershed represented by older group of rocks, granitoid gneisses and basement complex rocks. The older rocks consist of hornblende schist, biotite schist, sandstone and syenite, while granitoid gneisses are represented by hornblende gneiss, hornblende-biotite gneiss, and migmatitic gneiss. Basement complex rock includes hornblende and biotite granites (Welmel Irrigation project 2006.)

3.1.6. Hydrogeology of welmel water shed

From the hydraulic conductivity values obtained from calibration in the above table it can be seen that many geological formations have similar hydraulic properties, for instance geologic mediums (1,3,5,9, 16) ,(6 and 8),and (12 and13) have the same hydraulic conductivities where as others if not the same they have close similarity. Geologic characteristics of the welmel water shed can therefore be better understood if geologic mediums with similar hydraulic conductivity are grouped together. Accordingly, the following groups have been made.

- High hydraulic conductivity geologic medium (>1×10*-4 m/s)
- Moderately high hydraulic conductivity geologic medium (1×10*-4 to 1×10*-5 m/s)
- low hydraulic conductivity geologic medium (1×10*-5-1×10*-7 m/s)
- Very low hydraulic conductivity geologic medium (1×10*-7 to 1×10*-11 m/s)

3.1.7. Soil

Soil is one of the important factors which control the movement and occurrence of groundwater potential (Natural Resource Conservation Service, 2015). The Welmel watershed area has eight soil types, i.e., eutric cambisols, chromic cambisols, leptosols (formerly lithosols), rendzic leptosols, developed from limestone (formerly rendzinas), chromic luvisols, pellic vertisols and chromic vertisols (Yared et al. 2020). The largest area is occupied by chromic vertisols and rendzic leptosols (altogether, 49% of the studied area) (Yared et al. 2020).

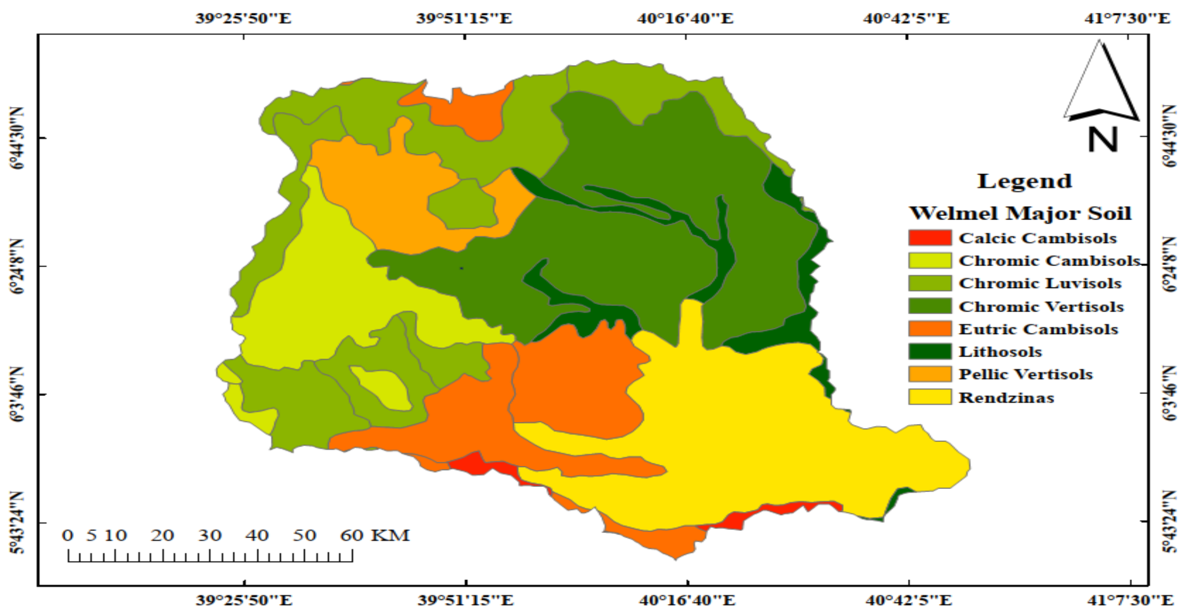

Fig 3.3.Soil map of the study area

3.1.8. Welmel water shade woreda

Welmel water shade woreda are Adaba, Berberi, Dinsho, Goba, Goro, Delomana, Gura-Damelo ,Harena Buluk, Madawalabu ,Mena, Sinana and administrative districts of Oromia regional state,south-eastern Ethiopia (Figure 3.4) showed below

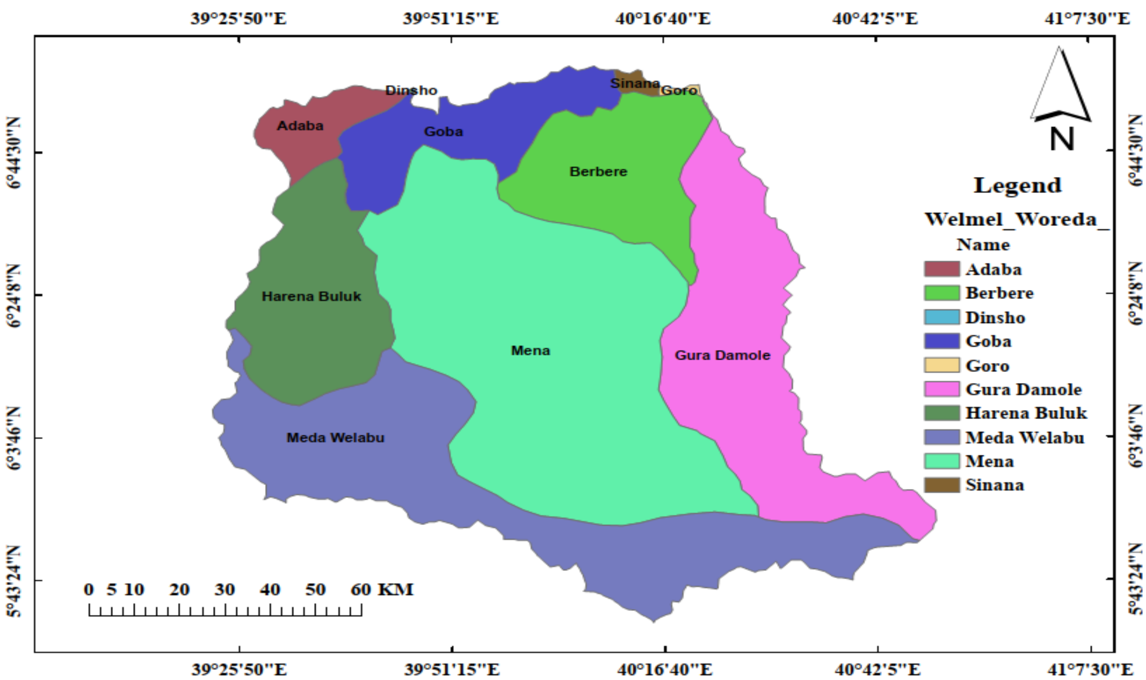

Figure 3.4.woreda map of study area

Data Collection and Analyses

To meet the objective of studies various data were collected from various sources .Published and unpublished literature of different articles have been reviewed and used as input to obtain more information about findings, methods, gaps and recommendations in/of previous studies. Software and computer programs employed for analysis of raw data .In general types of data and its sources are listed in table (3.2) below and preparation of thematic layers were reviewed in Section 3.4 .

Table 3.2 Types of data and data source

Data Types	Data	Scale/Resolution /Format	Source	Functions
Primary Data	DEM Data	SRTM (20m*20m) Resolution	United States Geological Survey (2018)	Used to generate Slope, Drainage and Geomorphology map of the study area
	Landsat 8 of (2018) data	ETM+ (20m*20m) (2018 year)	United States Geological Survey (2018)	Used to generate Land use Land cover map of the study area
	Rainfall data	Excel Format	National Metrological Agency(1989-2013)	Used to generate Rainfall map of the study area
	Borehole Data	ExcelFormat (2010)	Collected by Handled GPS	Used to validate the groundwater potential ma
Secondary Data	Geology Map	1:800,000	Ethiopia Geological Survey (2018)	Used to generate Geological and Lineament Map of the study area
	Digital soil Map	Shape File	Ministry of Agriculture	Used to generate the soil map of the study area

3.4. Preparation of Thematic Maps

Parameters influencing groundwater potential and their relative importance were reviewed from previous literature and hydrological experts. In process of identification and evaluation of criteria, nine (9) factors, these are (Land uses Land cover, Soil, Drainage density, Slope, Geomorphology, lineaments, Elevation, lithological formations and rainfall characteristics).

A) Geomorphological Landforms Thematic Map

The geomorphology thematic map of study area was prepared by topographic position index (TPI) methods of landform classification (Gebru et al., 2020). SAGA GIS software was employed as it provides simple process for sophisticated hydrological and terrain modelling (Fisher et al., 2017). The preprocessed SRTM DEM of 20*20m resolution was used for landform classification (Drăguţ and Eisank, 2012). TPI compares the elevation of each cell in a DEM to the mean elevation of a specified neighbourhood around that cell. Positive TPI values represent locations that are higher than the average of their surroundings. Negative TPI values represent locations that are lower than their surroundings. The TPI values near zero indicates either flat areas or areas of constant slope (Jones et al., 2000; Mokarram and Sathyamoorthy, 2016).

B) Lineament Density Map

Lineaments are straight or approximately linear landforms that are widely distributed across the surface of the earth and are closely related to underground concealed faults (Aschalew Gurmu, 2019). Most of the lineaments are formed as faults and fractures in the direction of slightly inclined stratigraphic regions. Depend on the valuable information related to geological structures, tectonics, hazard assessment, and natural resource availability the direction, density and number of lineaments will be decided. Just likes of these descriptions, the study area Groundwater potential also affected by such structure.

C) Geology Thematic Map

The geologic thematic map of study area was prepared from the geological map sheets collected from GSE and MoWIE. The geological map of the study area at scale of 1:250,000.The relative weight of lithological units, scale value are given in Table 4.3 (Banti, 2017; Kidanu, 2018)

D) Rainfall Thematic Map

Meteorological data collected from NMSA, SOMSC and MoWIE for Melka Amanna ,Dello Mena, Angetu stations. Thiessen polygon method is a good alternatives in cases where there are large differences in the catches and the rain gages are not uniformly distributed throughout the watershed (Barbalho et al., 2014; Subramanya, 2008). It is frequently used, easier and more reproducible method (Ayenew et al., 2013; Doyo, 2020; Munyaneza et al., 2014). ArcGIS was employed to prepare the Thiessen polygon of study area. In process, the weather stations were geo-referenced with respective location and average annual rainfall. The clustered polygon shapefile was converted to raster format for reclassification and overlay analyses. Depending on the contribution of rainfall classes the classified rainfall distribution classes were ranked. The highest rank was assigned for high rainfall classes while the lowest rank for low rainfall class

E) Drainage Density Thematic Map

The drainage network of study area was derived from DEM. Drainage density is the total length of streams of all orders (km) per drainage area (km^2) (Magesh et al., 2012; Sukristiyanti et al., 2018).

The drainage density is be given by:

$$DD = \sum_{i=1}^{n} \left(\frac{Li}{A}\right) \quad \text{...Equation (3.1)}$$

Where DD is drainage density, $\sum Li$ is the total length of the stream in the watershed and A is the total area of the watershed.

Low drainage densities indicate excessive permeability of the underground formation, dense vegetation and low relief (Kudnar and Rajasekhar, 2019). Surface runoff is not rapidly removed from the watershed, showing a slow hydrologic response. The high drainage density of the watershed reflects high runoff and low infiltration, showing a quick hydrological response to rainfall events. Area of high drainage density has an impermeable sub-soil material and sparse vegetation (Sukristiyanti et al., 2018).

Commonly very high drainage density was recorded at the volcanic mountain’s and near the mountain’s foot, while very low drainage density was recorded at the central rift floor (Drummond and Erkeling, 2014). Depending on the contribution of drainage classes for groundwater potential, the rank are given, finally drainage density map was reclassified on basis of the scale value.

F) Slope Thematic Map

The thematic map of slope was extracted from SRTM DEM of 20*20-meter spatial resolution by using ArcGIS 10.7.1.The steeper the surface the greater is the slope. Regional topography and slope data can provide important information on the nature of geology. The slope map was generated from the digital elevation model (DEM) using ArcGIS 10.7.1 spatial analysis tool. High slope regions have high runoff and low infiltration rate that are not suitable for groundwater recharge, because of water cannot get enough time to infiltration to

G) Elevation Thematic Map

The thematic map of elevation was extracted from DEM by using ArcGIS 10.7. The generated map of elevation was ranked as per contribution for groundwater potential and reclassified into four classes to prepare the final thematic layer of elevation.

The highest rank was given for low elevation zone and vice versa (Berhanu and Hatiye, 2020; Doyo, 2020; Godebo, 2018). elevation map was ranked and the thematic layer was reclassified by using scale value (Table 4.7).

H) Land Use and Land Cover (LU/LC) Thematic Map

To prepare the LU/LC map of study area the pre-processed Landsat 8 OLI/TIRS multi-spectral images of 2019 was used. Supervised images classification technique was employed by using the actual points and linking ERDAS Imagine 2015 with Google earth. Land use Land cover gives essential information on infiltration, Soil moisture, Groundwater, Surface water. It is a direct effect on the hydrological process of surface runoff, evapotranspiration and groundwater recharge. Water body, agricultural land and the water logged area are excellent sources of ground water recharge, while the bare lands and exposed rock surface areas are less important for ground water recharge.

I) Soil Texture Thematic Map

The soil map of welmel catchment was clipped from the soil map of Genale-Dawa River basin. The soils are classified on the basis of the revised legend of FAO/UNESCO soil map of the world (FAO, 1988). The soil shape file was converted to raster format on ArcGIS 10.7.1. software's platform. Since the rate of infiltration, permeability and recharge depends on the soil textures, the identified types of soils are reclassified on basis of soil texture (IUSS Working Group WRB, 2015). Clay soil particle diameter is less than 0.002 mm and not visible (Nachtergaele et al., 2009).

Loams are soils with mixed particles of sand, silt and clay. The rate of infiltration of sandy soil is higher than in a silty soil. In a clayey soil, it may be initially high (for heavy black clay with cracking), but becomes low when the soil is moist to wet. Using USDA soil texture classification method, the soil texture class corresponds to a particular range of separate fractions are determined .Finally, the identified soil texture was reclassified on the basis of groundwater potential contribution.

3.6. Delineation of Groundwater Potential Zones

A GIS and RS technique was applied to delineate the GWPZ of welmel watershed. The application of, Analytic hierarchy process, was used to develop the GWPZ's by integrating nine groundwater influencing factors. The thematic layer of geomorphology, lineament density, geology, slope, rainfall distribution, drainage density, LU/LC, elevation and soil was prepared.

The thematic maps which prepared for each parameters, were converted to raster data set having the same pixel and different weightage as per their groundwater potential controlling capacity.

Pairwise comparison matrix was generated, to weight parameters. The consistency for the generated matrix was checked using AHP techniques. These 9 thematic layers were supposed to control flow and storage of water in the area. The association of these influencing factors are weighted according to their reaction for groundwater occurrence. A parameter with a high weight illustrates a layer with high impact and a parameter with a low weight illustrates a small impact on groundwater potential. The weightages of each parameter were assigned according to Saaty's scale (1–9) of relative importance value. As per the classification, weights are assigned to the thematic layers based on their importance and water holding capacity.

3.7. Analytical Hierarchy Process (AHP)

The relative weight of classes and the magnitude factors influencing groundwater potential was computed by using the AHP. The three successive steps in AHP include; pair-wise comparison of thematic importance, matrix normalization and ranking and consistency check. To perform the pairwise comparison and identify the relative importance of factors, previous literatures were reviewed and experienced hydrological experts are decided. The comparison was made on a scale of numbers 1–9 which shows how many times a layer is important than the other (Saaty and Kearns, 1985). The main diagonal matrix contains 1, as each factor is as important as itself. The upper triangular matrix above the main diagonal matrix was filled by comparison of criteria in the row to the column, while the lower triangular matrix was filled using reciprocal values of the upper triangular matrix based on

Saaty's rating scale. The matrix was normalized by dividing each number in the column by the sum of the column.

$$\bar{a}_{jk} = \frac{a_{jk}}{\sum_{i=1}^{m} a_{jk}} \text{...Equation (3.2)}$$

Where $\bar{a}$ is value in the matrix, j is column number, k is row number, i is the theme or class, m is the total number of themes or classes. To produce thematic weights or classes relative weight w_j from the normalized values, Equation (3.8) was used. The normalized weights were then ranked in descending order.

$$w_j = \frac{\bar{a}_{jk}}{n} \text{...Equation (3.3)}$$

The final stage is to calculate a consistency ratio (CR) to measure how consistent the judgments have been relative to large samples of purely random judgments. A consistency ratio of 0 indicates perfect consistency of pair-wise comparison.

If the CR is much in excess of 0.1 the pair-wise comparison will be too inconsistent and the exercise must be repeated. The consistency is desirable to be less than 0.10 (Baby, 2013; Saaty and Kearns, 1985; Shamuyarira, 2017). Consistency check was done following the procedure by Saaty (1980).

$$\text{Consistency ratio (CR)} = \frac{\text{CI}}{\text{RI}} \text{...Equation (3.4)}$$

$$\text{Consistency index (CI)} = \frac{\lambda_{max} - n}{n-1} \text{...Equation (3.5)}$$

$$/\lambda_{max} I - H/ = 0 \text{...Equation (3.6)}$$

$$H = \sum Ratio = \frac{\sum (WSV)_i}{CW_i} \text{...Equation (3.7)}$$

$$\text{WSV} = \sum (\bar{a}_{jk})_i \text{...Equation (3.8)}$$

Where RI is the random index (Table 3.1), λ_{max} is maximum eigenvalue of the matrix, n-is the number of compared elements, WSV is weight sum value, CW criteria weight.

3.8. GIS Integration and Groundwater Potential Map

The GWPZ's of Welmel catchment was delineated by the integration of all reclassified thematic layers using weighted overlay analysis tools of ArcGIS 10.7.1.

The raster of common measurement scale value and varying weights overlaid by using Equation 3.14 (Andualem and Demeke, 2019). Since the summation of criteria weight of all thematic layers is adjusted to 100%, the maximum possible value of groundwater index is five and the minimum value is one. The maximum value of five indicates very high groundwater potential, while four, three, two and one indicates high, moderate, low and very low GWPZ respectively. The normalized weights of the themes multiplied by the normalized weights of the class are applied to evaluate the groundwater potential index.

The groundwater potential index is given by;

$$\mathrm{GWPI} = \sum_{w=1}^{m}\sum_{j=1}^{n}\left(W_j * X_i\right) \qquad \text{Equation (3.9)}$$

Where, GWPI is the groundwater potential index, W_j is the normalized weight of the j^{th} thematic layer, X_i is the normalized weight of the i^{th} feature of the thematic layer, m is the total number of thematic layers, and n is the total number of features of a given theme. The GWPI values was used to classify whether an area is very good, good, moderate, poor or very poor with respect to groundwater potential (Andualem and Demeke, 2019; Gebru et al., 2020; Lakshmi and Reddy, 2019).

3.9. Verification of the Results Using Water Point Information

The groundwater potential map is the prediction with the assumption that the weight for different groundwater indicating factors were assigned through judgment related to field condition. Therefore, to provide accurate prediction, the accuracy of identified GWPZ should be estimated based on the percentage of agreement and disagreement between expected potential and actual yield data (Adiat et al., 2012; Banti, 2017; Berhanu and Hatiye, 2020; Gebru et al., 2020; Tegegn, 2015). Hence, the identified GWPZ's are verified by comparing the output map with the existing water point's inventory data. The wells/springs/dug well point shape file was superimposed over the final GWPZ map (Figure 4.21). A multi-value extraction tool of ArcGIS spatial analyst tools was used to extract and record the GWPZ raster cell values on the attribute table of the water points feature classes. The process of weight assignment and layers overlay was repeatedly accomplished until the resulting GWPZ was reasonably agree with the actual yield of the field conditions.

3.10. Identification of the Groundwater Flow Direction

Data of the existing boreholes, hand-dug wells and springs with their respective location, yield, static water level and drawdown were collected from MoWIE and Bale zone water resources development and energy. Unfortunately the collected data of water points are not well organized. So that the water points which have not yield/discharge was discarded from the verification.

The hydraulic heads, static water levels and surface elevation of existing inventory data was used to identify the groundwater flow direction. The groundwater level contour map and flow direction vector was generated from the groundwater level data using GIS and Surfer 17.1 software (Doyo, 2020; Messene, 2017). The hydraulic head of the boreholes was computed as the difference between the surface elevation above mean sea level (m.a.s.l) and the static water level or depth to water level (Amah and Agbebia, 2015). The groundwater table layer was interpolated for entire study area from the point's hydraulic head. To determine the influence of topographic tilting on the groundwater flow direction and analyze groundwater flow with surface water flow, the contour maps of surface elevation and hydraulic head was produced by joining lines of equal elevation and hydraulic head values.

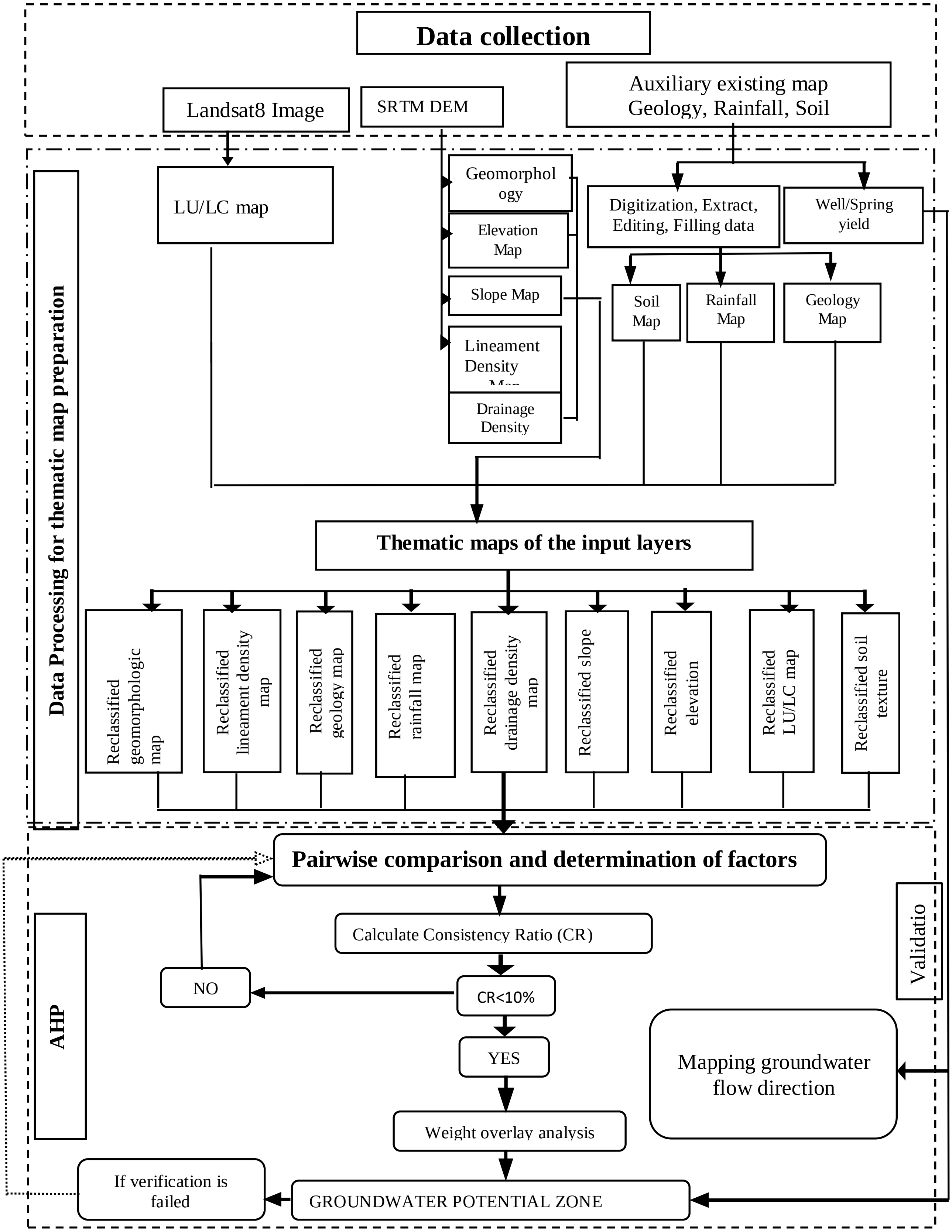

Figure 3.5: Flow chart of methodological approach.

4. RESULTS AND DISCUSSION

4.1. Characterization of Factors Influencing Groundwater Potential

4.1.1. The Thematic Map of Geomorphology

The TPI based landform classification of geomorphology shows ten classes of landforms including; high ridges, mid-slope ridges, upland drainage, upper slopes, open slopes, plains, valleys, local ridges, mid-slope drainage, and streams (Figure 4.1).

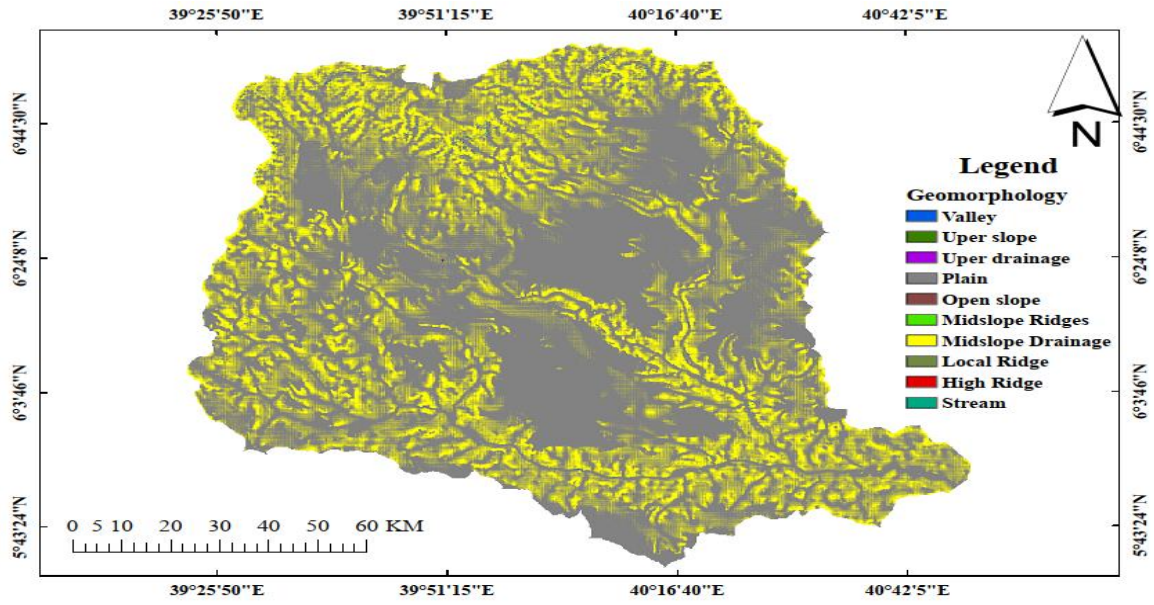

Figure 4.1: The landforms of study area

Depending on the contribution of landform classes, the identified geomorphologic landforms were reclassified into four classes. High relief and moderate relief are the areas with the least groundwater potential, while valleys and plains are types of landforms encouraging very high groundwater potential.

Table 4.1: The Area and scale value of the reclassified landform. (Gebru et al.,2020; Jenness, 2006; Kiflu et al., 2009).

Factor	Landforms	Area (km^2)	Contribution	Scale value
Land forms	Highridges,Upper drainage/Mid-slope ridges	9.88	Very low	1
	Stream/Localridge,Mid-slope drainage	10990.98	Low	2
	Open slope/Upper slope	3628.38	Moderate	3
	Valley/Plain	6.47	High	4

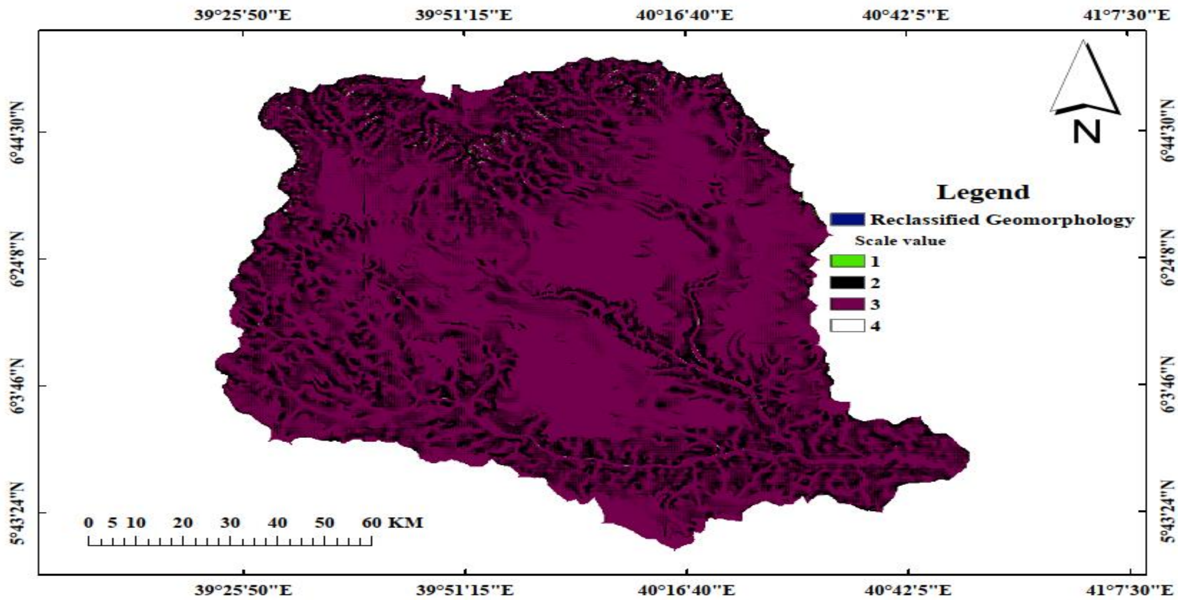

Figure 4.1: The reclassified landforms of study area

4.1.2. The Thematic Map of Lineament Density

Lineament are the structural discontinuity of the earth surfaces such as fault, foliation, joints and bedding planes present on the surfaces. It may be curve, linear and slightly curve which is the most essential for the infiltration and movement of water to the ground. The lineament density of Welmel is varying from 0 to 0.4006 km/km^2 .

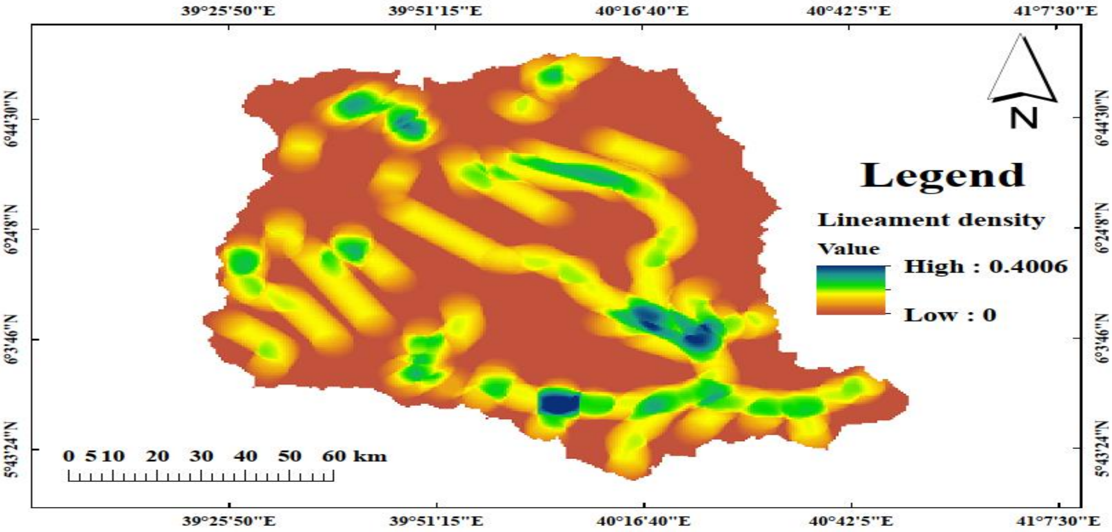

Figure 4.3: The lineament density map of study area

High lineament density area are good for ground water recharge and low lineament density are less suitable for groundwater recharge and discharges.Finally, the lineament density map was reclassified into four classes of varying groundwater contribution.

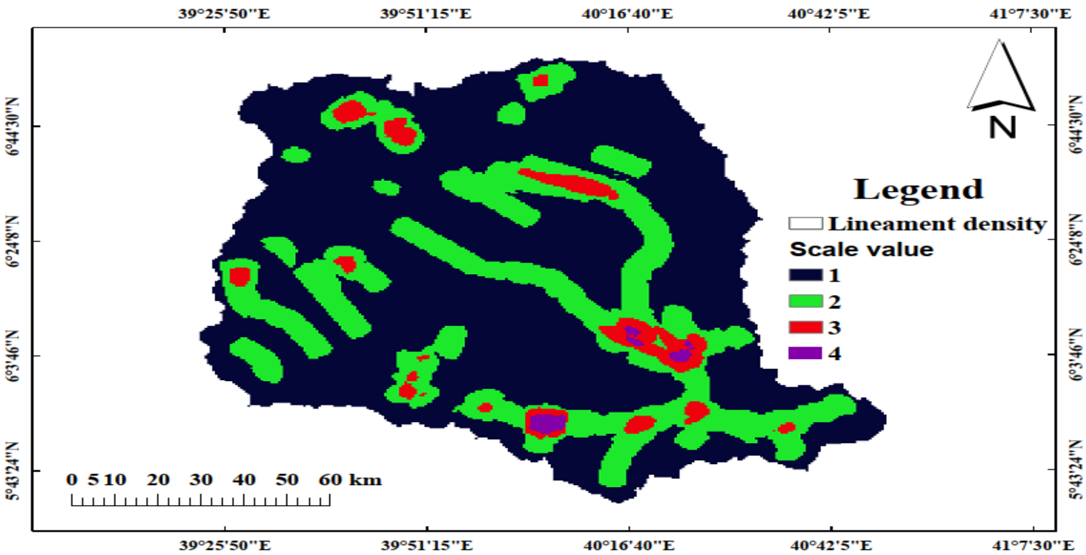

Figure 4.4: The reclassified lineament density map of study area

Table 4.2: Lineament density and Scale value**.** Source (Behzad et al., 2017; Lemecha, 2007; Waikar and Nilawar, 2014))

Factor	S. No.	Value (km/km^2)	Contribution*	Scale value
Lineament	1	0.31-0.4	High	4
	2	0.21-0.3	Moderate	3
	3	0.11-0.2	Low	2
	4	0-0.1	Very Low	1

4.1.3. The Thematic Map of Geological Formation

The geological map of the study was prepared from geological map of Ethiopia and Clipped with the shape file of welmel water shed using geo-processing Clip tool in Arc GIS 10.7.1.The way of Geologic formation and genetic type is essential condition for ground water flow, transport and mineral composition. Types of rocks determine peculiarities of hydrological cros-section structure, type of porosity values, the nature of permeability geological structure geomorphology and character of spatial heterogeneity of flow and transport parameters

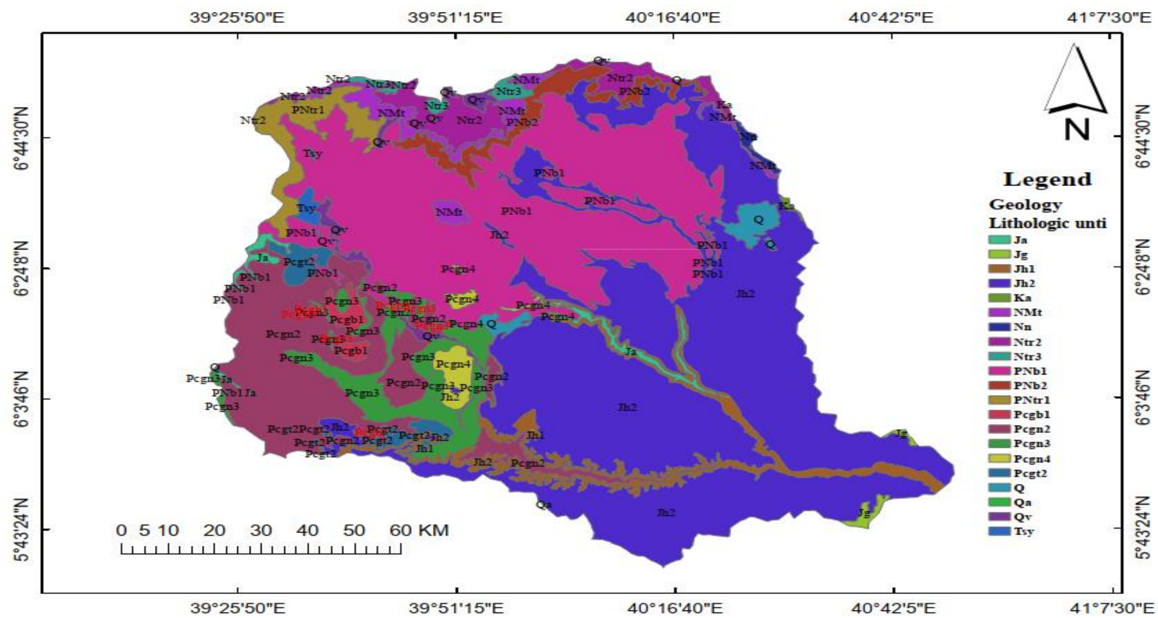

Figure 4.5: The geologic map of study area

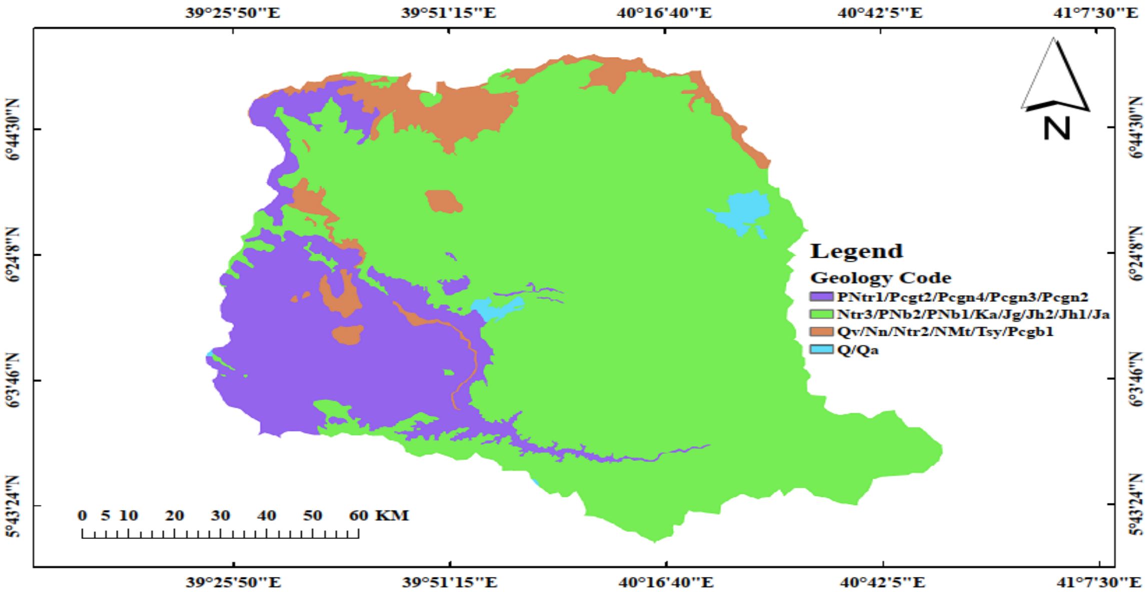

Figure 4.6: The classified code of geologic map of study area

The lithological units exposed in the study area includes; Upper Gabredarre formation (Jg), Alkali trachyte flows (Ntr3), Nazret group (Nn), Alkali trachyte and basalt flows (PNa3), Aphyric basalt (Nmt), Lower flood basalt (PNb), Ginnir Basalt (Qv) and Upper Gabredarre formations (Jg) (Figure 4.5). The short description of exposed geological formation is described in Appendix table 6

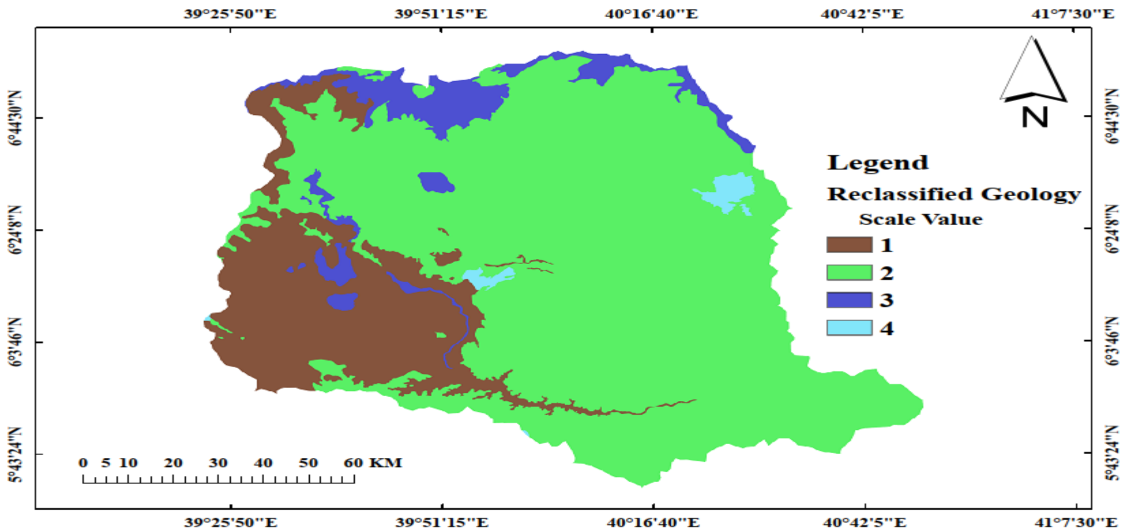

Figure4.7: The reclassified geological map of study area

Table 4.3: Geologic formation and their scale value. Source.(Kebede and Mulugeta, 2011; Kifle and Hailemriam, 2010; Zewdie, 2011)

Geological Unit	Area (km^2)	Contribution*	Scale Value
Q,Qa	145	High	4
Nn,Ntr2/ NMt…..Tsy,Pcgb1	923	Moderate	3
Ntr3,ka,/PNb1…Jh,Jh2,,	10491	Low	2
PNtr1/Pcgn3… Pcgt2	2953	Very low	1

4.1.4. The Thematic Map of Rainfall Distribution.

Rainfall impacts significantly the hydrological cycle, which has high effect on the area's groundwater capacity. The amount of infiltration heavily depends on the intensity and duration of rainfall. In particular, the northern part of the watershed experiences higher rainfall. The northern part of the watershed has a bimodal rainfall distribution as in most parts of south eastern Ethiopia from February to May (the "short rains") with a peak in April, and from June to September (the "long rains") with a peak in August

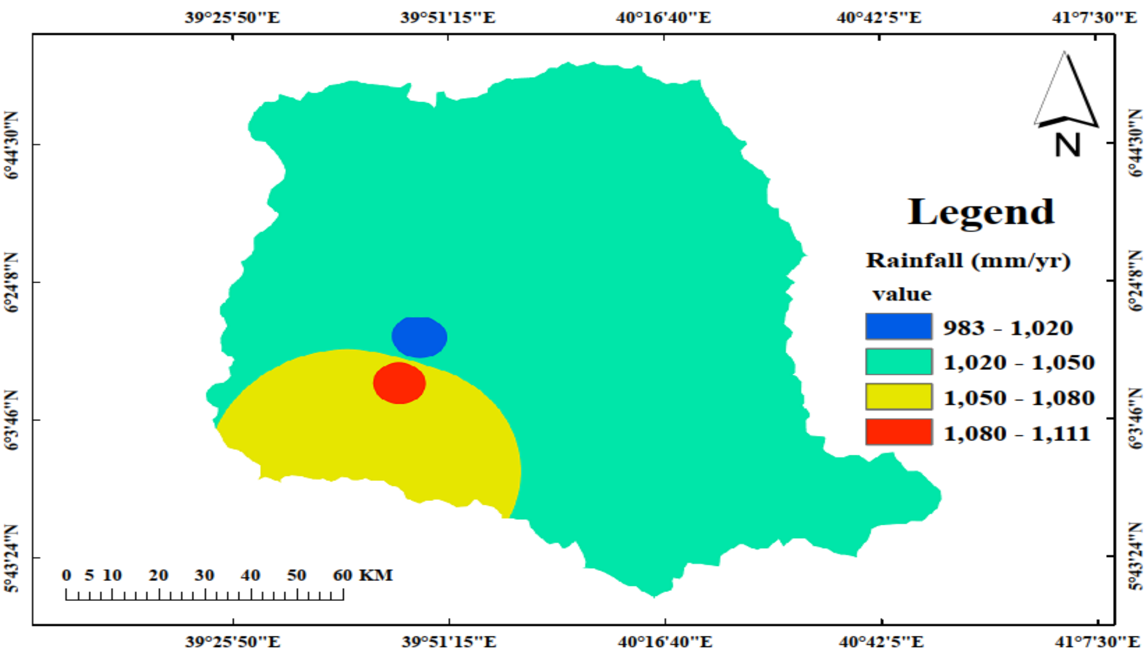

Figure 4.8: Rainfall map of study area

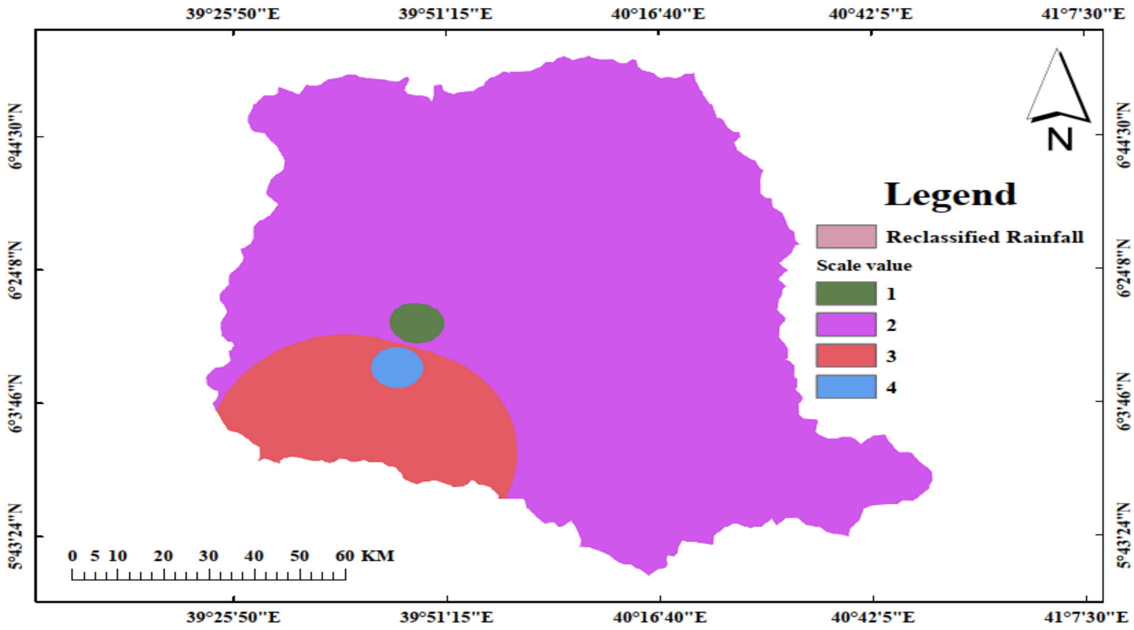

Figure 4.9: Reclassified Rainfall map of study area

Table 4.4: Rainfall distribution and Scale value. Source. (Berhanu and Hatiye, 2020; Doyo, 2020; Sridhar et al., 2019)

Factor	Rainfall(mm)	Suitability*	Scale value
Rainfall (mm/year)	1080-1111	High	4
	1050-1080	Moderate	3
	1020-1050	Low	2
	983-1020	Very low	1

4.1.5. The Thematic Map of Drainage Density

According to (Arulbalaji.petal.2019).Drainage Density plays Avery crucial role in groundwater availability and its network depends on lithology and it provides an important index of infiltration rate. It is inverse function of permeabity. Therefore, it is an important parameter in delineation of the groundwater potential zone. Drainage density is obtained by dividing the total length of the rivers in a drainage basin by total area of the drainage basin. High drainage density represents less infiltration and hence do not favour much on the groundwater potential of the area. Low drainage density represents high infiltration and hence contributes more to the groundwater potential of the area. It preparing from Digital

Elevation model (DEM) by line density tool ArcGIS 10.7.1 and reclassified in to four categories

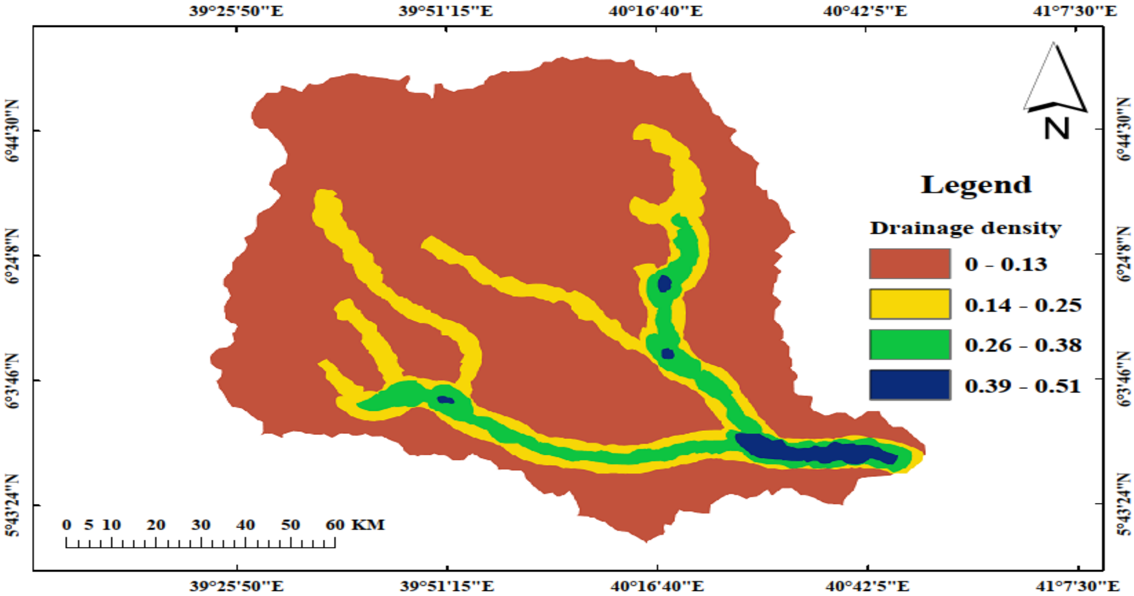

Figure 4.10. Drainage density map of study are

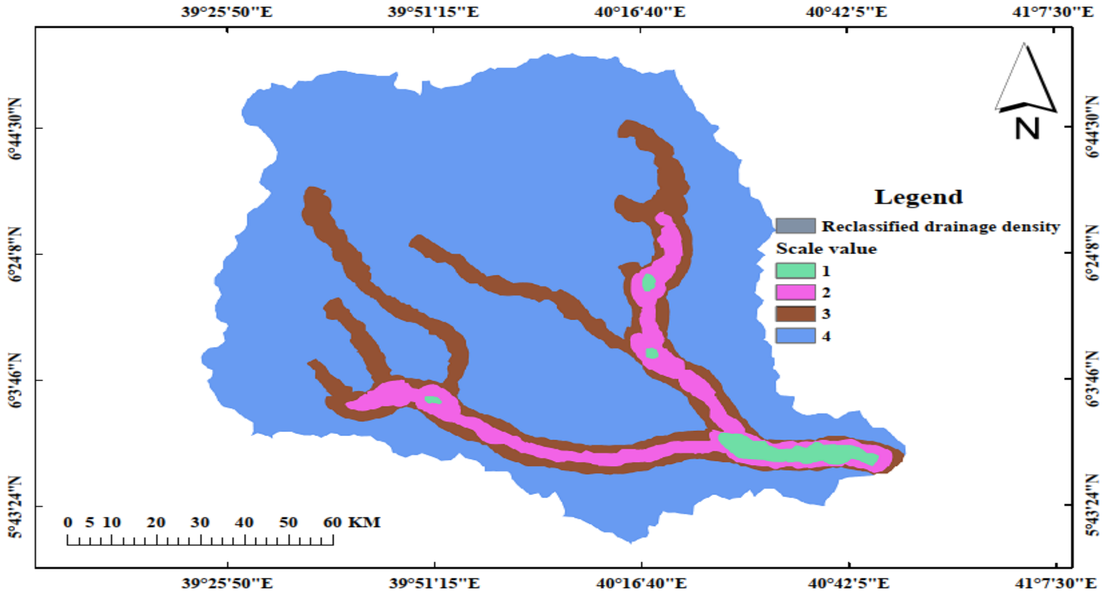

Figure 4.11.Reclassified drainage density map of study area

Table 4.5: Drainage density and Scale value .source. (Waikar and Nilawar, 2014)

S. No.	Drainage density* (km/km^2)	Contribution*	Scale value
1	0-0.13	High	4
2	0.14-0.25	Moderate	3
3	0.26-0.38	Low	2
4	0.39-0.51	Very low	1

4.1.6. The Thematic Map of Slope

Slope is the measurement of steepness from the ground surface. Regional topography and slope data can provide important information on the nature of geology. The slope map was generated from the digital elevation model (DEM) using ArcGIS 10.7.1. The slope map was classified into four classes of flat, gentle, moderate, and steep slope spatial analysis tool. High slope regions have high runoff and low infiltration rate that are not suitable for groundwater recharge, because of water cannot get enough time to infiltration to ground

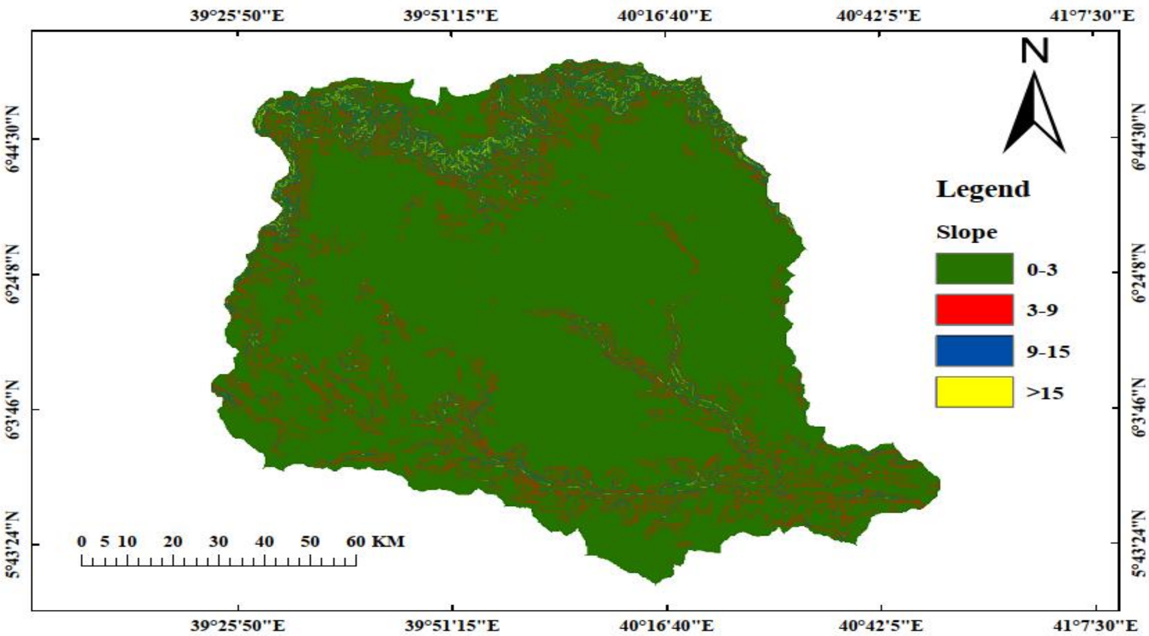

Figure 4.12. Slope map of study area.

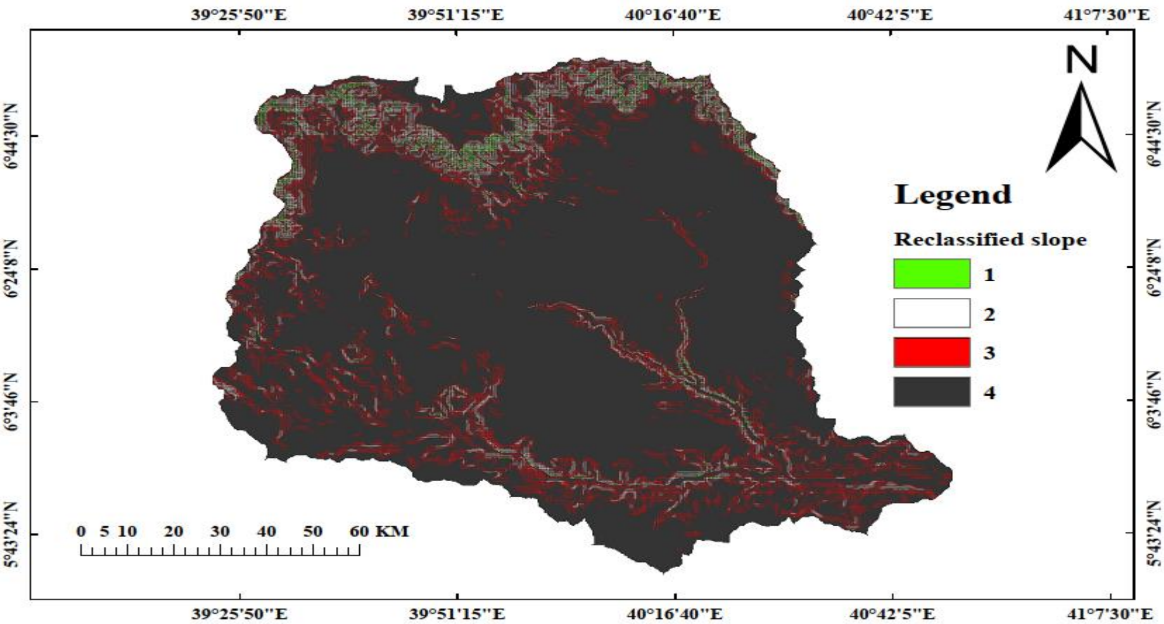

Figure 4.13: Reclassified slope map of study area.

Table 4.6: Slope range and relative weight of slope classes. Source. (Nuru,2018; Tegegn, 2015; Mamo,2007)

Slope (%)	Classes	Contribution*	Scale value
0-3	Flat	High	4
3-9	Gentle	Moderate	3
9-15	Moderate	Low	2
>15	Steep	Very low	1

4.1.7.The Thematic Map of Elevation

Elevations also lead to better environmental conditions, including better soil permeability and increased infiltrated surface water runoff (Fissaha et al., 2020; Wang et al., 2020). In addition, high elevations allow for favourable weather conditions, resulting in higher precipitation amounts which may be beneficial for recharge of groundwater resources (Tefera et al., 2019). The identification and monitoring of potential groundwater sites at any specific site relies heavily on understanding the effects of elevation (Drammeh et al., 2016)

Elevation is one of the main inputs parameters of delineation Groundwater potential zone. It is known that water tends to store at lower topography rather than at the higher topography (Ramu et.al. 2010). To prepare the elevation, slope and drainage map, either the SRTM or ASTER DEM 20m data could be used. In this study, SRTM DEM 20m was selected since it is more accurate both in its vertical and horizontal accuracy than ASTER DEM (Odutola et al., 2012; cited in Kibrit, 2018).Elevation range of the catchment from 362m to 4238 m above mean sea level. These values have been classified equally in to four class, such as high elevated (3269-4238) m, moderate elevated (2300-3269) m, low elevated (1331-2300) m, and very low elevated (362-1331) m.a.s. groundwater flow from high elevation to low elevation.

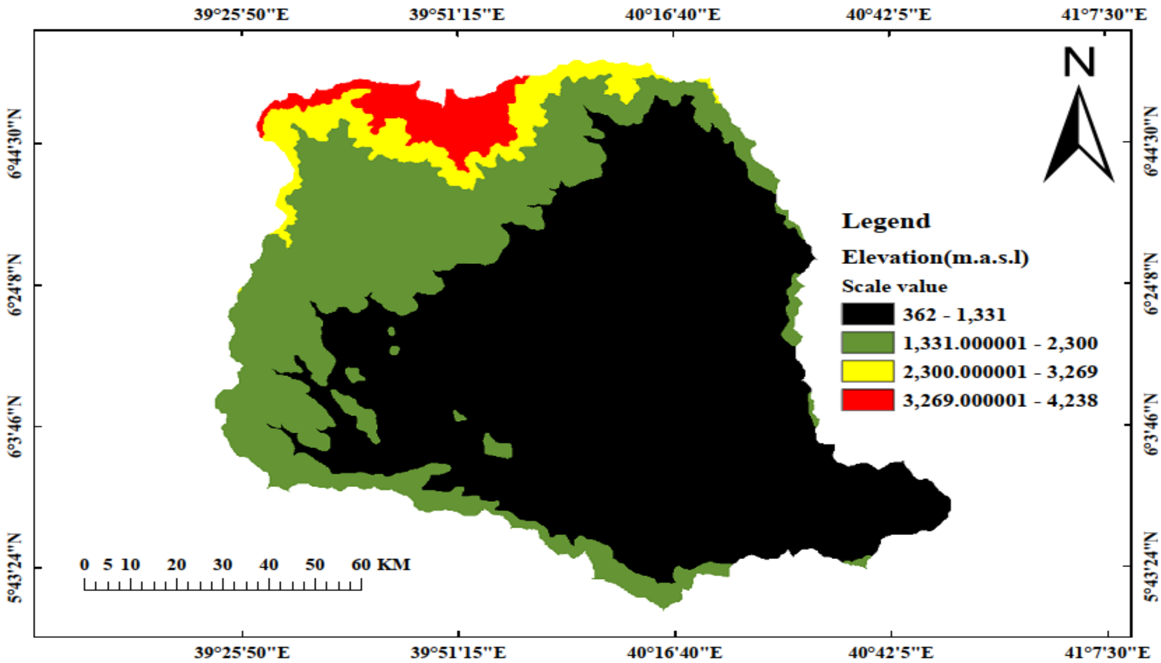

Figure 4.14: Elevation map of study area

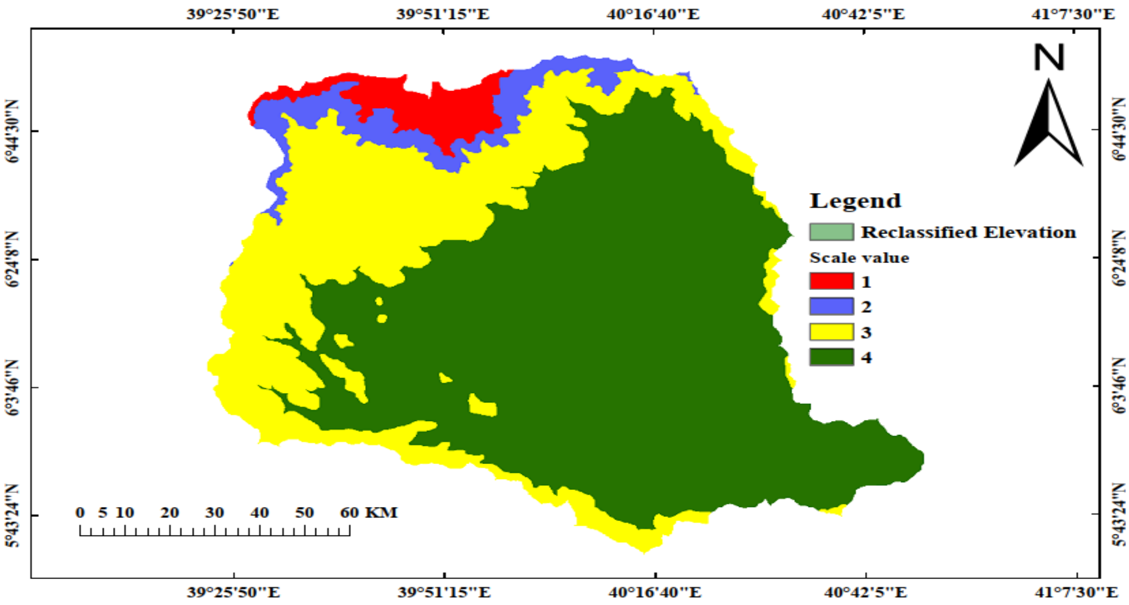

Figure 4.15:Reclassified Elevation map of study area.

Table 4.7: The elevation range and thematic layer reclassified. Source. (Berhanu and Hatiye, 2020; Godebo,2018)

Elevation (m.a.s.l.)	Contribution*	Scale value
362 – 1331	High	4
1331- 2300	Moderate	3
2300- 3269	Low	2
3269-4238	Very low	1

4.1.8. The Thematic Map of Land Use and Land Cover

The LU/LC of Welmel catchment was classified into seven major classes including; water, crops, bare land, bush land, forest, grass land and settlements (Figure 4.18). The land cove r of the watershed encompasses dense forest in the northern part and open forest in the middle of the watershed; however, the lower altitude southern part of the study area is characterized by shrublands, grasslands and degraded bare grounds. Land use Land cover gives essential information on infiltration, Soil moisture, Groundwater, Surface water. It is a direct effect on the hydrological process of surface runoff, evapotranspiration and groundwater recharge. Water body, agricultural land and the water logged area are excellent sources of ground water recharge, while the bare lands and exposed rock surface areas are less important for ground water recharge.

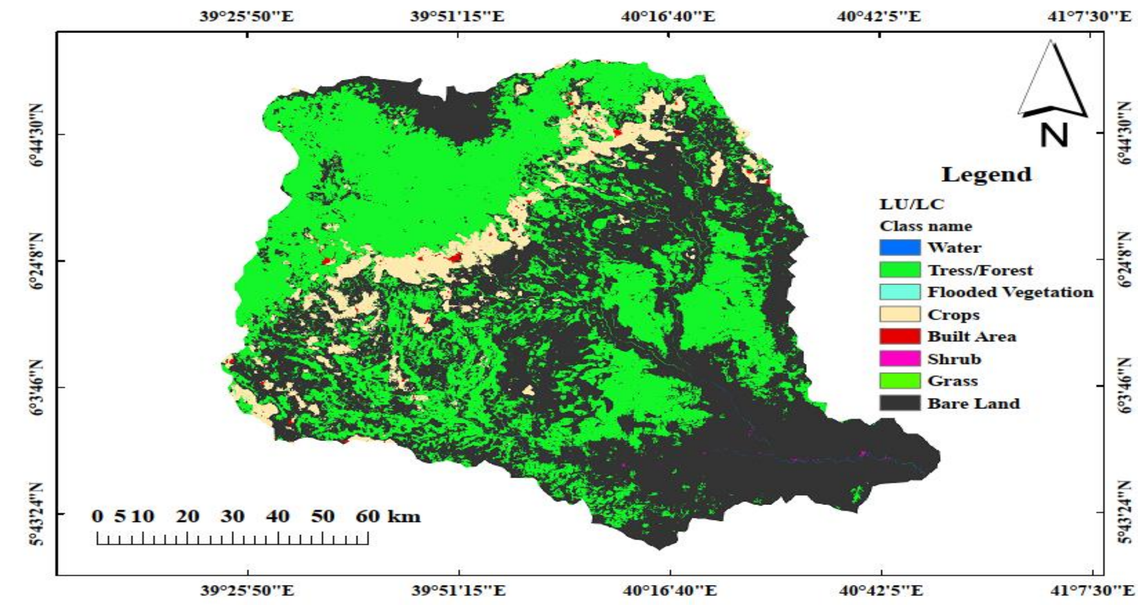

Figure 4.16 :Land use Land cover map of study area.

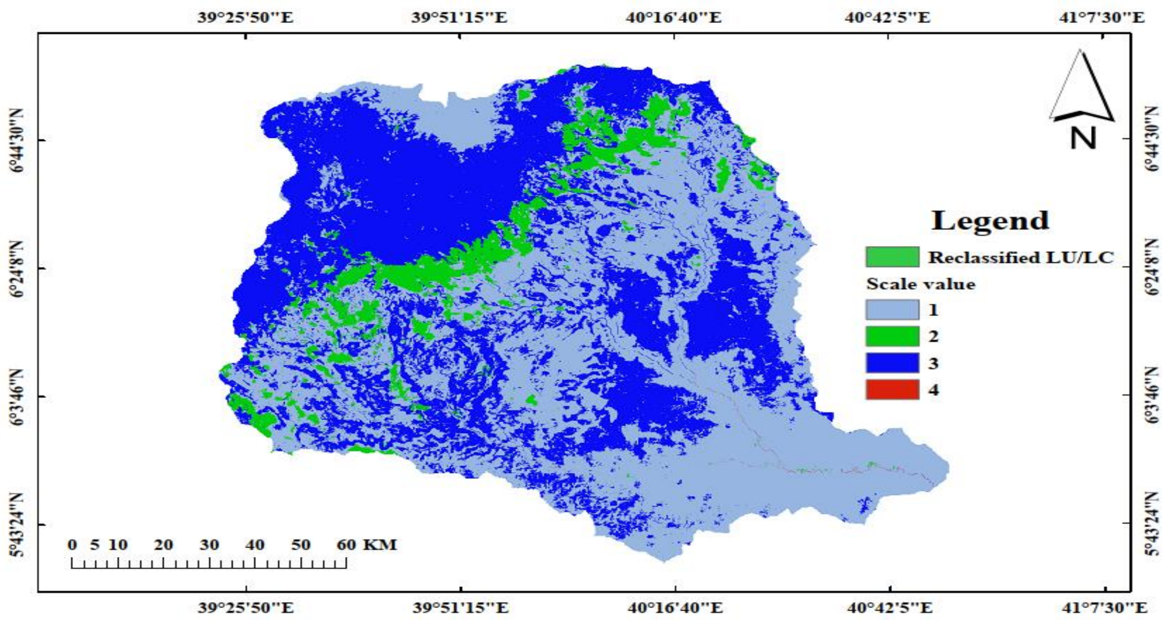

Figure 4.17: Reclassified Land use Land cover map of study area

Table 4.8: The classified LU/LC and Scale value. Source.(Lagesse, 2017;Serur and Sarma, 2016;Tegegn,2015)

Class name	Area (km^2)	Contribution*	Rank
Water	6	High	4
Tree/Forest	6114	Moderate	3
Flooded Vegetation	0.0054	Moderate	3
Crops	1000	Low	2
Built Area	36	Very low	1
Grass	0.084	Low	2
Shurb	5	Low	2
Bare Land	7351	Very low	1

4.1.9. The Thematic Map of Soil Texture

The rate of water infiltration is directly depending on the grain size of the soils. Soil textures are a valuable thematic layer for groundwater potential and recharge assessment. Water moves more quickly through large pores of sandy soil than through clayey soil. The sandy soils have a high infiltration rate than clayey soils. So that soil texture is strongly affecting the movement and storage of the groundwater. Based on the soil data derived from the literature, the study area has clay, clay loam and loam soil texture.

Welmel watershed area has eight soil types i.e. eutric cambisols, chromic cambisols, leptosols (formerly litho sols), rendzic leptosols, developed from limestone (formerly rendzinas), chromic luvisols, pellic vertisols ,calcic cambisoi and chromic vertisols (Yared et al. 2020). The largest area is occupied by chromic vertisols and rendzic leptosols ,the smallest area are calcic and pellic vertisoil.

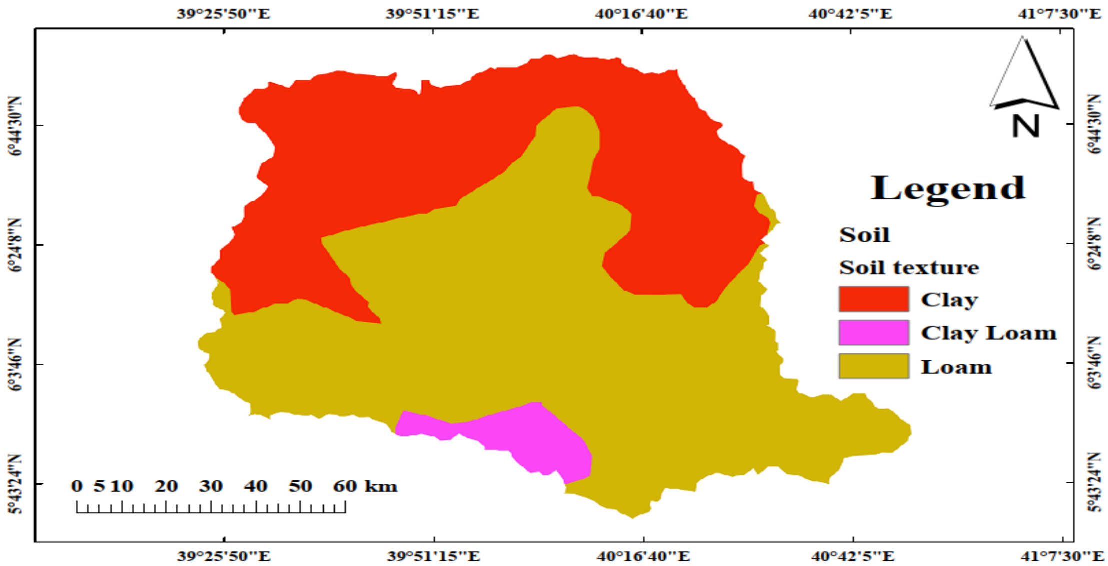

Figure 4.18: The soil texture classes of study area

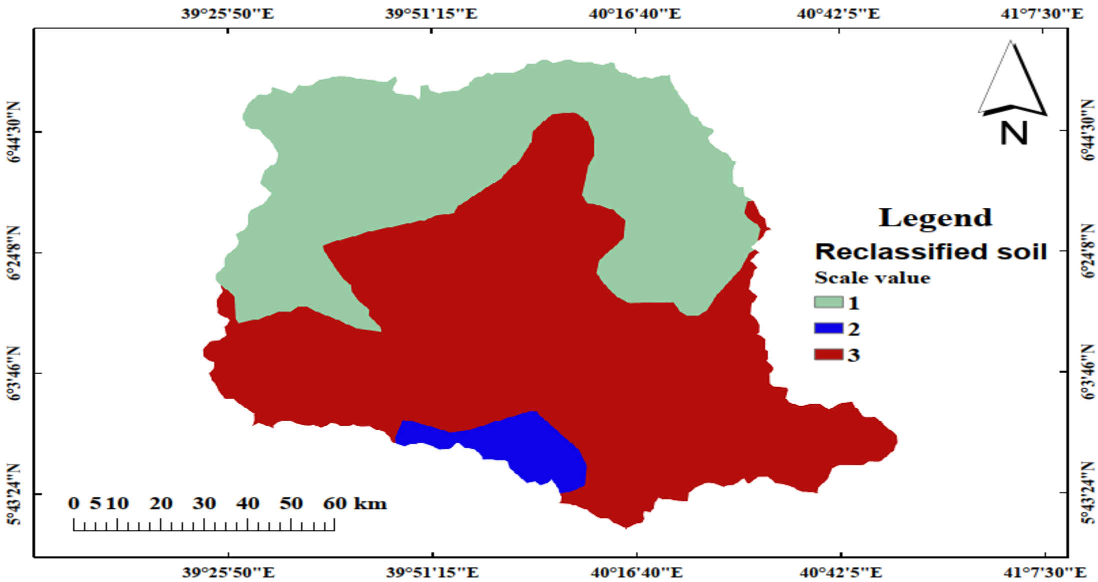

Figure 4.19: The reclassified soil map of study area

Table 4.9: The soil texture and scale value .source.(Assistance to Soil and Water Conservation Program, Phase III; Berhanu et al., 2013)

Soil texture class	Area (km^2)	Contribution*	Scale Value
Loam	5564	Moderate	3
Clay loam	504	Low	2
Clay	8444	Very low	1

4.2. Analytical Hierarchy process (AHP) to weight parameters

The first steps of AHP is generation of comparison matrix. The table below refers the generated pairwise comparison matrix for weighing of each parameter those affects the groundwater potential of the catchment.

Table 4.10 Rating on satty's 9-point continuous scale

Intensity of importance	Definition	Explanation
1	Equal importance	Two factors contribute equally to the objective
3	Moderately important or Somewhat more important	Experience and judgment slightly favour one over the other.
5	Strongly important or Much more important	Experience and judgment strongly favour one over the other
7	Very strong or Very much more important	Experience and judgment very strongly favour one over the other. Its importance is demonstrated in practice.
9	Extremely important or Absolutely more important.	The evidence favouring one over the other is of the Highest possible validity.
2,4,6,8	Intermediate values	When compromise is needed
1/3,1/5,1/7,1/9	Value for inverse comparison	

4.3. Assignment of Weight to Factors

The weight of physiographic, geology and climatic factor were determined on basis of the factors relative importance. The physiographic and geologic factors are the major factors affecting GWPZ of Welmel catchment. Geomorphological landforms determine runoff, groundwater recharge and to some extent rainfall conditions. Hence, it is a dominant factor influencing the GWPZ of study area. Lineament density, geology and rainfall distribution are the second, third and fourth factors influencing the GWPZ of Welmel catchment. The importance of lineament is related to the ability of lineaments to act as conduit sites for groundwater recharge and flow throughout the area. Types of rocks determine peculiarities of cross-section structures hydrological property affecting groundwater movement.

Table 4.3.1, which shows the importance of themes in the first row relative to the themes on the columns.

Factors	Geom	Lin	Geol	PCP	DD	Slp	Elv	LULC	ST
Geom	1	2	2	3	3	4	4	5	9
Lin		1	2	3	4	5	5	7	8
Geol			1	2	3	4	4	6	7
PCP				1	2	3	4	5	6
DD					1	3	3	4	5
Slp						1	2	3	4
Elv							1	3	3
LULC								1	2
ST									1

Similarly; the lower triangular matrix is the reciprocal of the above triangular matrix values was shown follow:

Table 4.3.2. Analysis of pairwise comparison matrix.

Factors	Geom	Lin	Geol	PCP	DD	Slp	Elv	LULC	ST
Geom	1								
Lin	½	1							
Geol	½	½	1						
PCP	1/3	1/3	1/2	1					
DD	1/3	¼	1/3	½	1				
Slp	¼	1/5	1/4	1/3	1/3	1			
Elv	¼	1/5	1/4	¼	1/3	½	1		
LULC	1/5	1/7	1/6	1/5	¼	1/3	1/3	1	
ST	1/9	1/8	1/7	1/6	1/5	¼	1/3	½	1

Table 4.3.3: Pairwise comparison matrix and the relative weights of factors

Factors	Geom	Lin	Geol	PCP	DD	Slp	Elv	LULC	ST
Geom	1	2	2	3	3	4	4	5	9
Lin	½	1	2	3	4	5	5	7	8
Geol	½	1/2	1	2	3	4	4	6	7
PCP	1/3	1/3	½	1	2	3	4	5	6
DD	1/3	1/4	1/3	½	1	3	3	4	5
Slp	¼	1/5	¼	1/3	1/3	1	2	3	4
Elv	¼	1/5	¼	¼	1/3	½	1	3	3
LULC	1/5	1/7	1/6	1/5	¼	1/3	1/3	1	2
ST	1/9	1/8	1/7	1/6	1/5	¼	1/3	½	1
SUM	3.48	4.75	6.64	10.45	14.12	21.08	23.67	34.50	45.00

The abbreviation Geol, Geom, Lin, PCP, Elv, DD, Slp, LULC, and ST represent; geology, geomorphology, lineament density, rainfall distribution, elevation, drainage density, slope, land use land cover, and soil texture, respectively.

Table 4.3.4 :pairwise comparison matrix changed to Decimal form

Factors	Geom	Lin	Geol	PCP	DD	Slp	Elv	LULC	ST
Geom	1	2	2	3	3	4	4	5	9
Lin	0.5	1	2	3	4	5	5	7	8
Geol	0.5	0.5	1	2	3	4	4	6	7
PCP	0.33	0.33	0.5	1	2	3	4	5	6
DD	0.33	0.25	0.33	0.5	1	3	3	4	5
Slp	0.25	0.2	0.25	0.33	0.33	1	2	3	4
Elv	0.25	0.2	0.25	0.25	0.33	0.5	1	3	3
LULC	0.2	0.14	0.17	0.2	0.25	0.33	0.33	1	2
ST	0.11	0.13	0.14	0.17	0.2	0.25	0.33	0.5	1
SUM	3.48	4.75	6.64	10.45	14.12	21.08	23.67	34.50	45.00

Step 2

The above pair-wise comparison matrix was normalized by dividing each value by the column total sum and subsequently averaging the row total. Example from the above table 1÷3.48=0.29, 0.5/3.48= 0.14

Table 4.3.5: Normalized pairwise comparison matrix and final weighted values.

Factors	Geom	Lin	Geol	PCP	DD	Slp	Elev	LULC	ST	CW	CW (%)
Geom	0.29	0.42	0.30	0.29	0.21	0.19	0.17	0.14	0.20	0.249	25
Lin	0.14	0.21	0.30	0.29	0.28	0.24	0.21	0.20	0.18	0.234	23
Geol	0.14	0.11	0.15	0.19	0.21	0.19	0.17	0.17	0.16	0.167	17
PCP	0.10	0.07	0.08	0.10	0.14	0.14	0.17	0.14	0.13	0.118	12
DD	0.10	0.05	0.05	0.05	0.07	0.14	0.13	0.12	0.11	0.088	9
Slp	0.07	0.04	0.04	0.03	0.02	0.05	0.08	0.09	0.09	0.054	5
Elev	0.07	0.04	0.04	0.02	0.02	0.02	0.04	0.09	0.07	0.041	4
LULC	0.06	0.03	0.03	0.02	0.02	0.02	0.01	0.03	0.04	0.027	3
ST	0.03	0.03	0.02	0.02	0.01	0.01	0.01	0.01	0.02	0.018	2

CW =represent criteria weight

CW1=0.29+0.42+0.30+0.29+0.21+0.19+0.17+0.14+0.20=0.249

CW1(%)=0.249*100=25,The same is true for the rest raw ,

The $\sum$CW% should be 100 , so in this case 25+23+17+12+9+5+4+3+2=100 .it is correct.

Step3. Evaluations of consistency Ration (CR)

To check whether the comparison is correct /consistent or not ,the consistency check can be performed using the equation given below .the consistency index (CI) can be calculated using the following equation .

Consistency ration (CR) = $\frac{\mathrm{CI}}{\mathrm{RI}}$ CR =consistency ratio, CI=consistency index, RI=random index

Consistency index (CI)= $\frac{\lambda_{\max-n}}{n-1}$ $\lambda_{\max}$ = highest Eigen value , n =number of parameters.

Steps to calculate highest Eigen value

As suggested by satty (1987), the maximum eigenvalue(λ_{max}) of comparison matrix can be calculated by the following procedure

1. Multiplying each value in the column(in the matrix table which is not normalized) by the criteria weight
2. Computing the weight sum value by adding the value in the row
3. Calculating the ratio of each weighted sum value to the respective criteria weight,and
4. Averaging the ratio of weighted sum value to the criteria weight

Table 4.3.6: Evaluations of consistency ration (CR) of weighed sum value.

C.Weight	**0.25**	**0.23**	**0.17**	**0.12**	**0.09**	**0.05**	**0.04**	**0.03**	**0.02**
Factors	Geom	Lin	Geol	PCP	DD	Slp	Elv	LULC	ST
Geom	1*0.25	2*0.23	2 *0.17	3*0.12	3*0.09	4*0.05	4*0.04	5*0.03	9*0.02
Lin	0.5*0.25	1*0.23	2*0.17	3*0.12	4*0.09	5*0.05	5*0.04	7*0.03	8*0.02
Geol	0.5*0.25	0.5*0.23	1*0.17	2*0.12	3*0.09	4*0.05	4*0.04	6*0.03	7*0.02
PCP	0.33*0.25	0.33*0.23	0.5*0.17	1*0.12	2*0.09	3*0.05	4*0.04	5*0.03	6*0.02
DD	0.33*0.25	0.25*0.23	0.33*0.17	0.5*0.12	1*0.09	3*0.05	3*0.04	4*0.03	5*0.02
Slp	0.25*0.25	0.2*0.23	0.25*0.17	0.33*0.12	0.33*0.09	1*0.05	2 *0.04	3*0.03	4*0.02
Elv	0.25*0.25	0.2*0.23	0.25*0.17	0.25*0.12	0.33*0.09	0.5*0.05	1*0.04	3*0.03	3*0.02
LULC	0.2*0.25	0.14*0.23	0.17*0.17	0.2*0.12	0.25*0.09	0.33*0.05	0.33*0.04	1*0.03	2*0.02
ST	0.11*0.25	0.13*0.23	0.14*0.17	0.17*0.12	0.2*0.09	0.25*0.05	0.33*0.04	0.5*0.03	1*0.02

Table 4.3.7 Consistency ratio (CR) of the generated matrix

Criteria weights	**0.25**	**0.23**	**0.17**	**0.12**	**0.09**	**0.05**	**0.04**	**0.03**	**0.02**			
Factors	Geom	Lin	Geol	PCP	DD	Slp	Elev	LULC	ST	WS	CW	Ratio
Geom	0.25	0.46	0.33	0.36	0.27	0.23	0.19	0.14	0.17	2.4	0.25	9.6
Lin	0.12	0.23	0.33	0.36	0.36	0.29	0.23	0.20	0.15	2.27	0.23	9.87
Geol	0.12	0.11	0.17	0.24	0.27	0.23	0.19	0.17	0.13	1.63	0.17	9.59
PCP	0.08	0.08	0.08	0.12	0.18	0.17	0.19	0.14	0.12	1.16	0.12	9.67
DD	0.08	0.06	0.06	0.06	0.09	0.17	0.14	0.11	0.10	0.87	0.09	9.67
Slp	0.06	0.05	0.04	0.04	0.03	0.06	0.09	0.08	0.08	0.53	0.05	10.6
Elev	0.06	0.05	0.04	0.03	0.03	0.03	0.05	0.08	0.06	0.43	0.04	10.75
LULC	0.05	0.03	0.03	0.02	0.02	0.02	0.02	0.03	0.04	0.26	0.03	8.67
ST	0.03	0.03	0.02	0.02	0.02	0.01	0.02	0.01	0.02	0.18	0.02	9

WS , is weight sum value, CW, is criteria weight,

Ratio=Weighted sum value ÷ criteria weights

After this calculate the value of Lamda max ($\lambda_{\max}$)

$$\lambda_{\max}=\frac{9.6+9.87+9.59+9.67+9.67+10.6+10.75+8.67+9}{9}= \frac{87.42}{9}= 9.71$$

Table 4.3.9: Random index (RI) value

$\lambda_{\max}$=9.71

- Then calculating the value of consistency index (CI)

Consistency index (CI) = $\frac{\lambda_{\max-n}}{n-1}$,where n=9

CI= $\frac{9.71-9}{9-1}=\frac{0.71}{8}$

CI=0.089

- Then find Random index (RI). Random index is the mean value of the consistency index depending on the computed matrix order given by saaty (1980) that has shown in Table 4.3.9.

For this study the number of parameters which affect the Groundwater potential zone determination are. nine, then the respective Random Index (RI) value of the number nine is 1.45.

Table 4.3.8. find Random index (RI)

N	1	2	3	4	5	6	7	8	9	10
RI	0	0	0.58	0.90	1.12	1.24	1.32	1.41	**1.45**	1.49

Finally calculate the consistency ration (CR)

$$\text{Consistency ration (CR)} = \frac{\text{CI}}{\text{RI}},\ \frac{\mathbf{0.089}}{\mathbf{1.45}}=0.061$$

$$\text{CR}=0.061$$

Depending on consistency ratio (CR) rule, If the value of CR>0.10, then the criteria weight values of the matrix indicates inconsistencies and the method (AHP) may not give a meaningful result (Saaty1980). But when the value of CR comes to this study was 0.061 it means that 6.1% less than 10% this is under acceptable limits which indicate the computed weight values are valid. There for it can be computed for weighted overlay analysis in GIS software, which used to delineate the Groundwater potential zone, is shown from the following tables.

Table 4.3.9. A Criteria weight values of each parameter.

No	Parameters	Criteria weights values	% of criteria weighted values
1	Geom	0.25	25
2	Lin	0.23	23
3	Geol	0.17	17
4	PCP	0.12	12
5	DD	0.09	9
6	Slp	0.05	5
7	Elv	0.04	4
8	LULC	0.03	3
9	ST	0.02	2

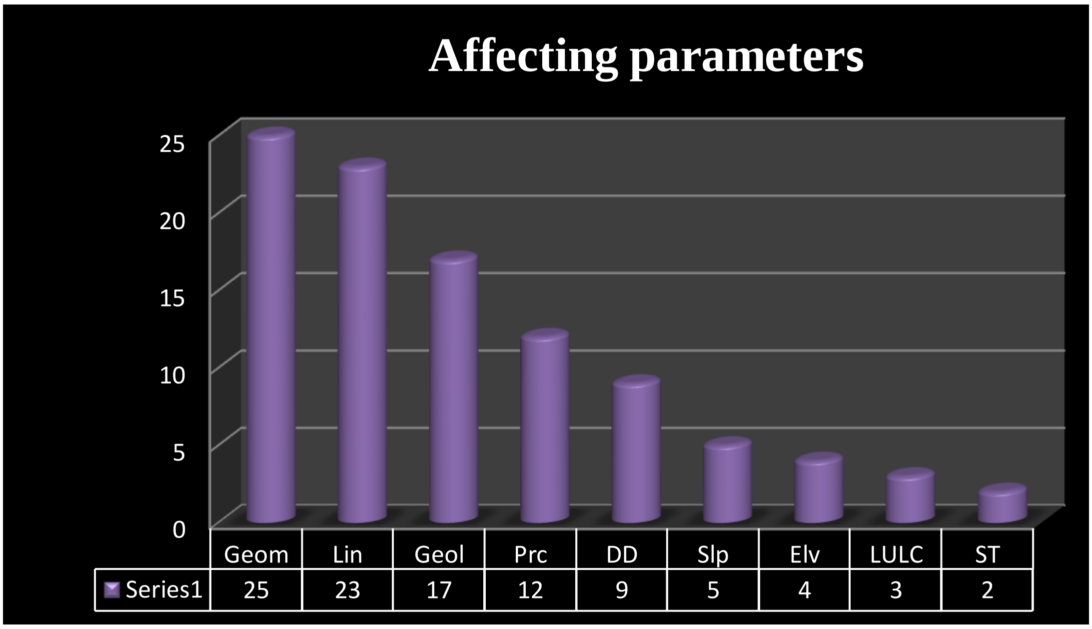

Figure 4.20. Weight of Groundwater potential affecting parameters

Depend on the above graph; the study area Groundwater potential is highly affected by parameters called Geomorphology and les affected by soil and lulc.

4.4.Delineation of Groundwater Potential Zones

The delineation/identification of groundwater potential zones for the study area was made by grouping of the interpreted layers through Weighted Overlay Analysis and finally assigned different potential zones. Depending upon the groundwater potentiality, each class of the main eight thematic layers (geomorphology, Geology, Land use Land cover, drainage density, lineament density, soil, Slope and Rainfall) are Prepared. The prospect map describing the ground water potential zone in the study area were identified and presented in (Figure 4.18). From this study Groundwater potential zones were categorized into four types viz., very Low (11%), Low (71%), Moderate(16%) and High (2%)

The study suggested that the GWPZM generated will serve as useful guidelines for planners, engineers and decision makers providing quick decision- making in the management of groundwater resources, site selection for GW exploration and exploitation. In the study generally the reason for high groundwater potential is area which has low drainage density, low slope, and very high lineament density and flood plain Geomorphological units. The reason for Very low ground water potential zone is area which has very high drainage density, very high slope, low lineament density and structural hill geomorphological units .

Therefore, depend on the relationship of these differences Groundwater potential parameters and their affecting level they already decided the value of normalized weight value (criteria weight values). There for; the linear equation of Groundwater potential zone delineation for Welmel.watershad is shown follow:

GWP= 25*Geomo+ 23*Line.d+ 17*Geolog+12* Rainfal+ 9*Drea.d+5*Slope+4*Eliv+3* lulc+ 2*Soil.

The weight overlay analysis of the linear summation of the above nine parameters and mapping of their thematic maps by a spatial analyst tools in ArcGIS gives delineation of Groundwater Potential zone map.

Depending of such delineation: the groundwater potential map classified as; very low, low, moderate and high potential zones.

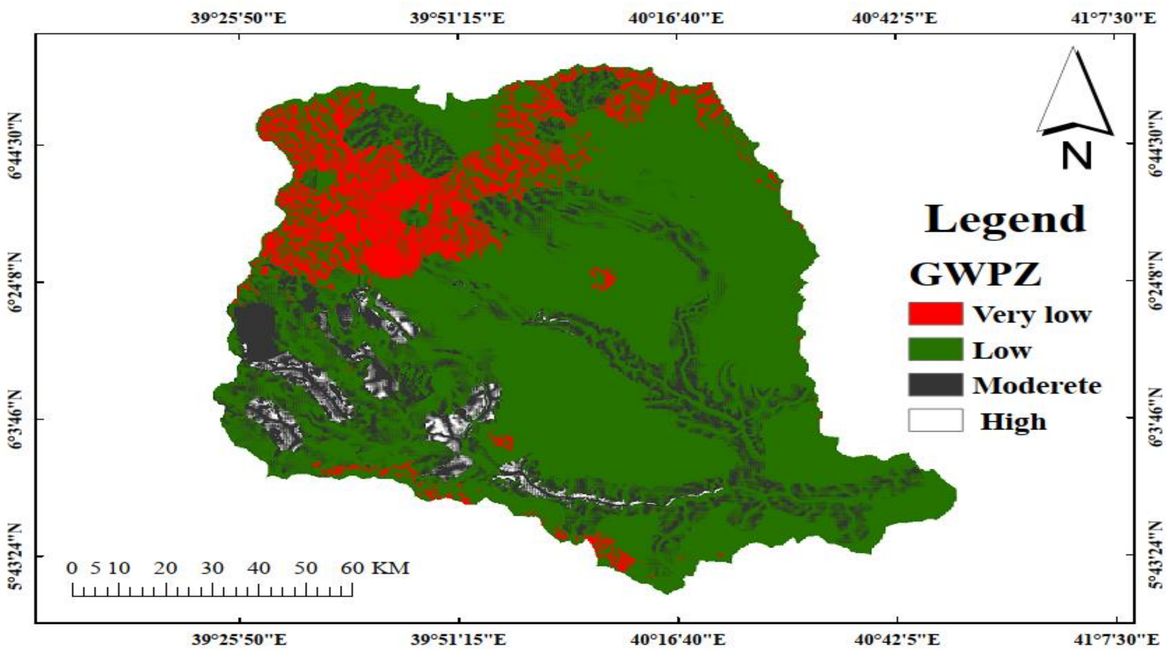

Figure 4.21. The groundwater potential zone map

4.5.Verification of the Result Using Water Point Data

Mapping of groundwater potential zone by using GIS and Remote sensing techniques with existing conventional data was validated when existing water inventory point was a close agreement with groundwater potential zone delineated.

The actual yields of thirty-one water points were checked with the identified GWPZ. The actual yield of boreholes and spring discharge were classified into five classes (Berhanu and Hatiye, 2020; Doyo, 2020; Gebru et al., 2020). The water points that fall in the highest yield of ≥15 l/s were classified under very high groundwater potential. Yields/discharge between 15-3.5 l/s, 3.5-0.5 l/s, 0.5-0.05 l/s and less than 0.05 were classified under high, moderate, low and very low GWPZ's.

based on this study, in our study area the actual yields of sixty-seven water points were checked with the identified GWPZ. The actual yield of boreholes and spring discharge were classified into four classes the water points that fall in the highest yield of ≥15 l/s were classified under high groundwater potential. Yields/discharge between 15-3.5 l/s, 3.5-0.1 l/s, and less than 0.1 l/s were classified under moderate, low and very low GWPZ's.

Table 4.3.10: Validation of the identified groundwater potential zones with actual yield

	Mapped GWPZ							
Actual GWPZ		H	M	L	VL	A	DA	Total
	H	0	0	1	0	0	1	1
	M	0	2	1	0	2	1	3
	L	0	4	53	1	53	5	58
	VL	0	2	3	0	0	5	5
OPA (%) =(Total number of agreement /Total Number of wells) *100%=82.08%								

The acronyms; H, M, L, VL, DA, A and OPA represent high, moderate, low, very low, disagreement, agreement and overall prediction accuracy. Hence, the overall prediction accuracy of groundwater potential is 82.08%.

The better agreement of the comparison between the water point's inventory data and GWPZ's approve the efficiency of GIS and Remote Sensing technique for mapping the groundwater potential zone of study area

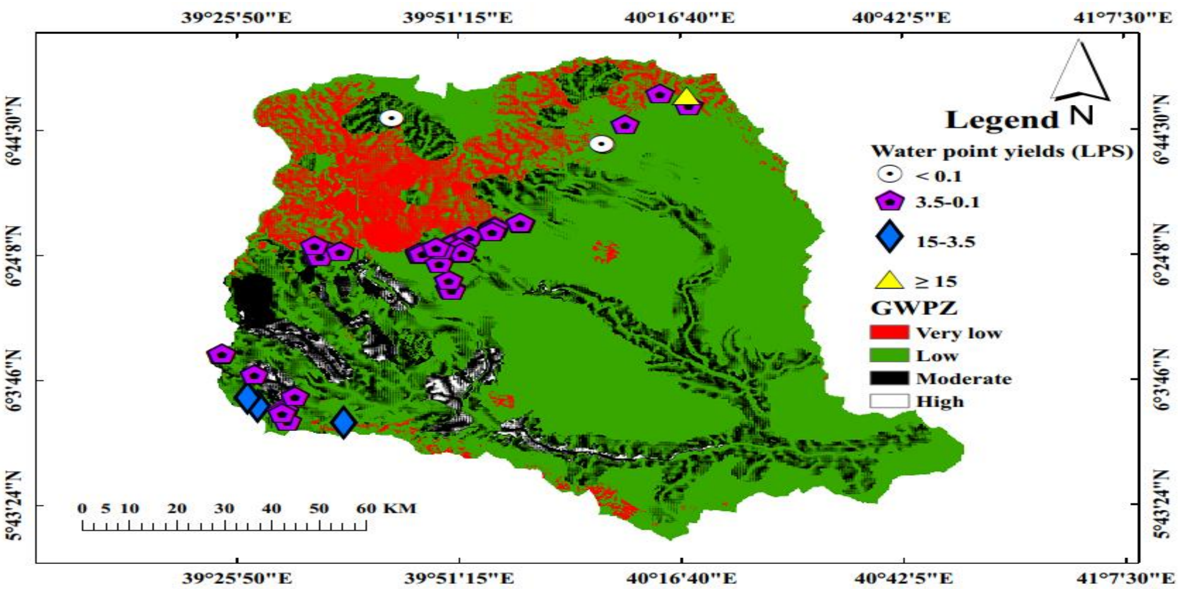

Figure 4.22: Validity map for groundwater potential zones

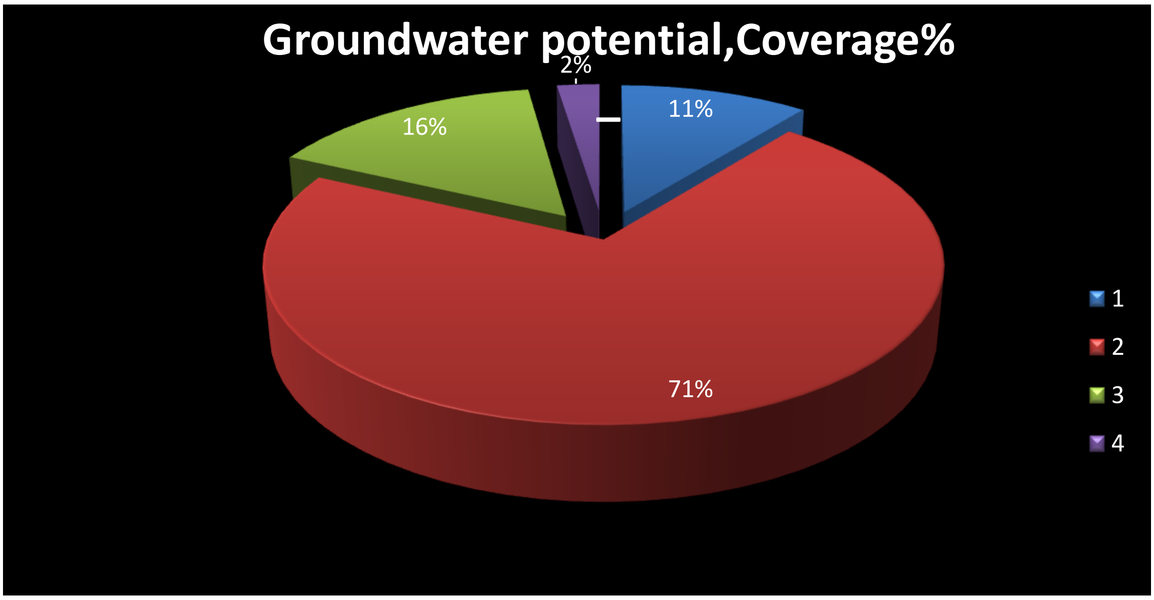

Figure 4.23: Groundwater potential coverage pie chart

4.6. Groundwater Flow Direction

In many areas of the world groundwater is a valuable resource that is used for providing drinking water, growing crops and much more. In areas such as this having full knowledge of the direction of flow of the groundwater is very important for the environmental bodies. It is also essential that the groundwater is not contaminated by landfill sites, leaky underground gas tanks or overuse of pesticides. With this importance in mind some environmental agencies conduct extensive research into the groundwater flow direction and plot their findings.

The course of flow of groundwater is shown from groundwater contour map. Hence, groundwater contour map for the shallow and deep aquifer system of the study location is generated from well point of static water level (SWL) in order to understand the flow direction. In most components of the area groundwater level distribution is comparable to the topography (slope), which follows the elevation variation. Accordingly, the inclination of the topography (slope) factor, geomorphology and aquifer (lithological) characteristic and lineament density are the most important factor control groundwater flow direction because this thing are greater susceptible for groundwater flow system occurring .The recharge and discharge zones of the study area were determined from the direction vectors (Figure 4.24). Divergent zone is a specific area where the water starts to flow to any other area, whereas convergent zone is the area where the water flows toward specific zones that comes from its surrounding (Doyo, 2020). The location, elevation, depth, static water level and hydraulic head of water points used for determination of groundwater flow direction was attached under Appendix table 9. The circles in rose colour shown in Figure 4.24 indicate the area of groundwater recharge vectors, whereas the circles in yellow colour show area of discharge with collecting vectors.

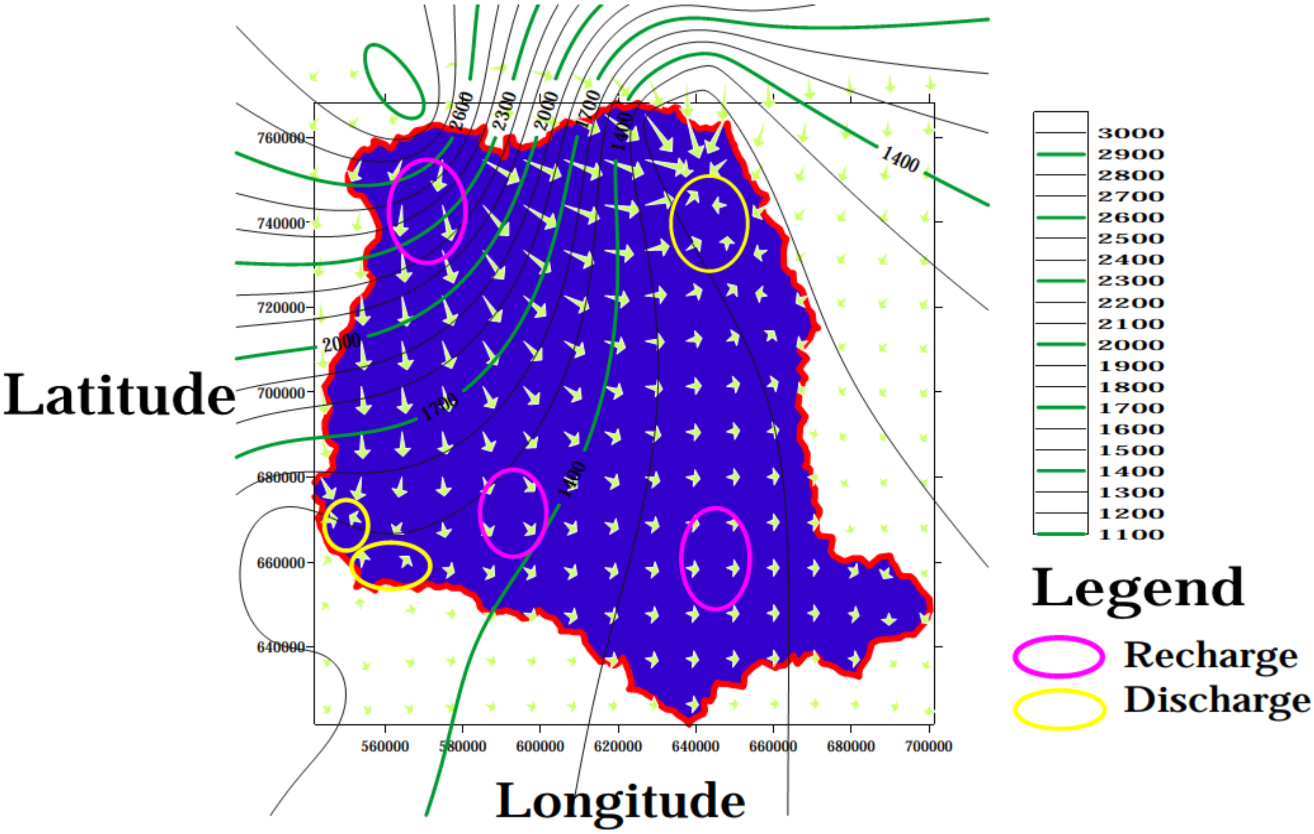

Figure 4.24: The groundwater flow direction and contour map (welmel Watershed)

The groundwater locally flows in different directions while the entire groundwater flow direction of contours arrow reveals the Southeast and North eastern flow direction. The complex geologic structures of the study area govern the occurrence and movement of ground and surface water flow (Kifle and Hailemriam, 2010).

The result is consistent with the previous study conducted by Kassahun and Mohamed (2018); Kebede and Mulugeta (2011); Kifle and Hailemriam (2010); Kiflu et al. (2009); Mulugeta and Tafa (2010).

In addition to the delineated GWPZ, the groundwater flow direction vector identified from densely populated topographic tilting enable to show the local (detail) groundwater recharge/discharge zone of study area. The Groundwater flow direction (GWFD) vector superimposed over the delineated GWPZ, shown in Figure: 4.24, depicts as a low GWPZ is recharge zone while, the high GWPZ is discharging zone.

5. SUMMARY AND CONCLUSION

5.1. Summary

Groundwater (GW) is the largest major source of fresh water for meeting domestic need, industrial, irrigation and other development initiatives in the world. The difficulty in obtaining productive aquifers is an odd feature in Ethiopia, because it's characterized by the wide heterogeneity of geology, topography and environmental conditions. Knowing groundwater occurrences, distribution, and identifying a good site for groundwater exploration are one of the biggest challenges, and key concern for water resources development and management in the most countries today. Improper groundwater potential site selection often leads an economic and time wastage for exploration, and unsustainable utilization resource is becoming increasingly an evident problem or challenging, and the key concern for many developing countries. The occurrence of groundwater potential zone is affected by many different geophysical and climatic factors like geology, topography and environmental conditions.

The groundwater potential zone of Welmel catchment was delineated by using GIS and Remote sensing techniques through analytical hierarchy process (AHP). The physiographic, geologic and climatic factors influencing groundwater potentials were identified and evaluated. To determine the scale value of clustered classes and the influence of thematic layers, the relative weight of classes and percentage of influences was computed by AHP method. The identified factors influencing groundwater potential of the study area include; geomorphological landforms, lineament density, geology, rainfall distribution, drainage density, elevation, slope, LU/LC and soil texture.

Geomorphological landforms determine runoff, groundwater recharge and to some extent rainfall conditions. Hence, it is a dominant factor influencing the GWPZ of study area. Lineament density, geology and rainfall distribution are the second, third and fourth factors influencing the GWPZ of Welmel catchment. The presence of lineaments are the structural discontinuity of the earth surfaces such as fault, foliation, joints and bedding planes present on the surfaces. It may be curve, linear and slightly curve which is the most essential for the infiltration and movement of water to the ground.

The slope is one of the important factor which highly controlling the infiltration and runoff capacity of precipitation and surface water flow. In areas characterized by flatlands and/or valleys, groundwater potential and recharge is high because it is easier for the water to enter (infiltrate) to the ground.

On the other hand, high slope regions have high runoff and low infiltration rate that are not suitable for groundwater recharge . Types of rocks determine peculiarities of hydrological cros-section structure, type of porosity values, the nature of permeability geological structure geomorphology and character of spatial heterogeneity of flow and transport parameters

Sedimentary rocks were considered as having a high potential for groundwater due to their high porosity and permeability relative to igneous and metamorphic rocks. The slope gradient directly influences the rainfall infiltration. The high residence time of rainwater permits extensive retention of rainwater to form pools and infiltrate to the water table and the deeper geologic formation.

Drainage pattern is a reflection of the rate that precipitation infiltrated compared with surface runoff. It indicates the inverse function of permeability capacity, infiltration capacity and recharge capacity of rocks and soil surface. High drainage density represents less infiltration and hence do not favour much on the groundwater potential of the area. Low drainage density represents high infiltration and hence contributes more to the groundwater potential of the area in addition to that Sparse vegetation and mountain relief which have high runoff and low infiltration result. The drainage density of an area depends on the topography, slope and sub-surface characteristics.

Rainfall impacts significantly the hydrological cycle, which has high effect on the area's groundwater capacity. The spatial distribution of rainfall of the study area which was significantly influenced by topographic variability of the sub-basin result in the spatial variability of GWPZ. In particular, the northern part of the watershed experiences higher rainfall. Due to the percolation of the higher precipitation, the major natural recharge of the welmel catchment is believed to occur at elevated regions.

Land use Land cover gives essential information on infiltration. It is a direct effect on the hydrological process of surface runoff, evapotranspiration and groundwater recharge. Water body, agricultural land and the water logged area are excellent sources of ground water recharge, while the bare lands and exposed rock surface areas are less important for ground water recharge.

To prepare the thematic maps of each factor and verify the delineated GWPZ, several data were collected from various sources. The historic time series of meteorological data, spatial data of soil, geology, DEM, satellite images and the existing water point's inventory data were used. Various software and computer programs employed for processing, identification and preparation of groundwater potential map include; ArcGIS 10.7.1, SAGA GIS, and Surfer 17.1. A weighting overlay approach of ArcGIS 10.7.1 was selected as the basic tool for the development of GWPZ. The groundwater prospect zones were evaluated based on the groundwater potential index computed from the integration of all groundwater influencing thematic layers.

The resulting groundwater potential index of the study area indicates four zones representing High, Moderate, Low and Very low GWPZ's. The total areal extent of the High groundwater potential is 350 km^2 (2%). The areal extent of moderate, Low and Very low GWPZ's are 2256 km^2 (16%), 10356 km^2 (71%), and 1547 km^2 (11%). In the study generally the reason for high groundwater potential is area which has low drainage density, low slope, and very high lineament density and flood plain Geomorphological units. The reason for Very low ground water potential zone is area which has very high drainage density, very high slope, low lineament density and structural hill geomorphological units .

The groundwater potential map was validated using the existing well yield and spring discharge. It indicated a good prediction accuracy of 82.08%. The groundwater locally flows in different directions while the entire groundwater flow direction of contours arrow reveals the Southeast and North eastern flow direction. The complex geologic structures of the study area govern the occurrence and movement of ground and surface water flow (Kifle and Hailemriam, 2010).

5.2. Conclusions

- Groundwater potential zone was delineated by using GIS and Remote Sensing techniques through Analytical Hierarchy Process methods were delineated and identified based on the influential factors for groundwater potential zone. In this research, nine parameters were selected which have more affects the occurrence of groundwater potential zone prior to overlay analysis. By assigning quantitative weights, it is possible to make important criteria that have a greater influence on the result than other criteria. The AHP, methods were adapted and give the value for each factor. This approach allows decision makers to give the judgments in order to reduce complexity in decision making processes.
- It can be concluded that integration of GIS and Remote Sensing techniques are very useful, time and cost effective tool for the identification/ delineation of groundwater potential zones. This study was focused on the integration of Remote Sensing and GIS technologies in the identification and delineation of groundwater potential zones in the welmel watershed. The remote sensing and GIS is a potentially effective tool and Very useful in delineation of groundwater potential zones.
- The resulting GWPZ of study area was classified into four zones representing High, Moderate, low and very low GWPZ's covering an area of 350 km^2, 2259 km^2, 10356 km^2 and 1547 km^2 respectively. The GWPZ was validated by using the existing water point's inventory data.
- A considerable extent of high groundwater potential is found in the South-western part of the study area.
- The overall prediction accuracy of identified groundwater potential zone with actual water point inventory data shows 82.08% agreement. Generally, the better agreement of the comparison between the water point's inventory data and GWPZ approve the efficiency of GIS and RS technique for mapping groundwater potential of welmel catchment.
- The geomorphologic landform, lineament density, geology and rainfall distribution shares the highest weightage. The geomorphologic landform is a dominant factor influencing the GWPZ of the study area.

5.3. Recommendations

Based on the major findings obtained from this study and the conclusion reached, the following recommendations are forwarded.

- ❖ This study specifically focuses on mapping the groundwater potential zone of welmel catchment. As it was a qualitative study the recharge and groundwater storage was not quantified. Hence, it is recommended to conduct a detail quantitative study using hydrological models
- ❖ The suitability of identified GWPZ was not assessed for various purposes. Further study is recommended to evaluate the suitability of groundwater potential zone for irrigation, water supply and other water resources development projects.
- ❖ The identified GWPZ area shall be protected from polluting chemicals to assure quality of the groundwater. Forestation of this area can also increase the available groundwater reserve by increasing the amount of infiltration and percolation hence; it is recommended to plane and execute environmental protection projects in these regions.
- ❖ Human activities have been exerted small to large scale changes on the hydrological cycle (Tadesse, 2017).Evidences suggest that, with extreme urbanization, more than one-half of rainwater runs off and only a fraction of it goes for deep infiltration (Arnold and Gibbons, 1996). The current scenario regarding groundwater resources suggests as the amount of water available is decreasing with time. Moreover, the problem is resulting in the global water crisis in terms of quantity (availability) and quality (Sudhir et al., 2010). Therefore, it is recommended to assess the effect/impact of LU/LC change and over pumping on the groundwater recharge and potential zone of study area.
- ❖ The same appropriate methods were recommended for complex areas to delineate groundwater potential and recharge zone in the small area.

REFERENCES

Abraham, Shiny, Chau Huynh and Huy Vu. 2019. Classification of soils into Hydrologic groups using Machine learning. Creative Commons Attribution 5(2):1–14.

Ahmed, Alaa, Mahmoud El Ammawy, Abdel Galil Hewaidy, Bothaina Moussa, Nabil Abdel Hafz and El Sayed El Abd. 2019. Mapping of lineaments for groundwater assessment in the Desert Fringes East El-Minia, Eastern Desert, Egypt. Environmental Monitoring and Assessment 191:556.

Aldharab, Hamdi., Syed Ahmad Ali, Javed Ikbal and Saleh. 2018. Spatial analysis of lineaments and their tectonic significance using Landsat Imagery in Alarasah Area-Southeastern Central Yemen. Journal of Geography, Environment and Earth Science International 18(2):1–13.

Alemayehu, Bireda. 2015. GIS and Remote Sensing based LU/LC change detection and prediction in Fagita Lekoma Woreda, Awi Zone, North Western Ethiopia. M.Sc Thesis. Addis Ababa University. Addis Ababa, Ethiopia. 85 p.

Andualem, Tesfa Gebrie and Girum Getachew Demeke. 2019. Groundwater potential assessment using GIS and Remote Sensing: A case study of Guna Tana Landscape, Upper Blue Nile Basin, Ethiopia. Journal of Hydrology: Regional Studies 24:100610.

Aredo, Mesfin Reta. 2018. Impact of LU/LC change on stream flow using MIKE SHE: case study of Shaya catchment, Ethiopia. M.Sc Thesis. Arba Minch University, Arba Minch, Ethiopia 84 p.

Arshad, Arfan, Zhijie Zhang, Wanchang Zhang and Adil Dilawar. 2020. Geoscience frontiers mapping favorable groundwater potential recharge zones using a GIS-based analytical hierarchical process and probability frequency ratio model : A case study from an Agro-Urban region of Pakistan. Geoscience Frontiers 11:1805–19.

Asrat, Asfawossen. 2015. Geology, geomorphology, geodiversity and geoconservation of the Sof Omar Cave system, Southeastern Ethiopia. Journal of African Earth Sciences. 108. 10.1016/j.jafrearsci.2015.04.015.

Ayenew, Tenalem, Merhawi GebreEgziabher, Seifu Kebede, and Sileshi Mamo. 2013. Integrated assessment of hydrogeology and water quality for groundwater-based irrigation development in the Raya Valley, Northern Ethiopia. Water International 38:480–92.

Banti, Bane Lammesa. 2017. Groundwater potential and recharge zone mapping by using GIS and Remote Sensing techniques in the case of Middle Awash River Basins, Ethiopia. M.Sc Thesis. Addis Ababa University. Addis Ababa, Ethiopia. 66 p.

Bayih, Berhanu & Tola, Mesfin. 2017. Practices and challenges of promoting major tourism destinations of Bale Zone for sustainable tourism development in Ethiopia. African Journal of Hospitality, Tourism and Leisure 6(2):19. ISSN: 2223-814X. http//:www.ajhtl.com

Behzad, Hamid., Abbas Charchi, Nasrolah Kalantari and Hossein Karimi Vadanjani. 2017. Delineation of groundwater potential zones using Remote Sensing (RS), Geographical Information System (GIS) and Analytic Hierarchy Process (AHP) techniques: A case study in the Leylia–Keynow Watershed, Southwest of Iran. Carbonates and Evaporites 7(2).

Belachew, Tadyalehu Mulatu. 2018. Impact of climate change on flood frequency of Tegona River, Ethiopia. M.Sc Thesis. Arba Minch University, Arba Minch, Ethiopia. 91 p.

Berhanu, Kibrit Gedam and Samuel Dagalo Hatiye. 2020. Identification of groundwater potential zones using proxy data: case study of Megech Watershed, Ethiopia. Journal of Hydrology: Regional Studies 28(2):1–20.

California Department of Water Resources (CADWR). 2005. Integrated water flow model (IWFM v2.3): Theoretical documentation, Modeling Support Branch, Bay-Delta Office, Sacramento, CA.

Calow JL and Selby WJ (2000). Groundwater potential map for the district of Leeds: a Geographic Information System model incorporating data from Site Investigations reports and the British Geological Survey's Digital terrain model. Applied Geography 20(3): 313–322.

Dabral, Sumit, Bindu Bhatt, Janak P. Joshi, and N. Sharma. 2014. Groundwater suitability recharge zones modelling-A GIS application. International Archives of the

Photogrammetry, Remote Sensing and Spatial Information Sciences - ISPRS Archives 8:347-53.

Debebe, 2020. Groundwater potential mapping using geospatial techniques: A case study of Dhungeta-Ramis subbasin, Ethiopia. Geology, Ecology, and Landscapes.

Desalegn, (2011). Groundwater potential evaluation and flow dynamics of Hormat-Golina River catchment, Kobo valley, North Ethiopia. Addis Ababa University.

Doyo. (2020). Groundwater potential mapping using remote sensing and GIS techniques: the case of Meki watershed, Central Rift valley, Ethiopia. Hawassa University.

Duan, H., Deng, Z., Deng, F. and Wang, D., 2016. Assessment of Groundwater potential based on multicriteria decision making model and decision tree algorithms.

Efren .2020. A groundwater flow model to aid in water resource management for the Carraipia Basin in the coastal semi-arid region of La Guajira state (Colombia). Electronic theses and dissertations. The University of Maine. 97 p.

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

Emiru, Tamam, Hasan Raja Naqvi and Mohammed Abdul Athick. 2018. Anthropogenic impact on LU/LC: Influence on weather and vegetation in Bambasi Wereda, Ethiopia. Spatial Information Research 26(4):427–36.

Epuh, E. E., M. J. Orji, H. A. Iyoyojie and O. E. Daramola. 2020. Groundwater potential mapping in Ikorodu, Lagos State, Nigeria, Using Multi-criteria analysis and Hydrogeophysics. Nigerian Journal of Technology (NIJOTECH) 39(1): 278 – 292

Evaluation of Groundwater Potential by GIS-Based Multicriteria Decision Making as a Spatial Prediction Tool : Case Study in the Tigris River. (2019).

FAO (Food and Agricultural Organization). 2003. The digital soil map of the World version 3.6. FAO/UNESCO. Rome, Italy.

FAO (Food and Agricultural Organization). 2015. Status of the World's Soil Resources (SWSR) – Main Report. Food and Agriculture Organization of the United Nations and Intergovernmental technical panel on soils. Rome, Italy. p 527–598.

Fisher, Rohan, Sarah Hobgen, Iradaf Mandaya, Norman Riwu Kaho, Tenggara Timur and Zulkarnain. 2017. Satellite image analysis and terrain modelling-version 2 SAGA GIS 4+. A practical manual for natural resource management, disaster risk and development planning using free geospatial data and software. Charles Darwin University.

Gaikwad. VS. Bhagat. 2017. Multi-criteria watershed prioritization of Kas Basin in Maharashtra (India): AHP and influence approaches. Hydrosp Anal 1(1):41-61..

Gebru, Hindeya, Tesfamichael Gebreyohannes and Ermias Hagos. 2020. Identification of groundwater potential zones using analytical hierarchy process and GIS-Remote Sensing integration, the case of Golina River Basin, Northern Ethiopia. International Journal of Advanced Remote Sensing and GIS 9(1):3289–3311.

Gintamo, Tesfaye Tessema. 2015. Groundwater potential evaluation based on integrated GIS and Remote Sensing techniques, in Bilate River catchment : South Rift Valley of Ethiopia. American Scientific Research Journal for Engineering, Technology, and Sciences 10:85–120..

Godebo.(2018). Application of remote sensing and GIS for Geological investigation and groundwater potential zone identification, Southeastern Ethiopian plateau, Bale Mountains and the surrounding areas. Addis Ababa University.

Gwenzi, & Nyamadzawo, (2014). Hydrological Impacts of Urbanization and Urban Roof Water Harvesting in Water-limited Catchments:

Harter and Morel-Seytoux (2013). Peer Review of the IWFM, MODFLOW and HGS Model Codes: Potential for Water Management Applications in California's Central Valley and Other Irrigated Groundwater Basins. Final Report, California Water and Environmental Modeling Forum, August 2013, Sacramento. http://www.cwemf.org.

Hogeboom. 2013 .The influence of groundwater abstractions on Lake Naivasha's water level. M.Sc. Thesis. University of Twente, The Netherlands. 90p.

IUSS Working Group WRB. 2015. World Reference Base for Soil Resources 2014, Update 2015 International soil classification system for naming soils and creating legends for soil maps. World soil resources reports No. 106. Rome, Italy..

Kabite and Gessesse, 2018. Hydro-geomorphological characterization of Dhidhessa River Basin,Ethiopia.

Kahsay, Gebreyohannes, Tesema and Emabye , 2019. Evaluation of groundwater quality and suitability for drinking and irrigation purposes using hydrochemical approach: The Case of Raya Valley, Northern Ethiopia.

Kassahun & Mohamed. (2018). Groundwater Potential Assessment and Characterization of Genale-Dawa River Basin. Open Journal of Modern Hydrology, 08(04), 126–144. https://doi.org/10.4236/ojmh.2018.84010

Kebede, Mintesnot, and Yonas Mulugeta. 2011. Hydrogeological map of Megallo map Sheet (NB 37-8). Geological Survey of Ethiopia, Addis Ababa, Ethiopia.

Kebede,(2013). Groundwater in Ethiopia: features, numbers and opportunities. In springer hydrogeology. Springer-Verlag Berlin Heidelberg 2013. https://doi.org/10.1007/978-3-642-30391-3

Kidanu & Kindeya. 2018. Identification of groundwater potential zone mapping using Remote Sensing and GIS techniques, in case of Inderta District, Ethiopia. M.Sc Thesis. Addis Ababa University. Addis Ababa, Ethiopia. 64 p.

Kifle, Astatike and Mulugeta Hailemriam. 2010. Integrated Hydrogeological mapping of Dodola map sheet (NB 37-7) Southeastern Ethiopia highlands with associated lowlands. Geological S0urvey of Ethiopia. Addis Ababa, Ethiopia.

Kiflu, Tafa & Mulugeta. (2009). Hydrogeological mapping of part of Asela map sheet (NB 37-3) South eastern high land of Ethiopia.

Kindie, Enku, Moges, Geremew and Atinkut. 2019. Spatial analysis of groundwater potential using gis based multi criteria decision analysis method in Lake Tana Basin, Ethiopia. In Zimale F., Enku Nigussie T., Fanta S. (Eds) Advances of Science and Technology.

Kramm, Tanja, Dirk Hoffmeister, Constanze Curdt, Sedigheh Maleki, Farhad Khormali and Martin Kehl. 2017. Accuracy assessment of landform classification approaches on different spatial scales for the Iranian Loess Plateau. ISPRS International Journal of Geo-Information 6:1–22.

Lagesse, Abel. 2017. Hydrological trend, variability and time series modeling of Weyib catchment. M.Sc Thesis. Addis Ababa University. Addis Ababa, Ethiopia. p 108.

Lakshmi, S. W. and Reddy, Y. V. K., 2018. Identification of Groundwater potential zones using GIS and Remote Sensing.

Lemecha, Gezahegn. 2007. Delineation of groundwater potential zones of Upper Tumet catchment, Menge area, Western Ethiopia using Remote Sensing and GIS. M.Sc Thesis. Addis Ababa University. Addis Ababa, Ethiopia. p 86.

Lemenkova. (2015). Processing Remote sensing data using Erdas Imagine for mapping Aegean Sea Region, Turkey. Informatics, 2, 11–15

Mamo, Abiy Getachow. 2007. Integration of Remote Sensing and GIS for groundwater resources assessment in Moyale-Teltele Sub-basin, South Ethiopia. M.Sc Thesis. Addis Ababa University. Addis Ababa, Ethiopia. p 88.

Melese and Belay. 2021. Groundwater potential zone mapping using analytical hierarchy process and GIS in Muga Watershed, Abay Basin, Ethiopia.

Mengistu, Demlie and Abiye. 2019. Review: groundwater resource potential and status of groundwater resource development in Ethiopia.

Messene, Genet Mathewos. 2017. Groundwater Flow direction, recharge and discharge zones identification in Lower Gidabo Catchment, Rift Valley Basin, Ethiopia. Journal of Environment and Earth Science 7(2):32–39.

Michael, Pelagio , Divina and Rheo. 2020. USDA soil texture calculator. Potential application of laser-induced breakdown spectroscopy data for the determination of Cation exchange capacity of agricultural soils, Chemistry 3798–3804Magesh, N. S., N. Chandrasekar and J. P. Soundranayagam. 2012. Delineation of groundwater potential zones in Theni District, Tamil Nadu, using Remote Sensing, GIS and MIF techniques. Geoscience Frontiers 3(2):189–96.

Mitiku, Dereje Birhanu. 2011. Numerical Groundwater Flow Modeling of the Meki River Catchment, Central Ethiopia. M.Sc. Thesis. Addis Ababa University. Addis Ababa, Ethiopia.

Moges, Bhat and Thrivikramji.2019. Investigation of groundwater resources in highland Ethiopia using a geospatial technology.

Mokarram & Sathyamoorthy. (2016). Relationship between landform classification and vegetation (case study: Southwest of Fars province, Iran).

Mukherje & Fryar (2008). Deeper groundwater chemistry and geochemical modeling of the arsenic affected western Bengal basin, West Bengal, India. Applied Geochemistry, 23(4), 863-894..

Mulugeta, Yonas and Yosef Tafa. 2010. Integrated Hydrogeological mapping of Ginnir map sheet (NB-37-4) Southeastern lowland and adjacent highland of Ethiopia. Geological Survey of Ethiopia. Addis Ababa, Ethiopia.

Nachtergaele, Freddy, Harrij Van Velthuizen, Luc Verelst, Niels Batjes, Koos Dijkshoorn, Vincent Van Engelen, Guenther Fischer, Arwyn Jones, Luca Montanarella, Monica Petri, Sylvia Prieler, Edmar Teixeira, David Wiberg and Xuezheng Shi. 2009. Harmonized World Soil Database (Version 1.1). 1–39.

Nagarajan& Singh. (2009). Assessment of Groundwater potential zone using GIS Technique. Journal of Indian Society of Remote Sensing, 37, 69–77.

Negewo & Sarma. (2021). Estimation of Water Yield under Baseline and Future Climate Change Scenarios in Genale Watershed, Genale Dawa River Basin, Ethiopia, Using SWAT Model. Journal of Hydrologic Engineering, 26(3), 1–13. https://doi.org/10.1061/(asce)he.1943-5584.0002047

Nuru, Adem Berihun. 2018. Assessment of potential groundwater zone using integrated GIS and Remote Sensing techniques in Sekota Wereda, Northern Ethiopia. M.Sc Thesis. Addis Ababa University. Addis Ababa, Ethiopia. p 59

Olaya. (2004). A gentle introduction to SAGA GIS. In J. Pineda & V. Olaya (Eds.), The SAGA User Group eV, Gottingen, Germany (1.1).

Patra, Sahoo, Mishra & Mahapatra. (2018). Impacts of urbanization on land use /cover changes and its probable implications on local climate and groundwater level. Journal of Urban Management, 7(2), 70–84.

PCI Geomatics Enterprises. 2017. Geomatica 2017 installation and licencing guide. PCI Geomatics Enterprises, Inc.90 Allstate Parkway, Suite 501, Markham, Ontario, Canada p 1-24.

PCI Geomatics Enterprises. 2018. Geomatica I guide version 2018. PCI Geomatics Enterprises, Inc. 90 Allstate Parkway, Suite 501, Markham, Ontario, Canada. p130.

Punmia, B. C., Pande Brij Basi Lal, Ashok Kumar Jain and Arun Kumar Jain. 2009. Irrigation and water power engineering. Sixteenth. Laxmi publication (p) LTD.113, Golden house, Daryaganj, New Delhi-11002, India p 1-961. .

Rahman, Atiqur, Sunil Kumar and Shahab Fazal. 2012. Assessment of LU/LC change in the North-West District of Delhi using Remote Sensing and GIS techniques. Journal of the Indian Society of Remote Sensing (5).

Raj, Kiran and Ashfaq Syed Ahmed. 2014. Lineament extraction from Southern Chitradurga Schist Belt using Landsat TM, ASTERGDEM and geomatics techniques. International Journal of Computer Applications 93(12):12–20.

Ramu,& Mahalingam . 2014. Identification of groundwater potential zones using GIS and Remote Sensing techniques: A case study of Mysore Taluk - Karnataka. International Journal of Geomatics and Geosciences 5(3).

Richman, Eliza and Admassu, Biniyam. 2013. Bale Mountains National Park: A traveller's guide book. The Ethiopian Wildlife Conservation Authority (EWCA). Frankfurt Zoological Society and the Bale Mountains National Park. European Union p 13.

RockWorks. 2008. RockWorks manual: Earth science and GIS software. Vol. 1. First edit. RockWare, Inc. 2221 East St., Suite 101 80401 Golden, CO USA. p 361. .

Rwanga & Ndambuki.(2017). Approach to Quantify Groundwater Recharge Using GIS Based Water Balance Model: A Review. International Journal of Research in Chemical, Metallurgical and Civil Engineering, Saaty. (2000). Fundamentals of decision making and priority theory with the analytic hierarchy process. RWS Publications.

Salwa . (2015). An overview of integrated remote sensing and GIS for groundwater mapping in Egypt. Ain Shams Engineering Journal, 6(1), 1–15.

Seifu. (2006). Groundwater occurrence in Ethiopia. Addis Abeba University Press. Sanford, Ward. 2002. Recharge and groundwater models:.

Selinus. 2013. Essentials of Medical Geology Revised Edition. Dordrecht: Springer Netherlands. Web. ISBN:

Semere, Solomon. 2003. Remote Sensing and GIS: Applications for groundwater potential assessment in Eritrea. Ph.D Thesis. Royal Institute of Technology SE-100 44 Stockholm, Sweden. p 136.

Sewnet, Demeke, Hasan Raja Naqvi, and Abdul Athick. 2016. Zonation of potential groundwater and its spatial correlation with indices and boreholes: Western Region of Blue Nile Basin, Ethiopia.

Shamuyarira. (2017). Determination of recharge and groundwater potential zones in Mhinga area, South Africa. University of Venda

Solomon. (2003). Remote Sensing and GIS : Applications for Groundwater Potential Assessment in Eritrea (Issue April)..

Sridhar, Venkataramana, Syed Azhar Ali and Venkataraman Lakshmi. 2019. Assessment and validation of total water storage in the Chesapeake Bay watershed using GRACE. Journal of Hydrology: Regional Studies 24(2018):100607.

Subramanya. 2008. Engineering hydology. In Engineering hydrology. Third edition. Edited by S. Mukherjee. McGraw-Hill publishing company limited. 7 West Patel Nagar, New Delhi 110008. 26–37 p.

Takorabt, Mebarka, Ahmed Cherif Toubal, Hamid Haddoum and Siham Zerrouk. 2018. Determining the role of lineaments in underground hydrodynamics using Landsat 7 ETM+ data, case of the Chott El Gharbi Basin (Western Algeria). Arabian Journal of Geosciences 11:76.

Tamiru and Wagari. 2021. Evaluation of data-driven model and GIS technique performance for identification of groundwater potential zones: A case of Fincha Catchment, Abay Basin, Ethiopia. Journal of Hydrology

Tegegn. (2015). Assessment of groundwater potential zones in Baro Basin using GIS and Remote sensing.

Todd, David Keith. 2005. Groundwater Hydrology. 3rd edition. John Wiley and Sons, Inc. edited by B. J. W. V. A. V. Zobrist. Hoboken, USA. p 636.

Tolcha, Ashenafi Tedla. 2009. Impact Assessment of LU/LC changes on Shaya River flow using SWAT (case study of Shaya watershed, in Bale). M.Sc Thesis. Arba Minch University. Arba Minch, Ethiopia.

Waika and Aditya. 2014. Identification of groundwater potential zone Using Remote Sensing and GIS technique. International Journal of Innovative Research in Science, Engineering and Technology 3:12163–74.

Woldeyohannes, Meseret. 2016. Estimating water balance of Tegona watershed in, Southeastern Ethiopia, using SWAT model. M.Sc. Thesis. Madda Walabu University, Bale Robe, Ethiopia.

Yifru, Mitiku, Tolera , Chang and Chung, Il-M., 2020. Groundwater potential mapping using SWAT and GIS-based multi-criteria decision analysis. KSCE Journal of Civil Enineerig.

Yismaw, Aman, Asaminew Besufikad, Tarekegn Dure, Argaw Ersido, Eriko Kebede, Dimberu Besfiat, Tsegaye Wondfraw and Tewodros Abdulahid. 2015. Geology geochemistryand gravity survey of Megalo map sheet memoir 45. Geological Survey of Ethiopia, Addis Ababa, Ethiopia. p 80.

Zawawi, Azita Ahmad, Masami Shiba and Noor Janatun Naim Jemali. 2014. Landform classification for site evaluation and forest planning: integration between scientific approach and traditional concept. Sains Malaysiana 43(3):349–58.

Zeinolabedini. 2015. Groundwater potential assessment using geographic information systems and AHP method (case study: Baft City, Kerman, Iran). International Archives of the Photogrammetry, Remote Sensing and Spatial Information Sciences 40:769–74.

APPENDICES

Appendix table 1: Saaty's scale of intensity relative importance and descriptions

Intensity of importance	Definition	Explanation
1	Equal importance	Two factors contribute equally to the objective
3	Moderately important or Somewhat more important	Experience and judgment slightly favour one over the other.
5	Strongly important or Much more important	Experience and judgment strongly favour one over the other
7	Very strong or Very much more important	Experience and judgment very strongly favour one over the other. Its importance is demonstrated in practice.
9	Extremely important or Absolutely more important.	The evidence favouring one over the other is of the Highest possible validity.
2,4,6,8	Intermediate values	When compromise is needed
1/3,1/5,1/7,1/9	Value for inverse comparison	

Source: (Baby, 2013; Dabral et al., 2014; Saaty and Kearns, 1985)

Appendix table 2: Software used for the study

S.No.	Software	Uses
1	Arc GIS 10.5	Preparation of geologic, drainage density, rainfall distribution, elevation, slope thematic map and weight overlay analysis
2	ERDAS-imagine	Land Use Land Cover classification
3	SAGA GIS	

Appendix table 3: Sources of data, scale and their respective resolution

S.No.	Data	Source
1	Weather data	NMSA and SOMSC
2	Soil data	MoWIE
3	DEM and Landsat (Landsat 8 OLI/TIRS multi-spectral) images (20*20m)	Earth explorer USGS website (www.earthexplorer.usgs.gov).
4	Geology (1:250,000)	Geological survey of Ethiopia and MoWIE
5	Borehole and spring	MoWIE and Bale zone water resources development and energy

Appendix 4. Geological coding

(Adopted form integrated water resource development master plan study: Geology sector)

No.	Code	Description of Geologic class
		Quaternary Volcanics and Sediments
1	Q	Undivided alluvium, eluvium and lacustrine sediments
2	Qa	Alluial deposits: gravel,sand silt and clay
3	Qv	pyrcasitic surge deposits: mainly bedded fall deposits scoria, rock fragments
		Tertiary Volcanic Sucessions
4	Nn	Nazeret Group: stratoid silics-ignimbites, tuffs, ash, rhyolites, trachye, minor basalt
5	Ntr3	Alkal trachyte flows
6	Ntr2	Alkali trachyte and basalt flows
7	PNtr1	Alkali trachyte and basalt flows, rhyolitic ignimbrite, minor tuff and bassal flows
8	NMt	Teltele basalt flows
9	PNb2	Ankaramite and minor divine-phyric basalt
10	PNb1	Lower flood basalts
11	Tsy	Hornblende-Alkali syenite, minor hornblende-nepheline syenite
		Mesozoic Sedimentary Successions
12	Ka	Amba Aradam Formation: varicoloured sandstones with inter bedding
13	Jg	Gabredarre Formation: micritic to microcrysaline and oolitic limestones
14	Jh2	Hamanlei Formation: micritic locally oolitic (grainstone) peletic limestones

15	Jh1	Hamanlei Formation: less fossiliferous limestones with beds of calcareous sandstone
16	Ja	Adigrat formation: variegated quatzos sanstones, intercalations of siltstones, shales andintrafomational conglomerates
17	pcgt2	Blotite and homblende granites
18	pcgb1	Metagabbro
19	pcgn4	wadera mylonite and mylonitic gneiss
20	pcgn3	Hornblende-biotite-quartz-feldspar and biotite-quartz-feldspar gneisses
21	pcgn2	Biotite-hornblende gneiss

Appendix table 5: Soil class and its coverage area.

Soil classes	Area (km^2)
Eutric Cambisol	1838
Chromic Cambisol	963
Lepto soil	877
Rendzic lepto soil	3373
Calcaric Cambisol	14
Chromic Luvisol	2785
Chromic vertisoil	3773
Pellic verti soil	889

Appendix table 6: Major soil groups and their short description

Major soil groups	Short description
Cambisols	Weakly to moderately developed soils. Most Cambisols are medium-grained and have a good structural stability, a high porosity, and good water holding capacity and good internal drainage. Most Cambisols also contain at least some weatherable minerals in the silt and sand fractions. Based on these characteristics, Cambisols have a good infiltration capacity to recharge groundwater. Parent material: Medium and fine textured materials derived from a wide range of rocks.
Luvisols	Soils with sub-surface accumulation of high activity clays and high base saturation. Porous and well aerated topsoil. Luvisols have a higher clay content in the sub-soil than in the topsoil. Parent material: A wide variety of unconsolidated materials including glacial till, and aeolian, alluvial and colluvial deposits.
Regosol	Regosols are very weakly developed mineral soils in unconsolidated materials that do not have a mollic or umbric horizon, are not very thin or very rich in coarse fragments (Leptosols), not sandy (Arenosols), and not with fluvic materials (Fluvisols). Parent material: unconsolidated, generally fine-grained material.
Vertisols	Vertisols (known as black cotton soil) are heavy clay soils with a high proportion of swelling clays. Vertisols are characterized by their sticknature and high water holding capacity and low infiltration capacity. These soils become very hard and form deep wide cracks from the surface downward when they dry out, which happens in most years. Parent material: Sediments that contain a high proportion of swelling clays, or swelling clays produced by neoformation from rock weathering.

Source: (FAO, 2015; IUSS Working Group WRB, 2015; Nachtergaele et al., 2009)

Appendix table 7: Welmel woreda Names and its Area

Woreda Name	**Area**_km^2
Adaba	398
Berbere	1313
Dinsho	1
Goba	1010
Goro	13
Gura Damole	2418
Harena Buluk	1481
Meda Welabu	3000
Mena	4833
Sinana	45

Apendix table 8: The average annual rainfall of study area

Stations	Lat.	Long.	Elev.	Area_km^2
Angetu	6.183	39.766	1450	5020
Dellomena	6.416	39.833	1313	7302
Melka Amanna	6.224	39.787	1048	2190

Appendix Table 9: Water Source Inventory Point (Validation Data)

Number	Type	Site Name	Zone	Woreda	UTM. X	UTM.Y	Elevation	Depth(	Yield(LPS)
1	SP	Burkitu (Cheketa Urene)	BALE	Berbere	643000	753074	1215		1.2
2	SP	Cheketa	BALE	Berbere	642569	755629	1235		15
3	SP	Gora Badamana	BALE	Berbere	636898	756572	1314		1.8
4	SP	Haro Dumal	BALE	Berbere	629588	747197	1154		0
5	DW	Weltai Deresa No 1	BALE	Berbere	624951	741025	1318	6	0
6	DW	Weltai Deresa No 2	BALE	Berbere	624777	741155	1320	6.01	0
7	DW	Weltai Deresa No 3	BALE	Berbere	624586	741314	1334	6.02	0
8	DW	Rira No 1	BALE	Goba	580293	748770	2930	6.03	0
9	DW	Rira No 2 (In School Compund)	BALE	Goba	580304	748996	2942	6.04	0
10	SP	Meleu (Burka)	BALE	Goro	647278	775730	2199	6.05	10
11	SP	Meleu (Burka)	BALE	Goro	647278	775730	2199	6.06	10
12	SP	Meleu (Burka)	BALE	Goro	647278	775730	2199	6.07	10
13	BH	Oborso No 1	BALE	Meda Welabu	544208	678019	1556	6.08	0.9
14	BH	Oborso No 2	BALE	Meda Welabu	544465	678347	1557	6.09	1.5
15	BH	Oda	BALE	Meda Welabu	551274	672099	1417	6.1	0.3
16	BH	Waduma	BALE	Meda Welabu	559273	644601	1533	6.11	0.3
17	BH	Waduma	BALE	Meda Welabu	559273	644601	1533	6.12	0.3
18	BH	Waduma	BALE	Meda Welabu	559273	644601	1533	6.13	0.3
19	BH	Waduma	BALE	Meda Welabu	559273	644601	1533	6.14	0.3
20	BH	Waduma	BALE	Meda Welabu	559273	644601	1533	6.15	0.3
21	BH	Waduma	BALE	Meda Welabu	559273	644601	1533	6.16	0.3
22	BH	Waduma	BALE	Meda Welabu	559273	644601	1533	6.17	0.3
23	BH	Waduma	BALE	Meda Welabu	559273	644601	1533	6.18	0.3
24	BH	Waduma	BALE	Meda Welabu	559273	644601	1533	6.19	0.3
25	BH	Waduma	BALE	Meda Welabu	559273	644601	1533	6.2	0.3

26	BH	Waduma	BALE	Meda Welabu	559273	644601	1533	6.21	0.3
27	BH	Waduma	BALE	Meda Welabu	559273	644601	1533	6.22	0.3
28	BH	Waduma	BALE	Meda Welabu	559273	644601	1533	6.23	0.3
29	BH	Waduma	BALE	Meda Welabu	559273	644601	1533	6.24	0.3
30	BH	Waduma	BALE	Meda Welabu	559273	644601	1533	6.25	0.3
31	BH	Waduma	BALE	Meda Welabu	559273	644601	1533	6.26	0.3
32	BH	Waduma	BALE	Meda Welabu	559273	644601	1533	6.27	0.3
33	BH	Waduma	BALE	Meda Welabu	559273	644601	1533	6.28	0.3
34	BH	Waduma	BALE	Meda Welabu	559273	644601	1533	6.29	0.3
35	BH	Waduma	BALE	Meda Welabu	559273	644601	1533	6.3	0.3
36	BH	Waduma	BALE	Meda Welabu	559273	644601	1533	6.31	0.3
37	BH	Waduma	BALE	Meda Welabu	559273	644601	1533	6.32	0.3
38	BH	Waduma	BALE	Meda Welabu	559273	644601	1533	6.33	0.3
39	BH	Waduma	BALE	Meda Welabu	559273	644601	1533	6.34	0.3
40	BH	Waduma	BALE	Meda Welabu	559273	644601	1533	6.35	0.3
41	BH	Waduma	BALE	Meda Welabu	559273	644601	1533	6.36	0.3
42	BH	Waduma	BALE	Meda Welabu	559273	644601	1533	6.37	0.3
43	BH	Waduma	BALE	Meda Welabu	559273	644601	1533	6.38	0.3
44	BH	Waduma	BALE	Meda Welabu	559273	644601	1533	6.39	0.3
45	BH	Waduma	BALE	Meda Welabu	559273	644601	1533	6.4	0.3
46	BH	Waduma	BALE	Meda Welabu	559273	644601	1533	6.41	0.3
47	BH	Waduma	BALE	Meda Welabu	559273	644601	1533	6.42	0.3
48	BH	Waduma	BALE	Meda Welabu	559273	644601	1533	6.43	0.3
49	BH	Waduma	BALE	Meda Welabu	559273	644601	1533	6.44	0.3
50	BH	Waduma	BALE	Meda Welabu	559273	644601	1533	6.45	0.3
51	BH	Waduma	BALE	Meda Welabu	559273	644601	1533	6.46	0.3
52	BH	Waduma	BALE	Meda	559273	644601	1533	6.47	0.3

				Welabu					
53	BH	Waduma	BALE	Meda Welabu	559273	644601	1533	6.48	0.3
54	BH	Waduma	BALE	Meda Welabu	559273	644601	1533	6.49	0.3
55	BH	Waduma	BALE	Meda Welabu	559273	644601	1533	6.5	0.3
56	BH	Waduma	BALE	Meda Welabu	559273	644601	1533	6.51	0.3
57	BH	Waduma	BALE	Meda Welabu	559273	644601	1533	6.52	0.3
58	BH	Waduma	BALE	Meda Welabu	559273	644601	1533	6.53	0.3
59	BH	Waduma	BALE	Meda Welabu	559273	644601	1533	6.54	0.3
60	BH	Waduma	BALE	Meda Welabu	559273	644601	1533	6.55	0.3
61	BH	Waduma	BALE	Meda Welabu	559273	644601	1533	6.56	0.3
62	BH	Waduma	BALE	Meda Welabu	559273	644601	1533	6.57	0.3
63	BH	Waduma	BALE	Meda Welabu	559273	644601	1533	6.58	0.3
64	BH	Waduma	BALE	Meda Welabu	559273	644601	1533	6.59	0.3
65	BH	Waduma	BALE	Meda Welabu	559273	644601	1533	6.6	0.3
66	BH	Waduma	BALE	Meda Welabu	559273	644601	1533	6.61	0.3
67	BH	Waduma	BALE	Meda Welabu	559273	644601	1533	6.62	0.3

The abbreviation of Y(LPS) , SP, BH, DW Yield liter per second, spring, bore hole, dug well