# Mapping Groundwater Potential and Land Suitability for Surface Irrigation Using Geo-Spatial Techniques in Keleta Watershed, Awash River Basin, Ethiopia

**Dawit Yohannes Meskele**

**A Thesis Submitted to the**

**Department of Water Resources Engineering**

**School of Civil Engineering and Architecture**

**Presented in Partial Fulfillment of the Requirement for the Degree of Master's in Water Resources Engineering (Specialization in Irrigation Engineering)**

**Office of Graduate Studies**

**Adama Science and Technology University**

**August, 2021**

**Adama, Ethiopia**

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## APPROVAL SHEET

I, the advisor of the thesis entitled "**Mapping Groundwater Potential and Land Suitability for Surface Irrigation Using Geo-Spatial Techniques in Keleta Watershed in Awash River Basin in Ethiopia**" and developed by Dawit Yohannes Meskele, hereby certify that the recommendation and suggestions by the board of examiners are appropriately incorporated into the final version of the thesis.

| Mesfin Benti (PhD) | | |
|---|---|---|
| Advisor | Signature | Date |

We, the undersigned, members of the Board of Examiners of the thesis by Dawit Yohannes Meskele have read and evaluated the thesis entitled "**Mapping Groundwater Potential and Land Suitability for Surface Irrigation Using Geo-Spatial Techniques in Keleta Watershed in Awash River Basin in Ethiopia**" and examined the candidate during the open defense. This is, therefore, to certify that the thesis is accepted for partial fulfillment of the requirement of the degree of Master of Science in Water Resources Engineering (Irrigation Engineering).

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| Chairperson | Signature | Date |
| Internal Examiner | Signature | Date |
| External Examiner | Signature | Date |

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

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|---|---|---|
| Department Head | Signature | Date |
| School Dean | Signature | Date |
| Office of Postgraduate Studies, Dean | Signature | Date |

# DECLARATION

I, hereby declare that this MSc Thesis entitled "**Mapping Groundwater Potential and Land Suitability for Surface Irrigation Using Geo-Spatial Techniques in Keleta Watershed in Awash River Basin in Ethiopia**" is my original work. That is, it has been submitted for the award of any academic degree, diploma, or certificate in any other university. All sources of materials that are used for this thesis have been duly acknowledged through citation.

| Dawit Yohannes Meskele | | |
|---|---|---|
| Name of the student | Signature | Date |

## RECOMMENDATION

I, the advisor of this thesis, hereby certify that I have read the revised version of the thesis entitled "**Mapping Groundwater Potential and Land Suitability for Surface Irrigation Using Geo-Spatial Techniques in Keleta Watershed in Awash River Basin in Ethiopia**" prepared under my guidance by Dawit Yohannes Meskele submitted in partial fulfillment of the requirements for the degree of Master of Science in Water Resources Engineering (Irrigation Engineering). Therefore, I recommended the submission of the revised version of the thesis to the department following the applicable procedures.

| Mesfin Benti (PhD) | | |
|---|---|---|
| Advisor | Signature | Date |

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# ACRONYMS AND ABBREVIATIONS

| | |
|---|---|
| CI | Consistency Index |
| CR | Consistency Ratio |
| DEM | Digital Elevation Model |
| NMA | National Meteorological Agency |
| ERDAS | Earth Resources Data Analysis System |
| FAHP | Fuzzy-Analytical Hierarchy Process |
| FAO | Food and Agricultural Organization |
| FMCDM | Fuzzy Multi-Criteria Decision Making |
| GIS | Geographical Information System |
| GWPZ | Ground Water Potential Zone |
| IDW | Inverse Distance Weighting |
| LULC | Land Use Land Cover |
| NASA | National Aeronautics and Space Administration |
| MCDA | Multi-Criteria Decision Analysis |
| MoWIE | Ministry of Water, Irrigation, and Energy |
| OWWDSE | Oromia Water Work Design and Supervision Enterprise |
| PCM | Pair-wise Comparison Matrix |
| PILSZ | Potential Irrigation Land Suitability Zone |
| RI | Random Index |
| SRTM | Shuttle Radar Topography Mission |
| UTM | Universal Transverse Mercator |
| WOA | Weighted Overlay Analysis |

# *ABSTRACT*

*In Ethiopia, surface water is the primary source of agricultural production, although groundwater is rarely used for crop production. Many irrigation systems derive their water from river diversions, which benefit only farmers who own land near the irrigation project, while others depends on rainy season. Using groundwater resources for irrigation could be a viable option for alleviating the food shortages. The broad aim of this study was to delineate the groundwater potential zone and potential land suitability zone for surface irrigation using GIS-based Multi-Criteria Decision Analysis (MCDA) techniques in the Keleta watershed, Awash River Basin, Ethiopia. The main influencing parameters to be considered to identify the groundwater potential zone (GWPZ) include landform, lithology, slope, soil, rainfall, land use/land cover, drainage density, and lineament density, while soil type, slope, soil drainage, soil depth, and land use/cover were considered for potential land suitability zone (PLSZ). The thematic layers of each factor were prepared and their weights were assigned, normalized, and ranked based on their suitability to groundwater occurrence and irrigation land suitability using Fuzzy-Analytic Hieraricy Process (FAHP) through Pair-wise Comparsion Matrix (PCM). The weighted overly analysis tool was used to develop GWPZ and PLSZ by integrating all reclassified thematic maps. The result revealed that the area can be categorized into three different classes such as low potential 59.18km$^2$ (5.04%), moderate potential 722.16km$^2$ (61.51%), and high potential 39.66km$^2$ (33.45%) for GWPZ whereas marginally suitable 139.38km$^2$ (11.87%), moderately suitable 809.37km$^2$ (68.94%) and high suitable 225.25km$^2$ (19.19%) for PLSZ. This indicates the study area has more groundwater potential and irrigation land suitability zone as compared to its total areal coverage. The delineated GWPZ was verified with the existing water invertory point data in which, 88% of the total were matched with its corresponding zones. The sensitivity analysis for each map was done and hence, slope was the most sensitive parameters whith the mean variation index of 1.89% for GWP and 1.58% for PLS. In the northeast and northwest parts of the area, the high GWP and PLS were found in the same area, therefore on-land surface irrigation development will be used in this area with minimum initial cost and the rest area will be irrigated from high GW perspective area through the conveyance system.*

***Keywords**: Geo-Spatial, MCDA, Fuzzy-AHP, GW potential, Irrigation land suitability, Keleta watershed.*

# 1. INTRODUCTION

## 1.1 Background

Groundwater is a vital resource that provides water for domestic use, irrigation, and industry in all climatic zones, including both urban and rural locations. Groundwater irrigation has grown rapidly over the past 50 years and now supplies over one-third of the world's irrigated area, and it makes a major contribution to water and food security for many millions of impoverished people across the world (Shah, 2014). And he also said that it has emerged as a strategic resource, not only in many arid and semi-arid countries but also in humid climates, because of its capacity to support intensive land use and high-value agriculture. This indicates that nowadays, the expansion of groundwater supply for irrigation is increasing in the whole area, and it is applied in many countries and all climate zones.

A recent study by MacDonald et al. (2012) indicates that Africa has substantial groundwater storage. They estimate that the annual groundwater storage in Africa is 100 times more than the annual renewable freshwater resources. Worqlul et al. (2015) argued that Ethiopia has significant surface water potential from its twelve major river basins, but there is high spatial and temporal variability. Due to this variability, a detailed groundwater resources study should be required to improve the occurrence of water stress in the area. Groundwater plays a critical role in supporting the agriculture industry (Altchenko and Villholth, 2015; Giordano, 2006). However, in Ethiopia, groundwater is less utilized and is not adequately used due to higher development and operational costs, and a lack of understanding of the resource dynamics (Awulachew et al., 2010). But, it is more suitable for irrigation than surface water since it has a slow response to climate variability and requires less treatment (Siebert et al., 2010).

In Ethiopia, groundwater is mainly used for domestic water use. There may be the limited cases where it is used for irrigation due to inadequate study of groundwater resource availability and potentially land suitability for crop production. Despite some gross estimates and large-scale assessments of groundwater irrigation potential, there is a little quantitative study on the groundwater resource potential for irrigation and other domestic water uses in many river basins (MoWR, 1999). Hence, utilizing groundwater for irrigation could be an alternative to improving the country's food shortages through investigating groundwater development and using groundwater sources as complementary system.

The Awash River Basin is the most utilized in Ethiopia, hosting most industrial activities and many small to large irrigation schemes that face high water stress during the peak of the irrigation season and frequent flooding during the rainy season (Adeba et al., 2015; FAO, 2020). The basin is densely populated and has intensive agricultural activity. The Keleta watershed is one of the Awash River basins and has high surface and groundwater resources. Because of climatic change and high population growth, the amount of water available and land suitability for agricultural activities is decreasing. To sustain this, proper water resources development and the assessment of potentially arable land for crop production should be significantly needed by identifying various influencing factors and assessing them through geo-spatial techniques.

Identification and mapping of groundwater potential zones is an important step for sustainable groundwater development, planning, and utilization. The concept of integrated remote sensing and GIS as a powerful set of tools used for collection, storage, and management of spatial data in a simplified manner (Aneesh and Deka, 2015; Aggarwal et al., 2019; Saravanan, 2012; Ramu, 2014; Pani et al., 2016) found GIS as a promising tool for groundwater exploration. Awulachew et al. (2007) indicated that the country has a large potential for arable land. However, less than 5% of this potential is irrigated, due to a lack of water storage facilities and infrastructure systems (e.g., pumps, water diversion, and conveyance structures). Irrigation land suitability assessment and mapping could play an imperative role in the sustainable utilization of scarce physical land resources. The current development in technology allows us to delineate the groundwater potential and potential irrigable land suitability more effectively and efficiently than ever through identifying the most influencing parameters.

Various studies were referred to select the parameters that influence groundwater potential (Murmu et al., 2019; Gnanachandrasamy et al., 2018; Chaudhary and Kumar, 2018; Das et al., 2019; Arulbalaji et al., 2019), and potential land suitability for surface irrigation using groundwater (Worqlul et al., 2017; Li and Chen, 2020). Through this, many more parameters were identified that may influence groundwater occurrence and potential land suitability. However, landform, drainage density, lineament density, slope, geology, land use/land cover, soil, and rainfall were the prime factors considered to influence the process of groundwater potential zone delineation, while soil type, slope, soil drainage, soil depth, and land use/land cover were factors considered for the potential land suitability for surface irrigation for this study. These parameters define the occurrence, geological formation, and hydrological properties of the groundwater and helps to identify potentially suitable land for surface irrigation hence, should be analyzed through decision making.

An integrated Multi-Criteria Decision Analysis (MCDA), geo-information techniques were used to identify prospective groundwater potential (Jha et al., 2007; Mallick et al., 2014) and potential irrigable land suitability (Akıncı et al., 2013; Worqlul et al., 2015). MCDA is an efficient tool for water resources management and is also useful for identifying groundwater potential and irrigable land suitability. Based on expert opinion and the location-specific conditions, weights were assigned to different thematic layers and their feature classes. The Analytical Hierarchical Processes (AHP) method for MCDA has been widely used in recent decades and has been applied to groundwater potential zone mapping (Rahaman et al., 2015; Kaliraj et al., 2014; Ouma and Tateishi, 2014) and mapping of potentially arable land suitability (Girma et al., 2020; Balew et al., 2021).

In the AHP method, an inconsistencies occur at a certain level while making pairwise comparisons of the criteria. However, despite the popularity of AHP, the method is sometimes criticized for being unable to adequately deal with the inherent uncertainties and imprecision associated with mapping the perception of a decision-maker to crisp numbers (Chen et al., 2011). Further, a Fuzzy-Analytical Hierarchy Process (FAHP) would lead to an improvement in the accuracy of groundwater potential and potential irrigable land suitability maps due to the flexibility of the fuzzy membership function. Based on this context, the integrated approach of remote sensing and GIS with Fuzzy-AHP decision analysis was applied to the delineate the land suitability and groundwater potential zones for irrigation in the study area.

### 1.2 Statement of the Problem

The utilization of water resources in irrigated agriculture provides supplementary and full-season irrigation to overcome the effects of rainfall variability and unreliability. Hence, the solution to food insecurity could be provided by irrigation development producing more than one crop per year through the alternative use of well-sourced water. Groundwater would remain the ultimate source of freshwater while surface water sources have been depleted, and it is more suitable for irrigation than surface water since it has a slow response to climate variability and requires less treatment (Siebert et al., 2010).

The use of groundwater for agriculture in Ethiopia is not common since it is mostly used for domestic water supply. However, it can be used for irrigation in multiple ways, such as deep and shallow wells from underground aquifers (Awulachew, 2010). The identification of variables that influence the occurrence of groundwater could be a paramount need that may lead to declining groundwater levels in the peak usage of water and it should be identified before the design of a well-sourced water supply. Thus, the occurrence of ground water is highly influenced by different geophysical and climatic factors like geology, topography and environmental conditions, which make it difficult to obtain productive aquifers because the occurrence of ground water isn't uniform everywhere (Alemayehu, 2006).

An investigation of groundwater potential and potentially suitable land for irrigation are the main issues for this study to enhance agricultural productivity by improving food security through extending irrigation system in the study area. Any previous study didn't carry out the usage of groundwater potential for agricultural activities and assessment of potentially irrigable land suitability for surface irrigation using GIS-based MCDA in the Keleta watershed. Hence, most farmers in the study area were waiting for the rainy season instead of using groundwater for irrigation. The area is less suitable for using surface water for irrigation because of the location of irregular topography in the study region for designing and constructing of the diversion structures to supply water.

An area needs additional water sources and an investigation of land suitability analysis for surface irrigation to improve the causes of less agricultural producation. The rain-fed dependent agriculture could face significant crop productivity loss due to the unsuitability of using surface water for irrigation, erratic rainfall and regularly occurring of drought. Hence, to reduce and spall this problem and improve productivity, groundwater source-based irrigation practices by applying geo-spatial techniques to the area are essential. To verify the wise use of groundwater for irrigation and land suitability analysis, a systematic evaluation was required to study the land suitability influencing factors, and groundwater occurrence and distribution controlling parameters for the Keleta watershed.

## 1.3 Objectives

### 1.3.1 General objective

The main objective of the study is to identify groundwater potential and land suitability zone for surface irrigation using GIS-based MCDA with Fuzzy-AHP techniques in the Keleta watershed.

### 1.3.2 Specific objectives

The specific objectives of this study are:

- To identify the main factors that affect groundwater potential and land suitability, and assign their weightages using Fuzzy-AHP analysis.
- To map the groundwater potential and land suitability zones through integration of their different thematic layers using GIS techniques.
- To inter-link and compare the groundwater perspective and land suitability zone for surface irrigation in geospatial domain in the watershed.

## 1.4 Research Questions

The study was conducted to answer the following questions:

- Which parameters influence the occurrences of groundwater potential and land suitability zones and how their weightages are assigned using Fuzzy-AHP analysis?
- How to delineate the location suitability for groundwater potential and land suitability zones based on geo-spatial data analysis?
- How to compare the groundwater perspective and potential land suitability zone for surface irrigation in geospatial domain?

## 1.5 Significance of the Study

Ethiopia has one of the most abundant water resources in Africa, but there is less utilization of groundwater for different purposes, especially for irrigation use (Awulachew et al., 2010). Utilizing groundwater resources for irrigation could be an alternative to improving the country's food shortages through investigating groundwater development and using groundwater sources as complementary systems rather than waiting for the rainy season to produce crop yields. An area having erratic rainfall and less suitability for water diversion from river sources is alternatively used as groundwater resources for irrigation. Because groundwater resources for irrigation should follows on-land irrigations system and require less conveyance system, and also requires less treatment and a slower response to climate variability than surface water sources. So, using groundwater resources for irrigation would helped to enhance agricultural productivity and minimize conflict over the river water use.

This research delineates the groundwater potential and potential land suitability zones for surface irrigation in the study by assessing the occurance and movement of the different groundwater control and land suitability influencing parameters. Thus, the results of an area can be used to identify the location of groundwater potential and arrable land suitability, and the different bodies can benefit from this detailed map, which includes government, private organizations, and the community who are living in the study area. In particular, the government and non-government bodies can benefit when they can simply by making decisions on sustainable development, planning, management, and use, and they save time and money by reducing the time and cost of selecting GW potential and arable land suitable sites for irrigation. Hence, this is an input for understanding the hydro-geological and bio-physical systems of groundwater, which is essential for the location of new wells to meet the crop water demand, and the physical characteristics of the area for agricultural land suitability that can be used as data for further research work.

The study region is less suitable for the design and construction of diversion structures to use the surface water for irrigation due to the irregularity of the topography. Therefore, this intended thesis should provide reliable and valid findings about the possibility of groundwater for irrigation which can be used to enhance agricultural products, increase profit, and ensure food self-sufficiency for the relevant stakeholders or community. The collected and digitized data should be essential to produce a properly organized geodatabase for an individual, which will enable us to make decisions and reviews by concerned researchers to properly use groundwater resources for irrigation in the study area.

### 1.6 Scope of the Study

This study attempted to map groundwater potential and land suitability for surface irrigation using integrated GIS and remote sensing techniques in the case of Keleta Watershed, Arsi zone, Oromia regional state, Ethiopia, which cover a total drainage area of 1174 $km^2$. The factors considered for occurrences and movement of groundwater potential were landform, drainage density, lineament density, soil type, slope, land use/cover, rainfall, and geology. Also, slope, soil type, land use/land cover, soil drainage, and soil depth were the main influencing factors considered for mapping irrigation land suitability zone using integrated GIS and remote sensing techniques. This study should be focused on the determination of groundwater potential for irrigation and the identification of available land suitability for crop production, and classified the area as low (marginal), moderate, and high zones based on their suitability level in spatial domain. However, this study didn't consider the analysis of groundwater quality and any expected costs, such as design and construction, pumping, operation and maintenance costs, and also didn't consider soil quality parameters for land suitability analysis.

The limitation of this study were lack of the groundwater invertory point data and the precipitation data which are not full and well recorded in the area. This well yield data would not actually determine the exact potential yield of the site and the precipitation data also may influence the result of groundwater potential zoning in the study area.

## 1.7 Thesis Organization

This thesis is divided into five (5) sections. The first section (Introduction) describes the study's context and gives a quick outline of the research. It also explains why this research was conducted (study problem), as well as the study's objectives, and underlines the study's significance and scope. A brief explanation of groundwater irrigation potential and surface irrigation land suitability was focused on in the second section (Literature Review). It also includes several theoretical and empirical studies from across the world and Ethiopia that are relevant to the current study (the use of GIS and RS as groundwater irrigation potential and land suitability site selection tools, as well as factors impacting GWP and irrigation land suitability). The third section (Methods and Materials) offered a brief explanation of the study area, materials used, data collected, and its source, as well as data preparation and analysis methods employed to achieve the study's overall goal. The study's results and discussion are presented in the fourth section, which corresponds to the research objectives and past work, respectively, and the thesis's conclusions and recommendations are presented in the fifth section.

# 2. LITERATURE REVIEW

This chapter goes over some key definitions as well as the theoretical foundation for determining groundwater potential and irrigation land suitability zones. It also helped to understand the history and current status of groundwater potential for irrigated agriculture. The factors influencing GW potential and land suitability, selection of an appropriate decision-making method for the identified factors, GIS and RS applications in groundwater and land suitability studies, and related empirical research were reviewed.

## 2.1 Description of groundwater resources and potential

Different authors define groundwater resources and potential at different times. According to Rashman (2016), groundwater is the most important natural resource found beneath the earth's surface stored in a void space of geological stratum used in economic development, domestic life, and any ecological diversity. Also, he concluded that the occurrence and flows system of groundwater depends on geological characteristics of its porosity and permeability and the formation of landforms such as high mountains, rift valley’s and flat areas, and the role of landform on surface runoff and infiltration to the ground. According to Adem (2019), groundwater potential means having a latent possibility or likelihood of occurrence of groundwater in an area. Areas or zones of abundant groundwater available for use are referred to as areas of good groundwater potential and productive water-bearing zones are referred to as good groundwater potential aquifers.

In many regions of the Earth, groundwater is an appreciated natural resource for the dependable and economic provision of a better quality water supply. There is only 2.8% of the total available water on the Earth that is categorized as fresh water, with 97% of which being groundwater (Sekhri, 2013). More than 50% of the global population relies on groundwater resources to cater to their basic day-to-day water needs, while the majority of farmers depend on groundwater to cater for their wellbeing and contribute to the food security of so many others (Beekman and Xu, 2003). Groundwater also represents approximately 43% of all water used in irrigation globally (Siebert et al., 2010). It is preferred the most because it is more usually protected from the hazards of pollution; hence it requires less treatment when compared to surface water.

To utilize the ground water resource properly, understanding of the groundwater occurrence and distribution in space and time, proper management, and efficient exploitation is necessary. The available studies on the groundwater resources of the country are very limited, in that, the delineation of aquifer systems, the water balance, and determination of the aquifer characteristics have not been conducted (Awulachew et al., 2010). So that any sustainable utilization of groundwater resources demands, the systematic study and raising, and technical and manpower capability should be necessarily required.

## 2.2 Groundwater irrigation potential in Ethiopia

Groundwater has become an important water source for irrigation and it is an integral part of the strategy "to overcome food scarcity" in many developing countries, including Ethiopia (Tadesse et al., 2009). It can be used for irrigation in multiple ways, such as deep and shallow wells from underground aquifers. In Ethiopia, the annual groundwater potential is 40 $Gm^3$ per year (Awulachew et al., 2007) and from the estimated irrigation potential of 5.3Mha, the groundwater potential could realize about 1.1Mha of irrigation development (Awulachew et al., 2010). This indicates the agricultural crop productions using ground water sources was a very small when compared with the availability of groundwater potential and irrigaiable land in current status. However, groundwater as a resource for agricultural development offers several advantages compared with other sources of irrigation, including the reliability of the water source, on-demand water supply through natural water storage, and domestic water supply with no transboundary considerations.

Despite these advantages of groundwater, it is not widely exploited in agriculture in Ethiopia due to costly development and operations; depth of access can increase investment requirements; lack of information regarding aquifer characteristics, delineation, available water, sustainable recharge amount, and so on, is limited and not well understood due to complex Ethiopian geology and lack of studies (Sime, 2017). Availability in many places for instance, in highlands, steep terrains, inland valleys, and plain areas and relative constancy of supply, which can help to buffer the high variability of surface water resources (Awulachew, 2010). Therefore, Ethiopia has enough groundwater resources and only a significant investigation is needed to fulfill the irrigation water demand.

## 2.3 Factors influencing the occurrence of groundwater

The occurrence of groundwater comes from the dynamic hydrological system in which it comes into existence with the process of infiltration at the surface. Then, it percolates into the ground, which comprises different rock formations having different hydrogeological properties. The occurrence and movement of ground water depending on the storage capacity and the rate of transmission. However, the hydro-geological properties of aquifer developed at the time of formation of the rock thereby changing the ground water storage and transmitting abilities both horizontally and vertically (Bernard, 2003).

Groundwater movement like surface water is affected by the nature of slope or elevation. Thomas (2003) states that groundwater moves from higher elevations to lower elevations and from the location of higher pressure to lower pressure. The different factors considered to study the control of ground water occurrence and potential in different previous works. Groundwater development yield depends on aquifer characteristics such as hydraulic conductivity, aquifer thickness, storability, aerial extent, groundwater levels, available drawdown, and recharge. This indicates that the nature of the soil, geology; climate, and properties of an aquifer are the major factors controlling the movement and storage of groundwater in any part of the world (Buddemeier and Schloss, 2000).

The occurrence of groundwater depends upon climatic, geological, hydrological, ecological, and physiographical factors and the interaction among them rather than any occurrence by chance (Arkoprovo et al., 2012). Varies studies had been taken and discussed on deciphering of the ground potential zone by considering the most important controlling variables, such as geomorphology, lithology, slope, soil, LULC, lineament density, drainage density, and rainfall (Hussein et al., 2017; Dar et al., 2020; Libasse, 2007; Andualem and Demeke, 2019; Prasad et al., 2008). Finally, they summarized as all the above parameters are very important factors in ground water potential zone mapping. Based on these findings and review, all the above factors are selected for this study. Moreover, the effects of these parameters are effectively and efficiently considered to sustain groundwater potential development of the area.

The main influencing factors considered for the groundwater potential assessment for this study are listed and described as follows.

### 2.3.1 Rainfall

Rainfall is one of the primary sources of groundwater and is expressed as the depth of precipitated water in inches, measured by rain gauge for selected periods. The relationship of rainfall to groundwater occurrence is modified by factors like topography, vegetation, and surface geology; all these factors affect the quantity of water that gets underground

(Libasse, 2007). Concerning different surface conditions which affect the amount of water that goes to the ground, the average annual rainfall amount of water that percolates into the ground should be considered regardless of surface condition. In general, rainfall distribution increases the possibility of occurance of groundwater potential zones is also be increased. The zones with low precipitation were assigned with a low rating value while the highest rating value was appointed to zones receiving the highest precipitation (Tolche, 2021).

### 2.3.2 Land use/cover

Land use land cover is a significant factor affecting groundwater potential recharging. The land cover is the natural layer which includes features like water bodies, vegetation, mountain, and rock or bares while land use is the modified natural environment by human operation and comprising parameters like croplands, industry, plantations, built-up lands, and so on. The effect of land use/cover is manifested either by reducing runoff and facilitating or by trapping water on their leaf and go down to recharge groundwater. Land use/cover may also affect groundwater negatively by evapotranspiration, assuming interception to be constant (Yusuf, 2013). Also, he said that the area covered with vegetation, water body, agriculture will produce high groundwater potential while covered with settlement and bare land produce low groundwater potential due to having less infiltration rate from the natural rainfall.

### 2.3.3 Soil

Soils are the most important factors for groundwater potential and its quality. Soil texture has a valuable role in groundwater potential. The percolation or infiltration rate of water to the water tables is influenced by soil permeability. The permeability of the soil is directly related to the effective porosity of the soil and is greatly influenced by grains shape, size grains, adsorbed water, the degree of saturation, and impurities present. High permeability levels are observed in gravels and coarse sand; fine sand and loamy soils exhibit moderate permeability whereas the lowest permeability is shown by clay and silt soils (Saunders, 2001). Thus, the soil has high permeability and low water holding capacity should have yielded a high percolation to the groundwater.

### 2.3.4 Slope

The slope is an important factor controlling infiltration of water to the ground and the indicator of groundwater potential suitability. A higher degree of slope results in rapid runoff and increased erosion rate with insufficient recharge potential, where alluvial plain, flood plain, or plateau areas are more favorable for groundwater occurrence due to a longer duration of travel time downstream and provide adequate time for infiltration to increase groundwater recharge (Magesh et al., 2012). So that the slope steepness of an area increases and groundwater potential would be decreased.

### 2.3.5 Drainage density

The other determinant factor controlling groundwater occurrence is drainage density. The drainage density is a measure of the length of stream channel per unit area of the drainage watershed. Drainage density is the natural flowing of water runoff to lowland/common points. It indicates the behavior of surface and subsurface formation, the information of rock, soil permeability, infiltration of water, and surface runoff (Adem, 2019). It is determined by the ratio of total length of the stream network to total area of the watershed and expressed in $km/km^2$. The area where high drainage density values have high runoff and indicate a low possibility of groundwater availability and hence higher weights are assigning to the low drainage density area and vice versa (Pinto et al., 2017).

### 2.3.6 Lineament density

Lineaments are the structural discontinuity of the earth's surface such as faults, foliations, joints, bedding planes, and a map of linear features present on the surfaces. It may be a curve, linear, and slightly curve which is the most essential for the infiltration and movement of water to the ground (Morelli and Piana, 2006). It can be determined by the ratio of total length of all the lineaments demarcated to the total study area and expressed in $km/km^2$. High lineament density areas are good for ground water recharge and low lineament density are less suitable for groundwater recharge and discharges. The higher fault and lineament density can be used to speculate secondary porosity as most of the faults or fracture system serves as conduits for movement and storage of groundwater (Yusuf, 2013). In general, the thickness of weathered rocks is greater along the lineaments hence, the lineaments are assumed to have control over the availability of groundwater.

### 2.3.7 Landform

Landforms are a study of earth structure and also depict the various landforms such as a hill, valley, maintain, plateaus, alluvial fan, plain, and so on, relating to the groundwater potential zones and also structural features encountered by anyone engaged in geological fieldwork.

For the evaluation of groundwater resources, a geomorphological terrain classification leading to the delineation of hydro morphological is useful, considering both morphological and lithological factors. In groundwater exploration, geomorphology plays an important role in the identification of favorable zone for groundwater. More promising groundwater is in flood plains, alluvial fans and valley fill that are associated with thick alluvial and weathered materials to give high porosity and permeability, but, pediments generally are not favorable for groundwater potential zones (Brunsden, 1985).

#### 2.3.8 Lithology

The way of geologic formation and genetic type is the essential condition for ground water flow, transport, and mineral composition. Types of rocks determine peculiarities of hydrological cross-section structure, type of porosity values, the nature of permeability, geological structure geomorphology, and character of spatial heterogeneity of flow and transport parameters (Lemessa, 2017). Lithology plays a vital role in determining the groundwater potential of an area and it influences both the porosity and permeability of aquifer rocks for groundwater recharge. The porosity of rocks determines the storage capacity of rock formations, which means the sedimentary rocks were considered as high potential for groundwater occurrence due to high porosity and permeability than igneous and metamorphic rocks (Saranya and Saravanan, 2020). Thus, the area of rock having high permeability and porosity should have the ability to produce high groundwater occurrence.

### 2.4 Irrigation land suitability evaluation factors

Land suitability is the fitness of a given type of land for a defined use. The land may be classified in its present condition or after improvements for its specified use. The process of land suitability classification is the appraisal and grouping of specific areas of land in terms of their suitability for defined uses (FAO, 1976). Land evaluation is primarily the analysis of data about the land and its soils, climate, vegetation, and so on, in terms of realistic alternatives for improving the use of that land. For irrigation land suitability analysis, particular attention is given to the physical properties of the soil, to the land use land cover of an area, and the terrain conditions concerning methods of irrigation considered for the study. As extensively discussed in FAO land evaluation guidelines (FAO 1976, 1985), the suitability of these factors for surface irrigation methods and the given land utilization types can be expressed corresponding to the following suitability classes.

***Order S-suitability***: The classes under this order are: S1 (*highly suitable*) - land having no significant limitation to the sustained application of a given use, S2 (*moderately suitable*) - land having limitations which in the aggregate are moderately severe for a sustained application of a given use, S3 (*marginally suitable*) - land having limitation which in the aggregate are severe for a sustained application of a given use and were reduce productivity or benefits.

***Order N-suitability***: The classes of this order are: N1 (*temporarily not suitable*) - land having limitations which may be surmountable in time but which cannot be corrected with existing knowledge at a currently acceptable cost, N2 (*Permanently not suitable*) - land having limitations which appear as severe as to preclude a possibility of successful sustained use of the land of given land use. The factors considered for surface irrigation land suitability evaluation are narrated separately in subsequent sub-sections.

The factors considered for irrigation land suitability evaluation for this study are listed and described as follows:

### 2.4.1 Soil type

The assessment of soils for irrigation involves using properties that are permanent that cannot be changed or modified. It is main a factor that affects agricultural production cause it varies in drainage, texture, depth, water holding capacity, organic matter content, and other chemical properties. Even though the chemical properties such as salinity and alkalinity hazards are possibly improved by soil amendments or management practices, they could be considered as limiting factors in evaluating the soils for irrigation (FAO, 1997b). Accordingly, some soils considered not suitable for surface irrigation could be suitable for sprinkler irrigation or micro-irrigation and selected land utilization types. In general, the soil having coarse-grained and fine-grained particle size are unsuitable whereas having medium-sized particle is highly suitable for agricultural crop growth. Therefore, the soil properties such as soil texture/particle size should be significantly investigated for this study to evaluate land suitability for surface irrigation.

### 2.4.2 Slope

A slope is the incline or gradient of a surface and is commonly expressed as a percent. The slope is important for soil formation and management because it influences runoff, drainage, erosion and choice of irrigation types. The slope gradient of the land has a great influence on the selection of irrigation methods. According to FAO standard guidelines for the evaluation of slope gradient, slopes which are less than 2%, are very suitable for surface irrigation. But, which are greater than 8%, are not generally recommended (FAO, 1999). Thus, the slope factor could be highly influenced on land suitability for surface irrigation through increasing or decreasing flow velocity and it should be in suitable conditions as much as possible to enhance crop yield.

### 2.4.3 Land use land cover

Land use data helps to identify the productivity of an area for irrigation. Land cover and land use are often used interchangeably, however, they are quite different. The definition of land use establishes a direct link between land cover and the actions of people in their environment. Thus, a land-use can be defined as a series of activities undertaken to produce one or more goods or services. Given land use may take place on one, or more than one, piece of land, and several land uses may occur on the same piece of land. Definitions of land cover or land use in this way provide a basis for identifying the possible land suitability for irrigation with precise and quantitative economic evaluation. Therefore, matching of existing land cover/use with topographic and soil characteristics to evaluate land suitability for irrigation with land suitability classes, presents possible lands for new agricultural production (Boonyanuphap et al., 2004).

### 2.4.4 Soil drainage

The evaluation of soil drainage characteristics during irrigation land suitability assessment should be highly considered because it affects soil quality and nutrients as well as the water-holding capacity of the soil that influences the soil moisture and crop water  (Hussien et al., 2019). The soil drainage condition is important as it controls the continuous movement of water and salt through the soil profiles. Salt may be built up to a level that may be harmful to the landscape and vegetation unless it isn't continuously leached. In land suitability evaluation, well-drained soil in nature is highly suitable because it has a sufficient amount of nutrients and is good in nutrient retain capacity, and water penetration. In contrast, the poorly, imperfectly, and somewhat excessively drained soil is marginally suitable in causes a sufficient amount of water may not be stored in the soil particles.

### 2.4.5 Soil depth

The depth of soil also affects water holding capacity and nutrients of the soil and it should be highly considered for evaluating the land suitability for surface irrigation. Thus, the shallow depth soil is marginally suitable, and very shallow depth soil is unsuitable for surface irrigation because they are poor to very poor water holding capacity and moisture content. However, deep and very deep soils are good for surface irrigation and agricultural productivity due to their good nutrient availability, water holding capacity, and crop root penetration (Balew et al., 2021).

## 2.5 Application of RS and GIS in groundwater and land suitability studies

### 2.5.1 Remote sensing and GIS in groundwater study

Modern technologies such as remote sensing and GIS have proved to be useful for studying geological, structural, and geomorphological conditions together with conventional surveys. Thus, the integration of the two technologies has proven to be an efficient tool in groundwater studies (Adem, 2019). The remote sensing technique provides an advantage of having access to large coverage, even in inaccessible areas. It is a rapid and cost-effective tool in producing valuable data that helps in deciphering groundwater potential zone. According to Salwa (2015), GIS and remote sensing applications comprise groundwater delineation with other methods such as geospatial, numerical modeling, and geophysical methods and these methods are very expensive, laborious, time-consuming, and destructive. The investigation of remotely sensed data for drainage map, geological, geomorphological, and lineament characteristics of terrain in an integrated way was facilities effective evaluation of ground water potential zones (Arkoprovo et al., 2012). This technology is the most advanced and highly applicable in water resource development areas especially groundwater exploration.

Several researchers have used remote sensing and GIS techniques for the delineation of groundwater potential zones with successful results (Lemecha, 2007; Libasse, 2007; Getachew, 2007; Chowdhury et al., 2009; Adem, 2019; Lemessa, 2017; Hussein, et al., 2017 and Dar et al., 2020). In these studies, there are several thematic layers used that are different from each other, these include lithology, geomorphology, drainage pattern, lineament density, soil and topographic slope, land use land cover, groundwater recharge, surface water body, rain fall, vegetation types of loaded area, runoff and so on.  On the other hand, some researchers have integrated remote sensing, GIS, and geo-electrical techniques to delineate groundwater potential zones (Basudeo et al., 2005; Omran, 2008; Girish et al., 2009; Nagarajan et al., 2011 and Srivastava et al., 2012). They used geo-electrical surveys (VES) for deriving additional thematic layers of subsurface parameters such as delineate the detailed aquifer geometry, aquifer resistivity, aquifer thickness, thickness of the top layer, or depth to bedrocks and resistivity of the expected water-bearing zone.

### 2.5.2 Remote sensing and GIS in irrigation land suitability study

GIS can perform numerous tasks utilizing both spatial and attribute data stored in it. Remote sensing provides information about the various spatial criteria/factors under consideration. Remote sensing in combination with GIS will be a powerful tool to integrate and interpret real-world situations most realistically and transparently. Thus, an integrated technology of GIS and remote sensing is the most widely applicable method to assess the irrigation land suitability for crop production using surface water as well as groundwater resources. Various studies were taken out using this integrated technology (GIS-RS) to investigate land suitability on a global and country scale.

The assessment of potential land suitability for surface irrigation using groundwater ( Worqlul *et al*. 2017;  Li and Chen 2020) and using surface water (Abinet, 2018; Hussien et al., 2019; Girma et al., 2020; Balew et al., 2021; Gonfa et al., 2021) by considering physical land characteristics (land use/cover and slope), socio-economic activities (road proximity, river proximity, and market access), climate (rainfall and evapotranspiration) and the physical and chemical properties of the soil as well as groundwater data (natural recharge modulus and aquifer productivity). They selected and applied the different land suitability influencing factors in different places based on the characteristics of the land.

## 2.6 Multi-Criteria Decision Analysis

Groundwater potential assessment for irrigation and agricultural crop suitability involves integration information from various streams of science. There are many criteria upon which land suitability and groundwater potential depend. The suitability and water potential analysis evaluates many alternative climatic and physical characteristics of the land under the light of various criteria from various streams. Alternatives here are competing with one another; criteria are both qualitative and quantitative. The GIS-MCDA research has made a considerable contribution to the participatory GI-Science (Jankowski and Nyerges, 2001). Consequently, its support systems have the potential to improve the collaborative decision-making process by providing a flexible problem-solving environment where those involved in collaborative tasks can explore, understand, and redefine a decision problem (Kyem, 2004). So the selected factors for the land suitability and groundwater potential assessment are evaluated and analyzed by the multiple criteria decision-making process.

Multi-Criteria Decision Making (MCDM) provides the foundation for selecting, sorting, and prioritizing criteria/factors and helps in overall assessment to make a better decision. To obtain an optimum/appropriate solution for a problem, the weighted overlay analysis is the best method. Weighted Overlay Analysis (WOA) is a simple method for a combined analysis of multiclass maps. The efficiency of this method lies in that human judgment can be incorporated into the analysis. Weight represents the relative importance of a parameter vis-a-vis the objective. This method takes into consideration the relative importance of the parameters and the classes belonging to each parameter. There is no standard scale for a simple weighted overlay method. For this purpose, criteria for the analysis should be defined and each parameter should be assigned as importance.

### 2.6.1 Fuzzy-Analytic Hierarchy Process (FAHP)

Recently, many studies conducted through indices of land suitability as well as ground water potential models. Some of them are as follows: frequency ratio, weights of evidence, Analytic Hierarchy Process (AHP) and so on. AHP is one of the most effective multi-criteria decision making (MCDM) techniques which helps a decision-maker facing complex problems and conflict and internal multiple criteria. AHP method was first presented by Saaty (1980) and is widely used for MCDM, and has successfully been applied to many practical decision-making problems (Lai, 1995). In the current study, the AHP methodology will be applied only to get the relative weights of each criterion concerning the rest of the criteria. But, there is some weakness of the simple AHP method, such as; mutual dependency between alternatives and that the criterion can sometimes lead to relatively less accurate results, more decision-makers with different opinions make the problem more complex.

Despite its popularity, the method is often criticized for its inability to adequately handle the inherent uncertainty and imprecision associated with the mapping of a decision-maker perception to crisp numbers. However, in many cases, the preferred model of the human decision-maker is uncertain and fuzzy and it is relatively difficult to crisp numerical values of the comparison ratios to be provided by subjective perception. The decision-maker may be subjective and uncertain about his level of preference due to incomplete information or knowledge, inherent complexity, and uncertainty within the decision environment, lack of an appropriate measure or scale (Chen *et al*., 2011). Therefore, an effective evaluation procedure is essential in promoting decision quality for problem-solving, and hence the fuzzy-AHP method is the best way to solve these problems qualitatively and to obtain quite reliable results as much as possible.

Fuzzy analytic hierarchy process (FAHP) and fuzzy multiple criteria decision-making (FMCDM) analysis have been widely used to deal with decision-making problems involving multiple criteria evaluation/selection of alternatives (Altrock and Krause, 1994; Mcintyre and Parfitt, 1998), have shown advantages in handling unquantifiable/qualitative criteria and obtained quite reliable results. This research was used the triangular FAHP to determine the criteria weights from subjective judgments of decision-making domain experts. Since the evaluation criteria of the best plan have diverse connotations and meanings, there is no logical reason to treat them, as if they are each of equal importance. Here the decision-maker or the user should perform a simple Pairwise Comparison Matrices (PCM) series which is comparing all the criteria to one other and the values are determined according to the scale introduced by Saaty. Furthermore, the Fuzzy-MCDM was used to evaluate the synthetic performance for the best plan alternatives, to handle qualitative (such as natural language) criteria that are difficult to describe in crisp values, thus strengthen the comprehensiveness and reasonableness of the decision-making process.

## 2.7 Previous studies on Awash River Basin

The combined study of groundwater potential for irrigation and irrigation land suitability for agricultural productivity didn’t conduct in any area of the Awash River basin. But, the partly studies could be carried out in the different areas of the Awash River sub-basin and some of them are pointed as follows.

### 2.7.1 Previous studies on groundwater potential zone mapping

Yusuf (2013) conducted on ground water potential zone using remote sensing and GIS in Dire Dawa catchment considering main influencing parameters such as lithology, slope, land-use, lineament, drainage, soil, rainfall, geomorphology, and water level depth. He obtained that a large part of the study area is classified under good category and the groundwater potential of the study area is related mainly to geology, geomorphology, slope, and lineaments. He concluded that generally in the central and northern half of the catchment, spatially very good and good categories are distributed along with plain geomorphic units, near to lineaments, less dense drainage density, and where the lithology is affected by secondary structure and having interconnected pore spaces.

An integrated approach with remote sensing, Geographic Information Systems (GIS), and more traditional fieldwork techniques was adopted to map the groundwater potential sites in the Modjo Catchment considering factors like drainage density, lineament, LULC, soil, rainfall, landform, slope, and lithology (Libasse, 2007). He said that the spatial distributions of the various ground water potential zones obtained from the model generally show regional patterns of lithology, landform, and lineaments while the remaining one influences in less extent. He conclueded that the results demonstrate the integration of remote sensing, GIS, traditional fieldwork, and geomorphology provide a powerful tool in the assessment and management of water resources and the development of groundwater exploration plan.

According to Lemessa (2017), ground water potential and recharge zone mapping was conducted using GIS and remote sensing in the Middle Awash basin considering nine main influencing factors such as rainfall, slope, geomorphology, geology, lineament density, drainage density, surface runoff, and land-use/cover and soil texture. He said that result shows the rainfall and slope have a higher weight and lithology has the lowest weight for identifying the potential of groundwater potential and recharge zone in the study area respectively. The produced map of the groundwater recharge zone reveals that the northwestern and southeastern highlands of the study area are the most suitable areas (34 % and 32% ). This result of groundwater potential and recharge was validated and shows 0.88 correlations of high and very high areas with that of existing water source and spring data.

Soressa (2017) conducted the identification of groundwater potential zones using geospatial techniques in case of Adama watershed by considering eight main influencing parameters includes, geology, geomorphology, drainage density, lineament density, rainfall, soil type, slope and landuse/cover. He said that the resulted maps shows 47.94% was moderate, 33.51% was high, 16.73% was low, 1.23% was very low and only 0.59% was very high groundwater potential in the area. And the resulted potential zone map was validated by exisiting 55 borehole data, in which 35 falls on the high and 20 falls in the moderate class. Moreover, no boreholes were found in low groundwater potential zones which reflects the accuracy of results.

### 2.7.2 Previous studies on potential land suitability zone mapping

Shitu and Berhanu (2020) studied to assess the potential land suitable for surface irrigation in the Borkena watershed using GIS by considering factors such as soil type, slope, land use/cover, and distance from water sources. The final existing and potentially irrigable land was identified by weighting overlay of these factors of suitability. They conducted that the physical suitable area determination factors were weighted together using weighted overlay in Arc GIS software by restricted other land use/cover for irrigation development without agricultural land indicates only 16.13% highly suitable (S1), 47.12% moderately suitable (S2), 31.58% marginally suitable (S3) and 5.17% non-suitable (N) area for surface irrigation development. They summarized that most portion of an area falls in high to moderate land suitability for surface irrigation.

Bushira and Abdule (2020) are conducted to assess the spate irrigation potential of the Logiya watershed using GIS-based AHP. Potentially suitable sites for the spate irrigation area were evaluated based on land use/cover, slope, and soil suitability. CROPWAT software was used to estimate the reference crop evapotranspiration, effective rainfall, net irrigation, and gross irrigation water requirement. They said that the suitability model developed shows only 26.15% of the total area falls under marginally to highly suitable categories for spate irrigation development. The Logiya watershed seasonal river flow from July to October was 301.64 $Mm^3$. However, the annual flood water available from the river was less than the total GIWR by 8.77 $Mm^3$ during the growing period. They summarized that the surplus water available from the river before July might be stored and used for irrigation during the water deficit period during growing seasons.

Gonfa et al. (2021) conducted that the land suitability and surface water potential assessment in Becho Plain, Upper Awash basin. Slope, land use/cover, and soil properties were used to identify irrigable land suitability and their overall suitability classes were assigned using the GIS-based AHP method. And surface water availability was evaluated using the SWAT model and also the water requirement for dominant crops was also estimated. They said that the results indicate nearly 70% of the land area is identified as suitable while the remaining 30% of the land is restricted for surface irrigation. And the water supply and demand analysis revealed that there is sufficient water availability in the area for irrigation development. Thus, they summarized that the area has ample land and water resources for irrigation and development.

# 3. MATERIALS AND METHODS

The explanation of the overall methods which helped to achieve the objectives of the study is presented in this section. These include the data sources and materials used, study area description and delineation, methods of thematic map preparation for each factor, filling of missing data and methods of data analysis (Fuzzy-AHP), weight overlay for GW potential and land suitability, and sensitivity analysis of factors were described in detail.

## 3.1 Description of the study area

### 3.1.1 Geographical location

The study area, Keleta watershed is found in the Arsi Zone, east-central part of the Oromia region at a distance of around 200 km from Addis Ababa, the capital city of Ethiopia. The geographical extent of the study area is located between $7^0$ 58′ to $8^0$ 23′ N latitude and $39^0$ 13′ to $39^0$ 32′ E longitudes (Figure 1). Keleta watershed is one of the Middle Awash River sub-basin and which covers a total drainage area of 1,174 $km^2$. There are two small towns in the watershed namely Sire and Huruta and the three small towns namely Kulumsa (south-westren), Diksis (south-eastren) and Dera (north-westren) near by watershed.

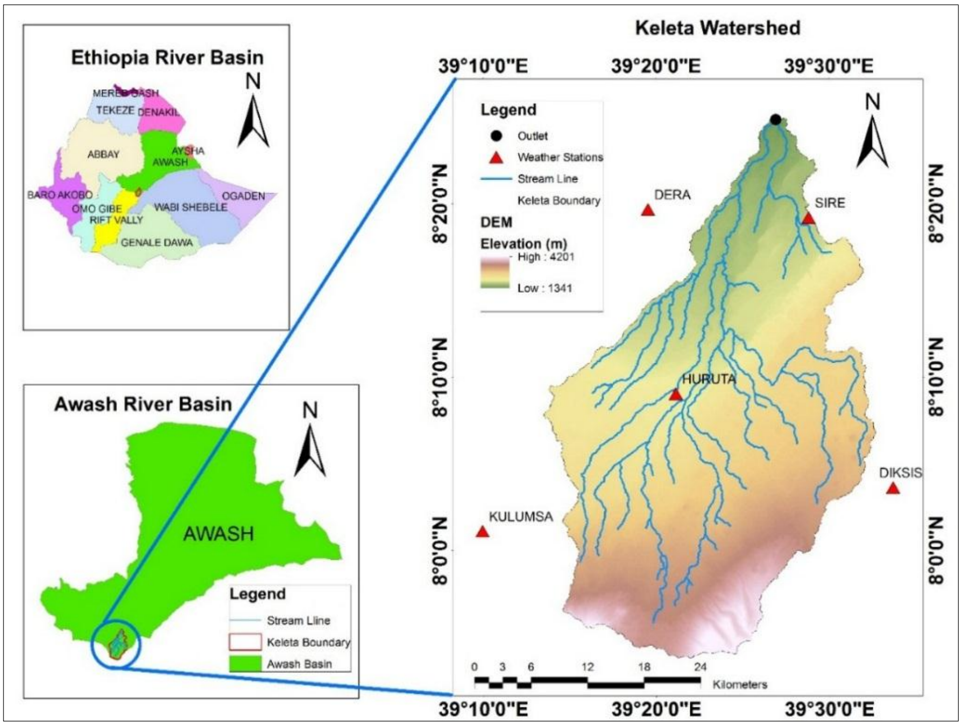


Figure 1. Map of the study area

### 3.1.2 Topography, Elevation, and Slope

The study area has a very diverse topography and it is characterized by higher mountains at the upper periphery and depressed landform at the lower part which has an elevation ranging from 1341 to 4201 meters above sea level (Figure 1). Most of the area is located in a low land area with an average elevation of less than 2100 meters and the altitude decreases as one moves from south to north eastern direction. The slope gradient varies from flat lands on valley bottom to very steep slopes on the surrounding mountain areas and the nature of the slope in the area is generally characterized as a steep slope.

### 3.1.3 Climate

In Ethiopia, the climate condition is highly influenced by altitude and an area having the highest altitude has the highest precipitation and vise-versa due to the orographic nature of the rainfall. Keleta watershed has low altitude as well as high altitude areas around Chilalo-mountains. The annual climate of the area is divided into rainy, minor rainy, and dry seasons. In the area, a long rainy season is summer (*kiremt*), which is from the beginning of July to September, and above 70% of rain has occurred. The minor rainy season (*belg*), is a small rain season accounting for 20-30% of the annual amount and stays from March to June. Dry period (*bega*), which extends between October and February, occasional rains during this period bring 10-20% of the yearly average (Degefie, 2007). The long-term fifteen years (2005-2019) daily recorded data was obtained from National Metereological Agency (NMA) and the mean annual rainfall of an area was calculated using the athematic mean method. Thus, on mean peak rainfall was occurring from June to September across the watershed (Figure 2).

From fifteen-year recorded metrological data, the average monthly maximum temperature varies from 21.7 $^{o}$C to 29.0 $^{o}$C and the average minimum temperature varies from 8.1 $^{o}$C to 14.9 $^{o}$C (Appendix Table A4). In the Keleta watershed, the hottest temperature emerges in March and the lowest temperate emerges in December (Figure 3). As per the temperature of the watershed, in general, the dry semi-arid falls in the lower part to the wet sub-humid in the upper part.

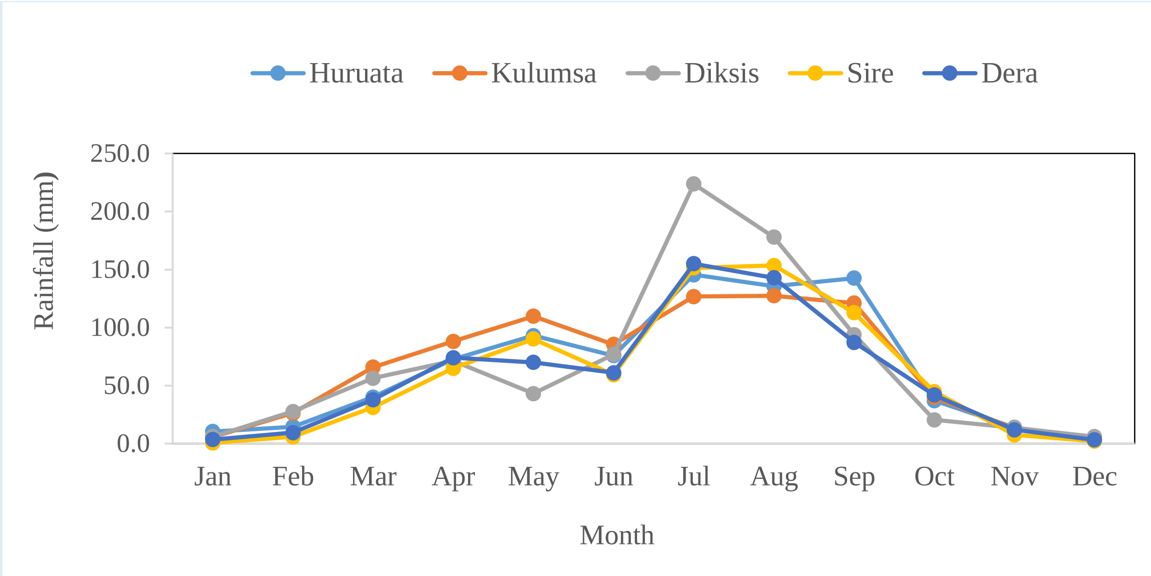


Figure 2. Average Monthly Rainfall (2005-2019)

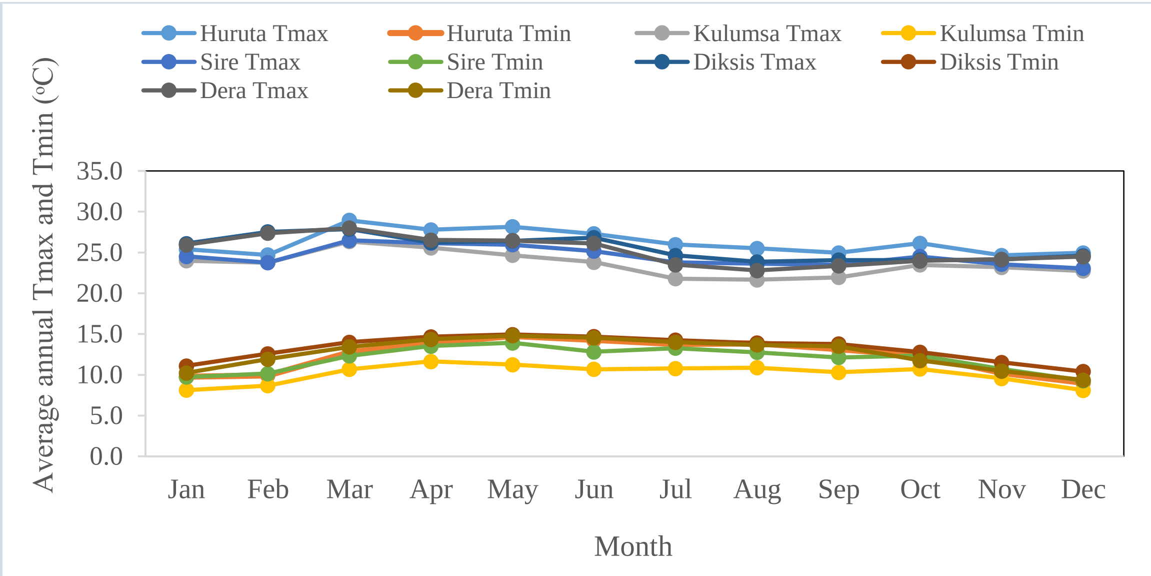


Figure 3. Min and Max Average Monthly Temperature (2005-2019)

### 3.1.4 Drainage pattern

Keleta River is one of the major tributaries of the Awash River in which its headwaters originate from the afro-alpine area of the Chilalo Mountain among many other rivers that flow to the northeast direction. The area has many intermittent rivers to drain the main river and has a dendritic drainage pattern (Figure 4). Some of the major streams found in the area are Chanco, Beddessa, Gura, Robi, Goro, Wabero, Wedecha, Boru, and Shoya. The Chanco from Eastern, Wedecha and Boru from the western, Bedessa in middle is the biggest streams in the area. These different dendritic streams collect the runoff from higher elevated areas means from the mountains area to the main Keleta River and finally to Awash River. During the rainy season, it drains peak runoff in all streams in response to high rainfall and to a lesser extent group of springs that issued at the contacts.

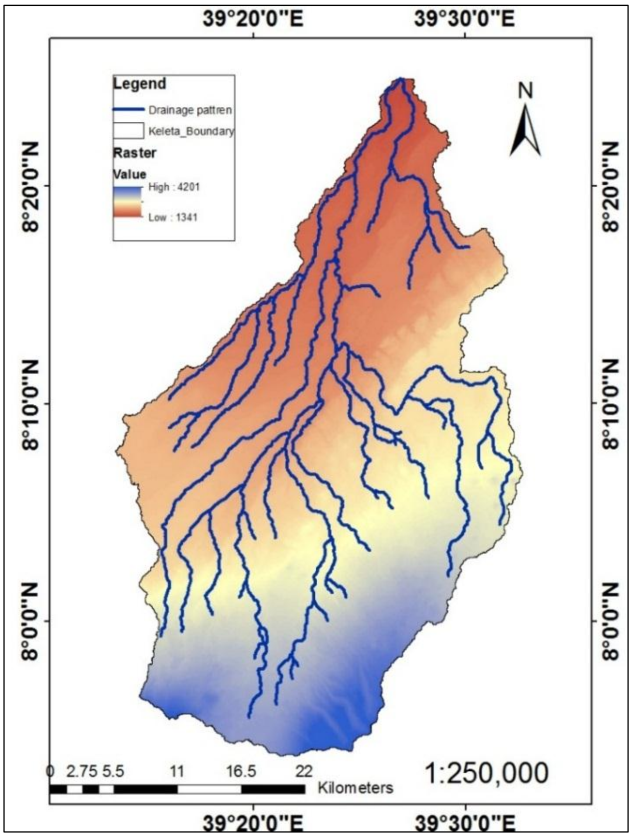


Figure 4. Map of Drainage pattern and Elevation

### 3.1.5 Agricultural activities

The agricultural activities of Keleta watershed are mainly dependent on rain-fed agriculture. Farmers in the area are producing and practicing the different type of cropping system in the long rainy season by preparing their land in the short rainy season. The major cropping system in the lower part is intercropping of cereal crops with legumes for example cropping Maize with Haricot bean and crop rotations is also some of the cropping systems of the lower part of a watershed. Whereas the upper part of the watershed is dominated by the mono-cropping of a single cultivar like Barely, Teff, or Wheat.

### 3.1.6 Land use land cover

The land use/land cover of Keleta watershed is diversely characterized. The major land use land cover of the watershed are cultivated land, built-up land, shrub land with exposed rock, afro-alpine with grassland, forest land, and shrubland. Around 60 % of the watershed is covered by cultivated land which is the most dominant land use in the area. The built-up land such as villages and roads are least dominated land from the rest one which covers 6.64 % of total area. The lower part of the watershed is covered with afro-alpine vegetation and grassland. The middle part is dominated by cultivated land and the shrubland with exposed rock land covered some areas along the Keleta River in the upper part of the valley.

## 3.2 Data description and thematic maps preparation

### 3.2.1 Data sources and materials

All relevant and significant data were collected from different sources to achieve the research objectives. The research would be done based on both primary and secondary data. For this study, the long-term daily meteorological data, including rainfall and temperature, of existing stations for 15 years (2005-2019) was obtained from the National Meteorological Agency (NMA). The physiographical data included slope, drainage density, and landform from DEM at 30mx30m resolution was downloaded from open topography of National Aeronautics and Space Administration, Shuttle Radar Topography Mission (NASA-SRTM) and land use/cover and lineament density data was downloaded from Landsat8 Operational Land Image (OLI) at 30 m resolution from United States Geological Survey (USGS) website. Soil data and geological data were obtained from the Ministry of Water, Irrigation, and Energy (MoWIE) at the scale of 1:25,000 were used for the study. Water inventory point data was collected from the Oromia Water Work design and Supervision Enterpirse (OWWDSE) which was used to verify the delineated groundwater potential zone of the study area. Different software and materials such as ArcGIS 10.4.1, ERDAS Imagine 2014, Google Earth Pro 2020, PCI Geomatica 2018, and MS Word and Excel were also used. Further, the details and their purposes are described in Table 1 below.

Table 1. Data type, sources, and software used for the study

| **Data** | **Sources** | **Scale** | **Purposes** |
|---|---|---|---|
| Meteorological data | NMA | 2005-2019 | To evaluate *rainfall map* by IDW using ArcGIS. |
| Slope, DD and LF data | SRTM-DEM | 30x30 m | To evaluate *slope, drainage density,* and *landform map* of the area using ArcGIS |
| LULC and LD data | Landsat8 OLI | | To evaluate *LULC* and *lineament density map* using ArcGIS spatial analysis tool |
| Soil data | MoWIE | 1:250,000 | To evaluate *soil maps* based on the FAO guideline classification using ArcGIS |
| Geological data | MoWIE | | To evaluate *lithology map* using ArcGIS |
| GW yield data | OWWDSE | | To validate the delineated GWP zone |

| **Software's** | **Purposes** |
|---|---|
| ERDAS Imagine 2014 | To layer stack, mosaic, and classification of images |
| Google Earth 7.3.1 | For ground verification |
| ArcGIS 10.4.1 | To generate, analyze, visualize data and map layout |
| PCI Geomatica 2018 | Used for lineament features generation and extraction |

### 3.2.2 Study area delineation

The preparation of boundary shape for the study area was the first stage. The study area shape was prepared through different stages in the ArcGIS platform from SRTM-DEM data of 30mx30m resolution. In this process, the SRTM-DEM was imported to Arc map, and the area was delineated using a spatial analysis tool. The hydrology tools in the spatial analysis tool took place to delineate watershed through the following steps: - Projected DEM to fill to flow direction to flow accumulation to the basin to polygon and finally, Keleta watershed was extracted.

### 3.2.3 Thematic mapping for groundwater potential and land suitability

After the delineation and identification of the boundary shape of the study area, the preparation of different thematic maps for each factor that influences the occurrence of groundwater potential and irrigation land suitability would be carried out from collected data in the Arc map. These maps were firstly projected into the Adindan datum of UTM zone 37N in the ArcGIS platform and different thematic maps were prepared and reclassified using a spatial analysis tool. The method of thematic map preparation for each parameter was described in detail as follows.

#### 3.2.3.1 Rainfall map

The fifteen-year daily rainfall data were obtained from five meteorological stations namely Kulumsa, Dera, Huruta, Diksis, and Sire which were located in and around the watershed. The missed rainfall data was filled before analysis because the precipitation data was consistent, the total study area's rainfall distribution was analyzed using the mean arithmetic approach due to the rain gauge stations utilized in the area were very close to one other and had similar topography. Then, the average annual rainfall data was prepared and the Inverse Distance Weighting (IDW) interpolation method in ArcGIS spatial analysis tool was used to prepare a spatial rainfall map by converting the point rainfall to areal rainfall in the watershed. Finally, the rainfall map for evaluation of groundwater potential zone was prepared from long-term annual average rainfall data using spatial analysis tool by IDW interpolation.

#### 3.2.3.2 Drainage density map

Shutter Radar Topography Mission of Digital Elevation Model (SRTM-DEM) from remote sensing data was used to derive the slope, drainage density, and geomorphology maps of the study area. The 30 m resolution of the DEM geo tiff file was downloaded from the open topography of NASA-SRTM. Then, this file was first imported into Arc map and projected to Adindan datum of UTM zone 37N. The study area was extracted from the DEM using the study area boundary shapefile. The development of drainage density involves filling sinks, flow direction, flow accumulation, and stream network extraction. Finally, a drainage density map was produced and calculated using a line density analysis tool through dividing the total lengh of the stream channel in watershed to total area of the watershed and reclassified using spatial analysis tools.

#### 3.2.3.3 Slope map

A slope map of the area was prepared from DEM with 30 m spatial resolution. The projected DEM data was used as an input for slope extraction in the Arc Map of ArcGIS spatial analysis tool. Finally, a slope maps of the study area were prepared for both studies using the surface tool in the spatial analysis tools and reclassified using the reclassify tool in spatial analysis tools based on their importances.

#### 3.2.3.4 Landform map

A 30 m resolution DEM data was also used to develop geomorphologic features of the land. The geomorphology of the study area was prepared by applying Hammond's landform classification method which means firstly developing a slope map, a local relief map, and profile map of the study area and overlying them. Then, the landform map was prepared on Arcmap by applying Hammond's (1964) landform model using a procedure suggested by the Missouri Resources Assessment Partnership (MRAP). And finally, the extracted landform features were generated and reclassified into major landform of valley fills, plains, hills, and curved (mountain) ridges.

#### 3.2.3.5 LULC map

The Landsat image from a satellite data source was used to generate the LULC map of the area. A cloud-free Landsat 8 Operational Land Image (OLI) satellite image (Raw 54/Path 169, dated 2 Feb 2019) at 30 m resolution was downloaded from United State Geological Survey (USGS) website and imported to ERDAS Imagine 2014 software to stack the layers, preparing the composite band and classifying LULC of the study area with the help of Google earth pro. Landsat 8 OLI has produced the land use/cover types for the study area in 30m resolution and served as bases from which land use/cover types were extracted. As result, the LULC map of the study area was developed from supervised maximum likelihood image classification in the ERDAS Imagine 2014 to categorize land use/cover types based on the site knowledge and spectral properties of features present. Finally, the image classification accuracy assessment was done by taking 20 points for each class, and the overall accuracy and kappa coefficient were calculated using Equation 3.1, which were 88.4% and 85.2% respectively. Generally, the kappa values vary between 0 and 1, and had three different classes, i.e., $k>0.75$ was excellent, $0.75>k>0.4$ was good, and $k<0.4$ was poor

(Cohen, 1960). Thus, the result of k was 85.2% and, which was acceptable in the condition of better model performance.

$$K = \frac{P_o - P_c}{1 - P_c} \tag{3.1}$$

Where: K denotes the kappa coefficient; Po denotes the correction of correctly simulated cells and Pc denotes expected proportion correction by chance between the observed and simulated map.

#### 3.2.3.6 Lineament density map

Lineament map of the study area was also prepared from Landsat 8 OLI image data in a 30m resolution. This data was imported to PCI Geomatica 2018 software platform and line extraction of the area was done using algorithm tools in the software. Then, importing the automatic line extracted shapefile into Arc map platform. Because the generated lineament was made up of several lines, it was split into single lines using the split command in ArcGIS. The resulting lineament raster was called a lineament map, and it was used to generate lineament density which was calaculated by the ratio of total length of all the lineaments demarcated to total study area. Finally, the Lineament density map of the study area was prepared using the line density tool and reclassified using the spatial analysis tool.

#### 3.2.3.7 Soil map

The convectional data were used to prepare the lithology and soil map of the study area. Geology and soil data of the Awash River basin were obtained from MoWIE, department of geoscience. These data were imported into Arcmap and projected to Adindan datum of UTM Zone 37N. After projection, the soil map of the Keleta watershed was clipped from the Awash River basin using the clip option found in the geo-processing menu bar. The description and classification of the soil physical properties were done based on the FAO guidelines, and seven different soil groups were identified which were found in the study area, such as Vertisols, Cambisols, Leptosols, Andisols, Regosols, Nitosols, and Luvisols. Finally, the different soil maps, such as soil type, soil depth, and soil drainage maps, were papered using the ArcGIS platform for both studies.

#### 3.2.3.8 Lithology map

The lithology map was also prepared from the geological survey of the Awash River basin map through extracting Keleta watershed in ArcGIS using the spatial analysis tool. The different lithological units are found in the study area, such as Bofa basalt, Chilalo formations, Nazareth series, Holocene sediments, Recent basalts, Dino formation, and Quaternary rhyolite volcanic center. In general, Cenozoic lithological units such as tertiary volcanic and quaternary groups were found in the study area.

## 3.3 Method of data analysis

After the collection of relevant data for groundwater potential assessment and land suitability evaluation, the successful analysis of information in the spatially and temporally is significantly required to identify the suitable zone. These suitability zones were prepared and identified based on the influence of different factors and integrating of them. Before the integration of data sets, the class weights and map scores were assessed based on Satty's Fuzzy-AHP and analyzed through pair-wise comparison of the significance matrixes.

### 3.3.1 Estimating and filling of rainfall missing data

Following the identification of significant factors that influence groundwater potential, the missing data of the rainfall factor was filled. The missing rainfall data of stations that occur at a specific rain gauge station for a specific period due to the absence of an observer or instrumental error were calculated using data from surrounding stations. Inverse Distance Weighting (IDW) was chosen as the method to fill in missing rainfall data because it has the potential to estimate missing rainfall values with the least amount of error to compare with other methods. In particular, it assumes that each measured point has a local influence that reduces with distance, and that weights change in proportion to the linear distance between the samples and the un-sampled point (Lixin and Revesz, 2004). The weights are unaffected by the spatial arrangement of the samples, and the weighting function is the inverse of the distance to the specified exponent, therefore the projected value for a site is given by:

$$P_X = \sum_{i=1}^{N} P_i * W_i; \; W_i = \frac{(\frac{1}{{d_i}^2})}{\sum_{i=1}^{N}(\frac{1}{{d_i}^2})} \qquad (3.2)$$

Where: $P_X$ denotes missed rainfall data at station X; $P_i$ denotes rainfall of surrounding station; N denotes the number of nearest known points surrounding (x, y); Wi denotes the weight assigned to each known point value Wi at location (xi, yi ); $d_i$ denotes the Euclidean distance between each (xi, yi ) and (x, y) (Lixin and Revesz, 2004).

To generate a rainfall map, the rainfall gauges measure point data at each station in the research area, which should be converted to averaged aerial rainfall using the interpolation method. Because rainfall measurement is a single-point observation, it cannot be utilized as a representative value for the entire area. As a result, the representative aerial depth of rainfall over the entire area is analyzed utilizing varied rainfall depth of different stations identified in the study location. For uniformly dispersed gauges and closely and evenly spaced gauging stations, the arithmetic mean method is the easiest and most reliable way to determine average rainfall. The following Equation can be used to compute it.

$$P_A = \frac{\sum_{i=1}^{n} P_i}{N} = \frac{P_1 + P_2 \ldots + P_N}{N} \quad (3.3)$$

Where: $P_A$ denotes the watershed's average rainfall depth; $P_1$, $P_2$, and $P_N$ denote the mean annual rainfall at stations 1, 2 up to N, respectively, and N denotes the total number of stations in the watershed.

### 3.3.2 Fuzzy-AHP techniques and weight assignments

After the preparation of all the different thematic maps, the multi-criteria decision analysis (MCDA) method was applied to enables us to assign the criteria weights to produce the potential groundwater and arable land suitability. The use of hierarchical development (Figure 6) to model the multi-criteria decision problem enables decision-makers to better understanding the problem, its context, and developing alternate approaches to the problem under examination. The decision's overall goal is at the top of the hierarchy, with criteria (theme layer) and alternatives (classes) in the middle and suitability zone at the bottom (Figure 6). The Fuzzy-AHP based MCDA method was used to evaluate the values for each criterion by constructing a hierarchy structure based on the pair-wise comparison matrix to assess the value of several alternatives within each criterion.

To handle the problem of hierarchy structure, each upper-level hierarchy (criteria/theme) was compared to the lower level hierarchy (alternatives/classes) based on their impact on the major influential layer above (Figure 6). Because every layer in the lower hierarchal level affects every element in the upper level in a full hierarchy. To determine the criteria weights from subjective judgments of decision-making domain experts, the application of the Fuzzy-AHP is better than using the simple analytical hierarchy process because it has qualitative criteria and gives reliable results (Mcintyre and Parfitt, 1998). In this study, the fuzzy rate was expressed by triangular fuzzy numbers (TFNs), and the triangular Fuzzy-AHP method was adopted to improve the effective calculation of fuzzy vectors in the interval by calculating the fraction of the discriminant matrix.

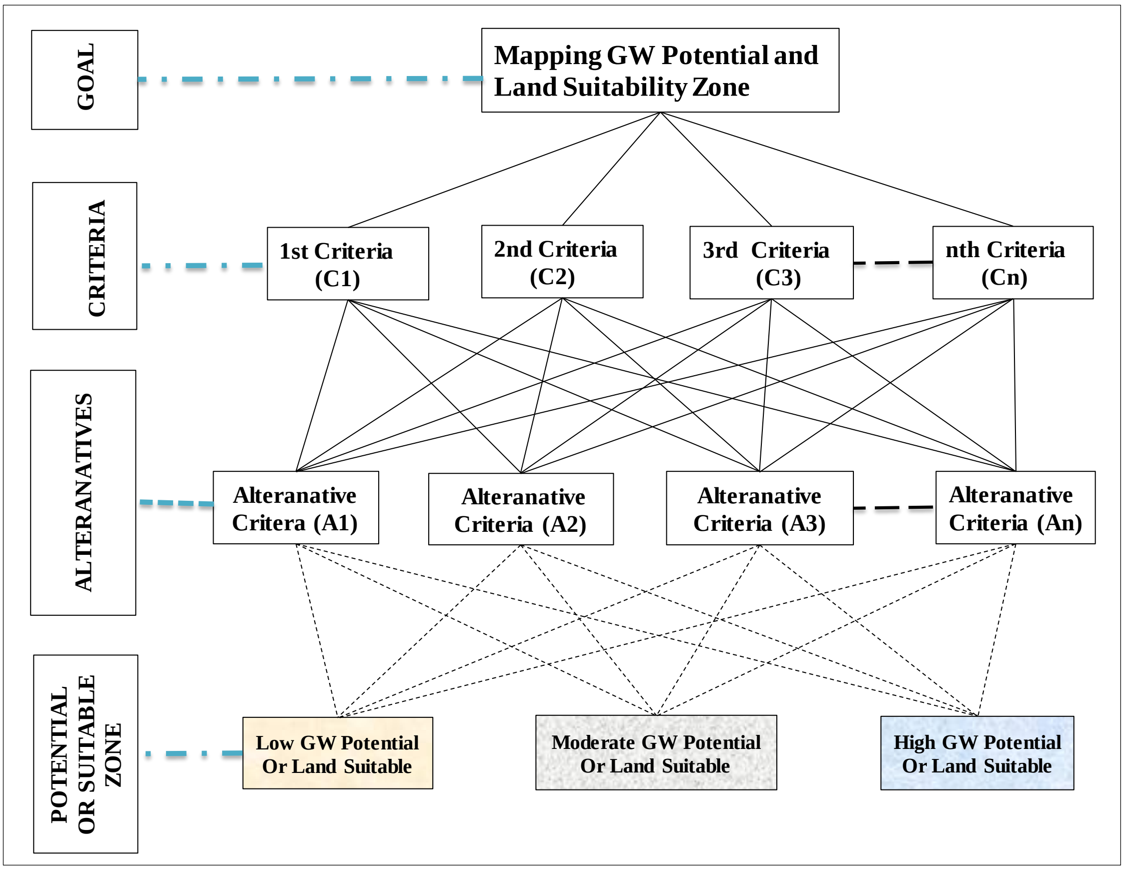


Figure 5. Fuzzy-AHP based identification of hierarchal structure

To compute and obtain the final weighted value of each criterion, the calculation can be separated into the following steps:

Firstly, set up a various leveled structure of involvement esteem and characterize near execution upsides of fuzzy numbers. Then, according to Chang (1996), fuzzy numbers which are denoted as (l, m, u) are set up in all of the hierarchies based on the linguistic values and the extent to the triangular fuzzy membership function are in the form of Equation (3.4) and given in (Table 2) below.

$$\mu_A(x) = \begin{cases} 0, & x < a \\ \frac{x-l}{m-l}, & a < x \leq m \\ \frac{u-x}{u-m}, & m < x < b \\ 0, & x \geq b \end{cases} \tag{3.4}$$

Where; *l* denotes the smallest possible value (lower bound), *m* denotes the most promising (middle) value, and *u* denotes the largest possible value (upper bound) of a fuzzy number.

Zadeh (1965) introduced the concept of linguistic variables to express human thinking in terms of fuzzy sets instead of crisp numbers to matching with a triangular fuzzy numbers are described in Table 2 as below.

Table 2. Linguistic variables and values for pairwise matrix for triangular fuzzy.

| Linguistic Variables | Fuzzy Number | Triangular Fuzzy Set | Reciprocal Fuzzy Set |
|---|---|---|---|
| Just Equal | 1 | (1,1,1) | (1,1,1) |
| Equally Important | | (1,1,1+x) | (1/(1+x),1,1) |
| Moderately Important | 3 | (3-x,3,3+x) | (1/(3+x),1/3,1/(3-x)) |
| Strongly Important | 5 | (5-x,5,5+x) | (1/(5+x),1/5,1/(5-x)) |
| Very Strongly Important | 7 | (7-x,7,7+x) | (1/(7+x),1/7,1/(7-x)) |
| Extremely Important | 9 | (9-x,9,9) | (1/9,1/9,1/(9-x)) |
| Intermediate Values | 2,4,6,8 | (x-1,x,x+1) x = 2,4,6,8 | (1/(1+x),1/x,1/(x-1)) |

Afterward, the opinion of each expert is converted into a matrix.

$$A = \begin{bmatrix} a_{11} & a_{12} & \cdots & a_{1n} \\ a_{21} & a_{22} & \cdots & a_{2n} \\ . & . & & . \\ . & . & & . \\ . & . & & . \\ a_{n1} & a_{n2} & \cdots & a_{nn} \end{bmatrix} \tag{3.5}$$

Where; $a_{ij}$ denotes a pair of each criterion

Subsequently, the opinions of all experts are synthesized, the geometric mean technique should be applied to define the fuzzy geometric mean and fuzzy weight of each criterion (Buckley, 1985; Ishizaka and Labib, 2011) to preserve the reciprocal property.

$$\tilde{A} = \begin{bmatrix} (\tilde{a}_{11} \otimes \tilde{a}_{12} \otimes \ldots \otimes \tilde{a}_{1n})^{1/n} \\ (\tilde{a}_{21} \otimes \tilde{a}_{22} \otimes \ldots \otimes \tilde{a}_{2n})^{1/n} \\ . \\ . \\ . \\ (\tilde{a}_{n1} \otimes \tilde{a}_{n2} \otimes \ldots \otimes \tilde{a}_{nn})^{1/n} \end{bmatrix} \tag{3.6}$$

Where; $\tilde{A}$ denotes fuzzy geometric mean for matrix A and $\otimes$ is the multiplication symbol of a fuzzy number.

Then, normalize the row of the fuzzy number vector of $\tilde{A}$ for the triangular fuzzy number to obtain the fuzzy synthetic extent value of the vector $\widetilde{S}$ for the fuzzy number (Zhang, 2010).

$$\tilde{S} = \begin{bmatrix} \tilde{A}_1 \otimes (\sum_{J=1}^{n} \tilde{A}_j)^{-1} \\ \tilde{A}_2 \otimes \left(\sum_{J=1}^{n} \tilde{A}_j\right)^{-1} \\ . \\ . \\ . \\ \tilde{A}_n \otimes (\sum_{J=1}^{n} \tilde{A}_j)^{-1} \end{bmatrix} \tag{3.7}$$

Where; $\widetilde{S}$ denotes normalized triangular fuzzy vector value and $(\sum_{J=1}^{n} \tilde{A}_j)^{-1}$ denotes the derivation of the sum of the fuzzy number vector $\tilde{A}$ for the triangular fuzzy number.

Subsequently to normalization, the de-fuzzification of $\tilde{S}$ was derived from the membership function to obtain non-fuzzy numbers for each criterion. $V^{tri}$ derived from the triangular membership function using the following equation (Zhang, 2010; Gumus *et al*., 2013):

$$V^{tri} = \frac{[(u-l)+(m-l)]}{3} + l \tag{3.8}$$

Where; $V^{tri}$ represents the set of triangular non-fuzzy numbers and others are described above.

In the end, define the final non-fuzzy normalization weight $\widetilde{W}$ for the fuzzy number through adjusting the total sum to unity.

$$\widetilde{W} = \begin{bmatrix} \tilde{v}_{1/\sum_{j=1}^{n} \tilde{v}_i} \\ \tilde{v}_{2/\sum_{j=1}^{n} \tilde{v}_i} \\ . \\ . \\ . \\ \tilde{v}_{n/\sum_{j=1}^{n} \tilde{v}_i} \end{bmatrix} \tag{3.9}$$

Where; $\widetilde{W}$ represent the normalized fuzzy weight for each criterion.

The Judgments of the pair-wise comparison within each thematic layer were checked by the consistency ratio. The consistency ratio is expected to be near perfect to produce a decision that is close to valid and is related to a comparison matrix. Saaty (2008) proved that for a consistent reciprocal matrix, the largest eigenvalue is equal to the size of the comparison matrix ($\lambda_{max} = n$) and determined a measure of consistency, which is called the CI, as a deviation or degree of consistency. The largest Eugen value ($\lambda_{max}$) is computed as the sum of the product of each logistic fuzzy number in the row with the relative fuzzy weight of each criterion in the column, and then dividing each result into each relative weightage, and finally, taking the average of the value of each lambda in the column. Then, whether the comparisons were consistent or inconsistent was checked using a consistency ratio (CR), as calculated by the following formula:

$$CR = \frac{CI}{RI} \quad (3.10)$$

$$CI = \frac{\lambda_{max-n}}{n} \quad (3.11)$$

Where; CR denotes consistency ratio, CI denotes consistency index, RI denotes random consistency index, $\lambda_{max}$ denotes the average maximum Eugen value and n denotes the number of criteria.

The consistency index (RI) is a randomly generated pairwise comparison matrix and is simply obtained from the random inconsistency indices (Saaty, 1980) that are shown in Table 3.

Table 3. The values of Random Index (RI)

| n | 1 | 2 | 3 | 4 | 5 | 6 | 7 | 8 | 9 | 10 | 11 |
|---|---|---|---|---|---|---|---|---|---|---|---|
| RI | 0 | 0 | 0.58 | 0.9 | 1.12 | 1.24 | 1.32 | 1.41 | 1.45 | 1.49 | 1.51 |

If CR < 0.10, the ratio indicates a reasonable level of consistency according to Saaty (1980). In this case, CR demonstrates the weighting of each criterion was consistent, and the relative weights were appropriate and acceptable for decision-making. However, if CR > 0.10, the value of the ratio indicates inconsistent judgments. As a result, it is necessary to examine the components' relative importance or to adjust the pairwise weight in the CR assessment.

### 3.4 Integration of layers for groundwater potential mapping

After categorization, a GIS model was implemented using the weighted overlay technique to derive the groundwater promising areas that were suitable for exploration. Each factor affecting groundwater potential of the study was adopted during the weighted overlay analysis to combine all thematic layers, weighted and ranked according to the influence on groundwater potential based on the judgment of past studies carried out by researchers of expertise gained through similar work on groundwater potential zone mapping. The determination of the groundwater potential values for a given area involves multiplying each scale value of reclassified layer (parameter) by its weight (or percent influence) which was suggested by Murmu et al. (2019). The resulting cell values were to produce the final output raster that represents the potential groundwater zone.

$$GWPZ = (DDw * DDr) + (SLw * SLr) + (SOw * SOr) + (LITHw * LITHr) + (LDw * LDr) + (LFw * LFr) + (LULCw * LULCr) + (RFw * RFr) \quad (3.12)$$

Where: GWPZ represents Groundwater potential zone, LF represents Landform map, SL represents Slope map, RF represents Rainfall map, LITH represents Lithology map, LD represents Lineament density map, DD represents Drainage density map, LULC represents Land use/cover map and SO represents Soil map. And the subscript “w” and “r” refers to normalized criteria of the weight of the theme and reclassified normalized weight of the individual feature of rank, respectively.

### 3.5 Validation of delineated groundwater potential zone

The results of different groundwater potential zones which were obtained from the analysis were validated with an existing water inventory point data to verify the study. For verification, the location of the observation site and groundwater potential level were overliad and must coincide with each other. For this purpose, the seventeen groundwater yield data (boreholes and spring sources data) were collected from the Oromia Water Work Design and Supervision Enterprise (OWWDSE) office. The obtained data was entered into Microsoft Office and then imported into the Arcmap platform to generate the data. It shows the actual yield and the availability of groundwater in the study area for result validation of the delinated groundwater potential zone map. Finally, the accuracy of the identified potential zones is estimated based on the actual yield of the total number of data for validation and the total number of agreed data.

### 3.6 Layers integration of potential land suitability mapping

The potential land suitability for surface irrigation was identified using the weighted overlay technique based on the percentage influence of five reclassified thematic maps (land use/ cover, soil type, soil drainage, soil depth, and slope) in the GIS model. Equation 3.13 is used to get the prospective irrigation land suitability value for a particular area by multiplying each scale value of every parameter by its weight or percent influence (Hussien et al., 2019). The final output raster, which shows land suitability areas, was generated using the cell values obtained.

$$PLSZ = (SLw * SLr) + (STw * STr) + (SDr'w' * SDr'r') + (SDe'w' * SDe'r') + (LULCw * LULCr) \quad (3.13)$$

Where; PLSZ denotes Potential land suitability zone, SL denotes Slope map, LULC denotes Land use/cover map, SDe denotes Soil depth map, SDr denotes Soil drainage map and ST denotes Soil type map. And the subscript "w" and "r" refers to normalize criteria of the weight of the theme and reclassified normalized weight of the individual feature of rank respectively.

### 3.7 Sensitivity analysis of groundwater potential and irrigation land suitability

Sensitivity analysis assesses the degree of uncertainty in related to the influence of assigned weights to each thematic layer on the output models. The map-removal sensitivity analysis (Lodwick et al., 1990) method was applied for this study which is used to explore the implications of removing one of the thematic layers from the suitability analysis. Each of the theme layers was removed in this manner, and a new GWP and PLS map was generated for the remaining layers, which are layered on top of each other. The sensitivity of the GWP and PLS maps are demonstrated by the removal of one of the thematic layers and the results of this investigation are expressed as a sensitivity index (Equation 3.14).

$$S = \left[ \frac{\left| \frac{PI}{N} - \frac{PI'}{n} \right|}{PI} \right] * 100 \quad (3.14)$$

Where: S denotes sensitivity index associated with one removal map; PI denotes potential index computed using all thematic layers; PI' denotes potential index computed excluding one thematic layer at a time; N and n denotes the number of thematic layers used to compute PI and PI', respectively.

### 3.8 Groundwater potential and irrigation land suitability

The assessment of groundwater sources for surface irrigation was the main aim of this study. Firstly, the groundwater potential and the irrigable land suitability zone map of the area were delineated separately through analyzing and integrating all the parameters that were considered for both studies. Then, the area coverage and the location of the groundwater potential level and the land suitability classes of each map were identified and computed separately. Thus, the results were expressed to identify and compare whether the available groundwater potential is quite matched or not with the potentially irrigable land for agricultural production in the study region.

### 3.9 Flow chart of the methodology

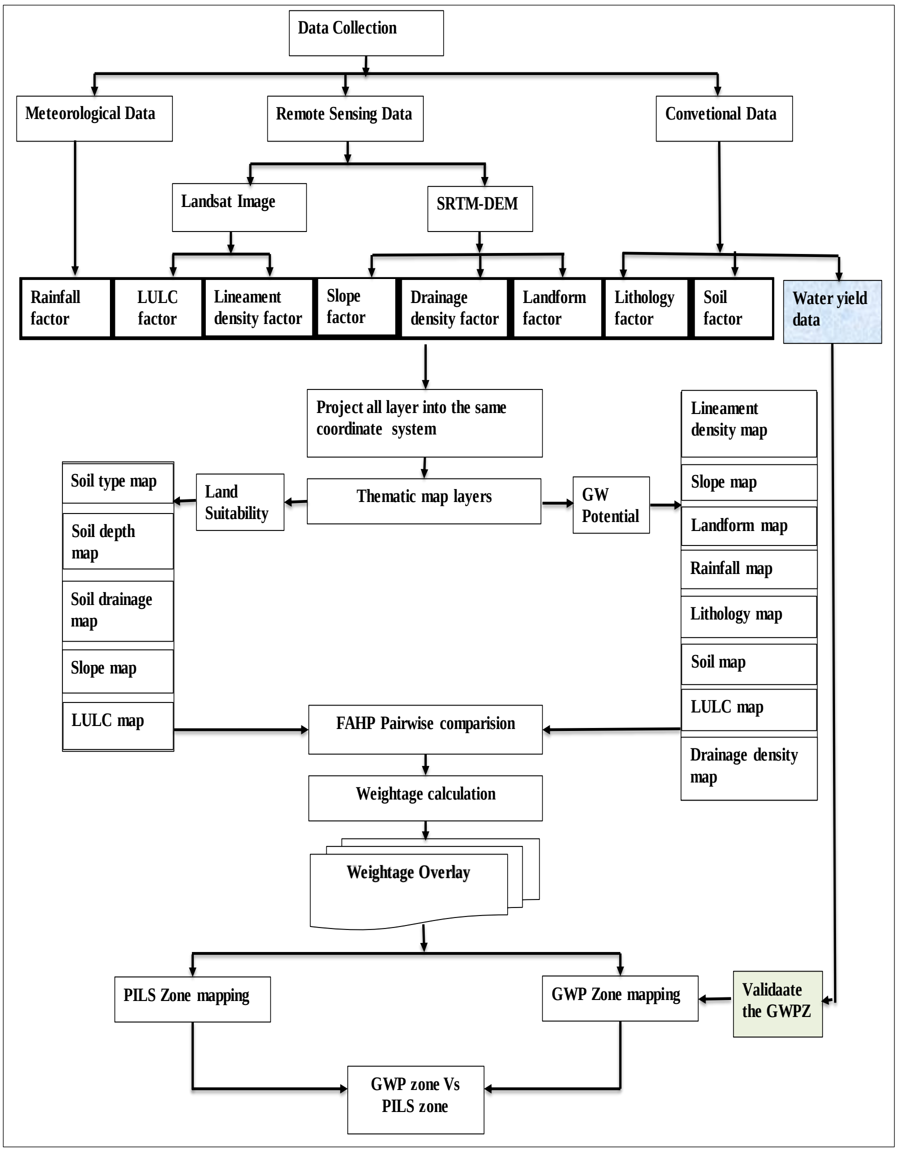


Figure 6. General flowchart modeling

# 4. RESULTS AND DISCUSSION

The results of using GIS and remote sensing to map groundwater potential and irrigation land suitability zones in the Keleta Watershed area are described in this chapter. The Fuzzy-AHP process was used to assign weights to each component that was thought to influence GWP occurrence and land suitability. For each component, the suitability class and reclassified thematic maps were discussed as well. Finally, a weighted overlay analysis was used to map groundwater potential and irrigation land suitability zones, with the final result revealing the ability of GIS and RS to delineate GWP and land suitability zones, as well as the ability of GWP and the appropriate irrigable land for agricultural production.

## 4.1 Assignment of weights for factors affecting groundwater potential

The eight selected factors (lineament density, landform, soil type, drainage density, slope, lithology, rainfall, and land use/cover) influencing the groundwater potential were assigned by applying a fuzzy pair-wise comparison ranking method. The weight assignment for each factor was examined according to their relative importance based on the fuzzy pair-wise comparison matrix in solving the stated problem using Fuzzy-AHP techniques. Thus, the assignment was done by comparing two factors to each other with the scores ranging from 1 to 1/9 as per the Saaty (1980) scale. These scores are given as inputs at appropriate cells in the matrix and further, the given values of weight assignment for each factor were presented in Table 4 below.

### 4.1.1 Weight normalization and principal Eugen vector

The percentage influences of each factor were evaluated to evaluate the groundwater potential zone. It was computed from the given weightage values by applying Equation 3.8 and then, the result was de-fuzzified from the membership function to obtain non-fuzzy numbers for each criterion using Equation 3.9. In the end, the average of each row's fuzzy number was taken to get the final values of each criteria's weightage (Table 5).

Table 4. Pair-wise comparison matrix of triangular fuzzy-AHP for GWP evaluation

| Factors | LF | | | SL | | | LITH | | | LD | | | RF | | | DD | | | LULC | | | SO | | |
|---|---|---|---|---|---|---|---|---|---|---|---|---|---|---|---|---|---|---|---|---|---|---|---|---|
| LF | 1 | 1 | 1 | 1 | 2 | 3 | 1 | 2 | 3 | 2 | 3 | 4 | 2 | 3 | 4 | 2 | 3 | 4 | 4 | 5 | 6 | 6 | 7 | 8 |
| SL | 1/3 | 1/2 | 1 | 1 | 1 | 1 | 1 | 2 | 3 | 2 | 3 | 4 | 2 | 3 | 4 | 2 | 3 | 4 | 4 | 5 | 6 | 6 | 7 | 8 |
| LITH | 1/3 | 1/2 | 1 | 1/3 | 1/2 | 1 | 1 | 1 | 1 | 2 | 3 | 4 | 1 | 2 | 3 | 2 | 3 | 4 | 2 | 3 | 4 | 5 | 6 | 7 |
| LD | 1/4 | 1/3 | 1/2 | 1/4 | 1/3 | 1/2 | 1/4 | 1/3 | 1/2 | 1 | 1 | 1 | 1 | 1 | 1 | 1 | 2 | 3 | 2 | 3 | 4 | 4 | 5 | 6 |
| RF | 1/4 | 1/3 | 1/2 | 1/4 | 1/3 | 1/2 | 1/3 | 1/2 | 1 | 1 | 1 | 1 | 1 | 1 | 1 | 2 | 3 | 4 | 2 | 3 | 4 | 4 | 5 | 6 |
| DD | 1/4 | 1/3 | 1/2 | 1/4 | 1/3 | 1/2 | 1/4 | 1/3 | 1/2 | 1/3 | 1/2 | 1 | 1/4 | 1/3 | 1/2 | 1 | 1 | 1 | 2 | 3 | 4 | 4 | 5 | 6 |
| LULC | 1/6 | 1/5 | 1/4 | 1/6 | 1/5 | 1/4 | 1/4 | 1/3 | 1/2 | 1/4 | 1/3 | 1/2 | 1/4 | 1/3 | 1/2 | 1/4 | 1/3 | 1/2 | 1 | 1 | 1 | 2 | 3 | 4 |
| SO | 1/8 | 1/7 | 1/6 | 1/8 | 1/7 | 1/6 | 1/7 | 1/6 | 1/5 | 1/6 | 1/5 | 1/4 | 1/6 | 1/5 | 1/4 | 1/6 | 1/5 | 1/4 | 1/4 | 1/3 | 1/2 | 1 | 1 | 1 |

Where: LF denotes Landform factor, RF denotes Rainfall factor, LD denotes Lineament Density factor, LITH denotes Lithology factor, DD denotes Drainage Density factor, SO denotes Soil factor, SL denotes Slope factor and LULC denotes Land use/cover factor.

Table 5. Calculation of geometric mean, relative and normalized weightage for GWP

| Factors | $r_i$ | | | $w_i$ | | | $W_{avg}$ | $W_{nor}$ | W (%) |
|---|---|---|---|---|---|---|---|---|---|
| LF | 1.93 | 2.80 | 3.60 | 0.14 | 0.27 | 0.47 | 0.29 | 0.261 | 26.10 |
| SL | 1.68 | 2.40 | 3.10 | 0.12 | 0.23 | 0.41 | 0.25 | 0.225 | 22.50 |
| LITH | 1.20 | 1.70 | 2.50 | 0.09 | 0.17 | 0.32 | 0.19 | 0.171 | 17.10 |
| LD | 0.77 | 1.00 | 1.30 | 0.06 | 0.10 | 0.17 | 0.11 | 0.096 | 9.60 |
| RF | 0.87 | 1.10 | 1.50 | 0.06 | 0.11 | 0.20 | 0.12 | 0.108 | 10.80 |
| DD | 0.57 | 0.70 | 1.10 | 0.04 | 0.07 | 0.14 | 0.08 | 0.074 | 7.40 |
| LULC | 0.35 | 0.40 | 0.60 | 0.03 | 0.04 | 0.08 | 0.05 | 0.043 | 4.30 |
| SO | 0.20 | 0.20 | 0.30 | 0.01 | 0.02 | 0.04 | 0.02 | 0.022 | 2.20 |
| Sum | 7.57 | 10.00 | 14.00 | 0.55 | 1.01 | 1.83 | 1.13 | 1.00 | 100 |

Where, ri denotes the geometric mean of fuzzy normalized values, wi denotes the relative fuzzy weights of each criterion, Wavg denotes the average fuzzy weight and Wnor denotes the normalized weight of each criterion, and the rest are described above.

The consistency ratio (CR) was used to double-check the fuzzy pair-wise comparison judgments inside each theme layer. Before computing CR, the Eugen value ($\lambda_{max}$) of the parameter was firstly determined through the sum of the product of each logistic fuzzy number in a row with the relative fuzzy weight of each criterion in a column and then dividing each result into each relative weightage. In the end, the average lambda maximum was determined by taking the average of each lambda in a column to calculate the consistency index. The consistency index was calculated to overcome for the formula of consistency ratio and was done based on Equation 3.11 which results in CI = 0.096. The consistency ratio of the expert was 0.068 (Table 6), which was computed by applying Equation 3.10, which is less than 0.1 and the given weight was valid for further analysis according to Saaty (1980).

Table 6. Calculation of Eugen vector and its value for GWP

| Factors | $R_i$ | | | Wi | | | λ |
|---|---|---|---|---|---|---|---|
| LF | 0.85 | 2.25 | 5.50 | 6.13 | 8.38 | 11.59 | 8.70 |
| SL | 0.76 | 1.89 | 4.67 | 6.27 | 8.37 | 11.30 | 8.70 |
| LITH | 0.55 | 1.39 | 3.63 | 6.35 | 8.40 | 11.17 | 8.60 |
| LD | 0.35 | 0.81 | 1.93 | 6.37 | 8.31 | 11.12 | 8.60 |
| RF | 0.40 | 0.90 | 2.23 | 6.40 | 8.42 | 11.37 | 8.70 |
| DD | 0.27 | 0.61 | 1.56 | 6.62 | 8.64 | 11.21 | 8.80 |
| LULC | 0.16 | 0.36 | 0.87 | 6.33 | 8.38 | 11.05 | 8.60 |
| SO | 0.09 | 0.19 | 0.42 | 6.39 | 8.46 | 11.09 | 8.70 |
| | Lambda max ($\lambda_{max}$) | | | | | | 8.70 |
| | Consistency Ratio (%) | | | | | | 6.80 |

Where: $R_i$ denotes fuzzy geometric mean for Eugen vector; $W_i$ denotes weights of fuzzy Eugen vector and λ denotes Eugen values.

### 4.2 Analysis of different input thematic layers for groundwater potential

The selection of indicators influencing groundwater potential mainly depends on the objective of the study and their relative importance was taken from previous literature. For the analysis of the potential groundwater zone, a total of eight parameters were considered for the study, such as lineaments density, lithology, soil, slope, drainage density, landform, land use/land cover, and rainfall. The classification, weight assignment, and suitability level of each thematic map were agreed upon and in the acceptable condition with other related studies such as (Dar et al., 2020; Yusuf, 2013; Siva et al., 2017; Tolche, 2021; Hussein et al., 2017; Agumase et al., 2019; Lemessa, 2017; Libasse, 2007; Adem, 2019; Oikonomidis et al., 2015). Thus, the analysis of the eight different thematic layers for each groundwater influencing factor in detail was presented as follows.

#### 4.2.1 Lineament density

Lineaments are the simple and complex linear properties of geological structures such as faults, cleavages, fractures, and the various surface of discontinuities (terraces and ridges) arranged in a straight line or a curved that are identified by remote sensing (Agumase et al., 2019). It plays a significant role in groundwater recharge and may provide the pathway for groundwater movement. Several studies (Dar et al., 2020; Andualem and Demeke, 2019; Yusuf, 2013) conducted that lineament density was directly proportional to groundwater potential of the study region, which means higher lineament density has a high probability to occur the groundwater potential whereas low density has low potential. The result reveals the faulting and fracturing areas increased porosity and permeability which are crucial for recharging to the subsurface groundwater and hence, the current study was consistent and accepted based on these findings.

For this study, the geospatial studies were conducted to take into account the ultimate objective of assessment of lineament density and, generally, it was classified in natural break class and into five classes. The result shows that a very high lineament density was observed in the near center to the upper part of the area with values ranging from 0.99 to 1.8 km/km$^2$ having good groundwater potential whereas areas with very low (0 to 0.12) have poor groundwater potential which was mainly observed at southeren, eastern and north eastern (Table 10 and Figure 7). The intermediate values were classified as highly suitable (0.65 to 0.98), moderately suitable (0.37 to 0.64), and poorly suitable, which ranged the values between 0.13 to 0.36 km/km$^2$

Table 7. The assigned weights and classes for Lineament Density

| Factor | Classes (Km/Km$^2$) | Area (%) | Suitability | Relative weight (%) | Rank | CR (%) |
|---|---|---|---|---|---|---|
| Lineament density | 0.99 - 1.80 | 2.75 | Very high | 52.0 | 5 | 8.2 |
| | 0.65 - 0.98 | 7.60 | High | 23.0 | 4 | |
| | 0.37 - 0.64 | 10.14 | Moderate | 15.0 | 3 | |
| | 0.13 - 0.36 | 13.84 | Low | 6.0 | 2 | |
| | 0 - 0.12 | 65.71 | Very low | 3.0 | 1 | |

It is expected that the thickness of weathered rocks is greater along the lineaments. Hence, they are assumed to enhance the availability of groundwater. The higher groundwater potential was estimated in an area where there is a high thickness of lineament. The direction of the lineament of the study area is towards the direction of the tributaries, which suggests that the direction of the aquifers mostly tends to be aligned with the surface water (Figure 7). Generally, about 65.71% of an area was very poor, 13.84% of the area was poor, 10.14% of the area was moderate, 7.6% of the area was highly suitable and only 2.75 % of the area was excellent for groundwater potential occurrences based on the influence of lineament density factor in the study area.

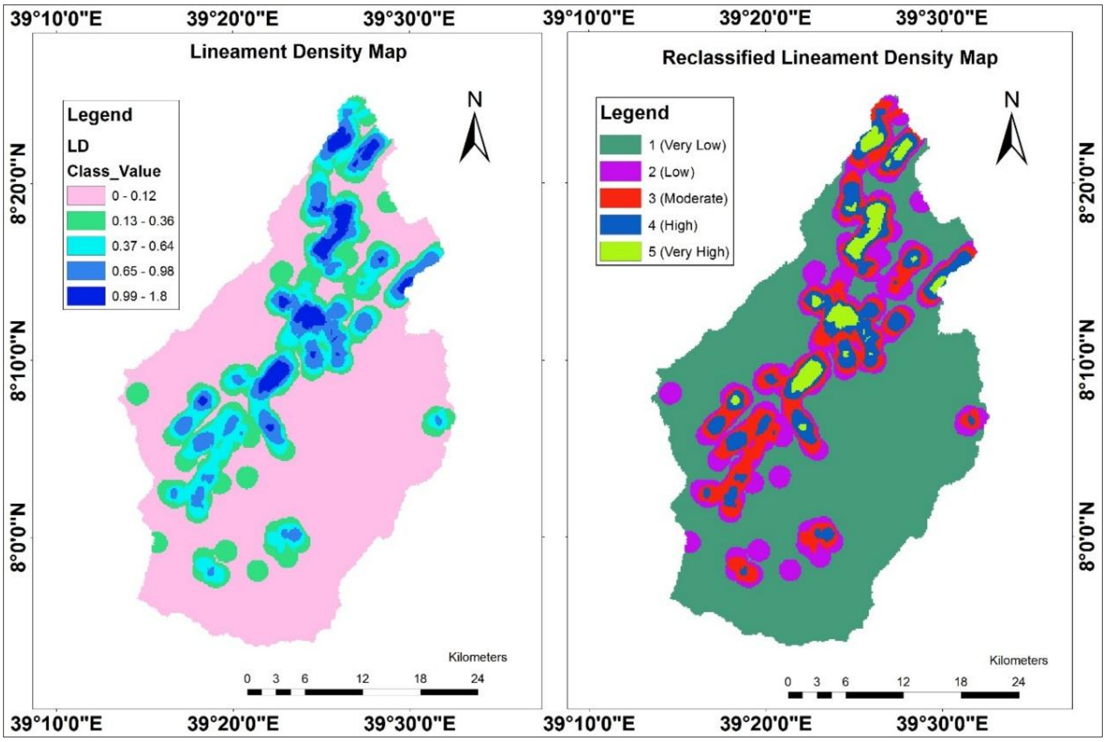


Figure 7. Lineament density and Reclassified lineament density map

### 4.2.2 Slope

The slope is an important factor for the identification of groundwater potential zones in any region. The gentile slope zones have moderate surface runoff which permits more opportunity for water to penetrate the ground while zones with steep slopes work with high runoff along these lines allowing less time for water and thus sensibly less infiltration. Adem (2019) reported that the area of a slope less than 3% was excellent for groundwater occurrence due to that the gentle areas have an infinity for holding rainfall and facilitate the recharge to groundwater while the area with greater than 30% has poor groundwater perspective. The nearly flat slope has been an excellent category for groundwater potential because flat terrain is appropriate for more infiltration and recharge, and the steep slope area was categorized as poor groundwater potential (Siva et al., 2017).

The slope of the study area varied from nearly gentile to steep slope and reclassified into five classes which was agreed with the above scholars. The highest rank was given to flat slope (0 to 3%) because it holds water to infiltrate into the ground whereas the lowest rank was assigned for very steep slope (>30 %) because they result in high runoff and low infiltration which cause low groundwater recharge. The nearly flat slope was mainly found in centeral area and steep slope was located around mountains and main stream drainage area of the study region. Further, the class, rate, and rank are given for each slope class based on the groundwater perspective are summarized in Table 8 below.

Table 8. The assigned weights and classes for the Slope gradient

| Factor | Classes (%) | Area (%) | Suitability | Relative weight (%) | Rank | CR (%) |
|---|---|---|---|---|---|---|
| Slope | 0 - 3 | 50.52 | Very high | 50.0 | 5 | 7.0 |
| | 3- 8 | 31.46 | High | 27.0 | 4 | |
| | 8 - 15 | 13.07 | Moderate | 14.0 | 3 | |
| | 15 - 30 | 4.13 | Low | 5.0 | 2 | |
| | >30 | 0.81 | Very low | 4.0 | 1 | |

Based on their influences, the remaining classes were taken as high (3-8%), moderate (8-15%) and low (15-30%) suitability for groundwater potential which covers an area of 31.46%, 13.07%, 4.13% and 0.81% from the total area respectively. This indicates that a major portion of the area was highly suitable and around 5% of the area was poor and very poor suitable for the occurrence groundwater potential based on the slope factor influence.

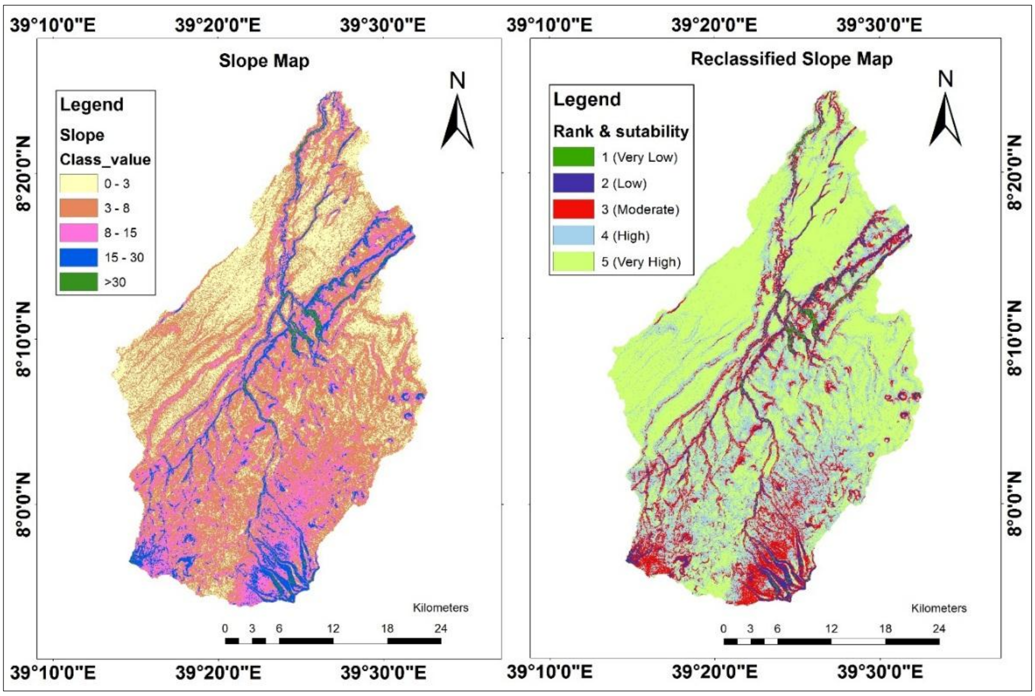


Figure 8. Slope and Reclassified slope map

### 4.2.3 Drainage density

Drainage density is a substantial measure of the linear scale of the landform component and it influences the groundwater occurrences. It indicates the behavior of surface and subsurface formation, the information of rock, soil permeability, infiltration of water, and surface runoff (Shalu, 2013). Drainage density is expressed as the total length of all streams per unit drainage. In an area where higher drainage density has generally poor groundwater potential due to an occurrence of larger surface runoff whereas areas of low drainage density allow more infiltration and less surface runoff to recharge the groundwater system. In the study, high drainage density was found at the lower part of the watershed around the mountains area which has an enable to occur the less groundwater potential. As is known that an area that has a curved ridge or steep slope causes the larger runoff rather than the infiltration of water to the ground system. Due to this the lower class (0 to 12 $km/km^2$) have highly suitable while the higher class (85.1 to 168 $km/km^2$) has very less suitable for the occurrence of groundwater potential and further their details with rates are presented in Table 9 below.

Table 9. The assigned weights and classes for Drainage Density

| Factor | Classes ($Km/Km^2$) | Area (%) | Suitability | Relative weight (%) | Rank | CR (%) |
|---|---|---|---|---|---|---|
| Drainage density | 0 - 11.9 | 40.97 | Very high | 50.0 | 5 | 7.8 |
| | 12 - 31.0 | 25.85 | High | 28.0 | 4 | |
| | 31.1 - 55.1 | 19.46 | Moderate | 12.0 | 3 | |
| | 55.2 - 85.8 | 9.82 | Low | 6.0 | 2 | |
| | 85.9 - 168 | 3.94 | Very low | 3.0 | 1 | |

As shown in Table 9, the structural drainage network was employed to explain the characteristics of the groundwater potential zone. An area where high drainage density values have high runoff and indicate a low possibility of groundwater availability and hence higher weighs are assigning to the lower drainage density area and vice versa (Tolche, 2021; Dar et al., 2020; Oikonomidis et al., 2015). In the present study, the higher drainage density was expected in the southern area around the mountains area and assigned with a very low rank of suitability for groundwater potential occurrence and vice versa (Figure 9), and the classification are agreed with these findings. Around the 41% of an area covered was an excellent, 25.85% of the area was highly suitable, 19.46% of the area was moderate, 9.82%

of the area was poor and only 3.94% of an area was very poor based on the influence of drainage density factor on the occurrence of groundwater potential.

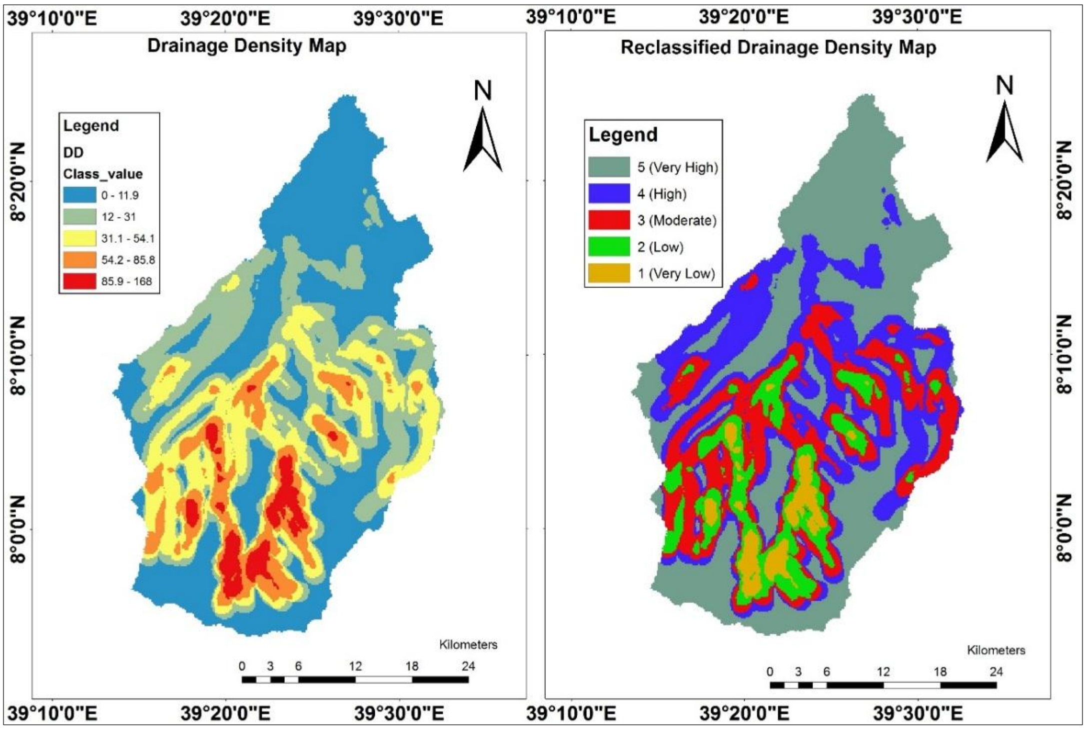


Figure 9. Drainage density and Reclassified drainage density map

### 4.2.4 Landforms

From the geomorphological study point of view, identification and investigation of various landforms and structural features in the study region are very important. Landform simply describes the shape and topography of the region and plays a vital role in groundwater availability and distribution. Integrating geomorphological background with hydrological characteristics of an area provides a simple way to understand the groundwater behavior (Siva et al., 2017). The volcanic terrain of Ethiopia comes in a variety of landforms that is of significant importance to groundwater occurrence and movement (Kebede, 2013). Landform characteristics of an area affect its response to a considerable extent. More promising groundwater is in flood plains, alluvial fans and valley fill that are associated with thick alluvial and weathered materials to give high porosity and permeability (Libasse, 2007).

In the study of groundwater potential point of view, the geomorphology of the study area was classified into four classes such as valley fill, hills, plains, and curved ridges or volcanic landform. A volcanic landform is the surface form that rises prominently above its surroundings and generally has a steep slope, located at the lower part of the study. The reverse is true for valley fill land for this study because the main drainage (high gorge) area was considered as a valley fill that was found at the center of the south to the northern edge of the watershed. Plain is a relatively flat area of earth surface exhibiting gentle slope and small local relief which covers the largest area of the watershed (Figure 10). Whereas, the hill is usually rounded natural elevation of land which have much less steep and lower than a volcanic form, and have also lower in altitude.

Table 10. The assigned weights and classes for Landform

| Factor | Classes | Area (%) | Suitability | Relative weight (%) | Rank | CR (%) |
|---|---|---|---|---|---|---|
| Landform | Plain | 44.86 | High | 57.0 | 4 | 5.8 |
| | Valley fill | 10.67 | Moderate | 31.0 | 3 | |
| | Hilly | 33.65 | Low | 7.0 | 2 | |
| | Volcanic | 10.82 | Very low | 6.0 | 1 | |

The given rating values of geomorphological classes varied in terms of characteristics and spatial distribution for groundwater potential. Hussein et al. (2017) reported that groundwater occurrence is more influenced by alluvial plains and plateaus which promote high potential while groundwater control is highly influenced by mountainous and residual hills locations which result in low groundwater potential. For this study, the plain area was more promising for groundwater potential due to the large recharge rate occur at the flat slope and given the high weightage than others.

And the gorge shape of the main drainage stream area was considered as valley fill for the study and has enabled to produce the moderate rate of groundwater potential whereas hilly and volcanic areas produce low and very low respectively which results in the poor potential for groundwater perspective due to less infiltration rate. About 44.86 % of the area was highly suitable, 10.67% of the area was moderate, 33.65% of the area was poor and 10.82% of the area was very poor based on the area coverage of landform factor which influences groundwater potential (Table 10).

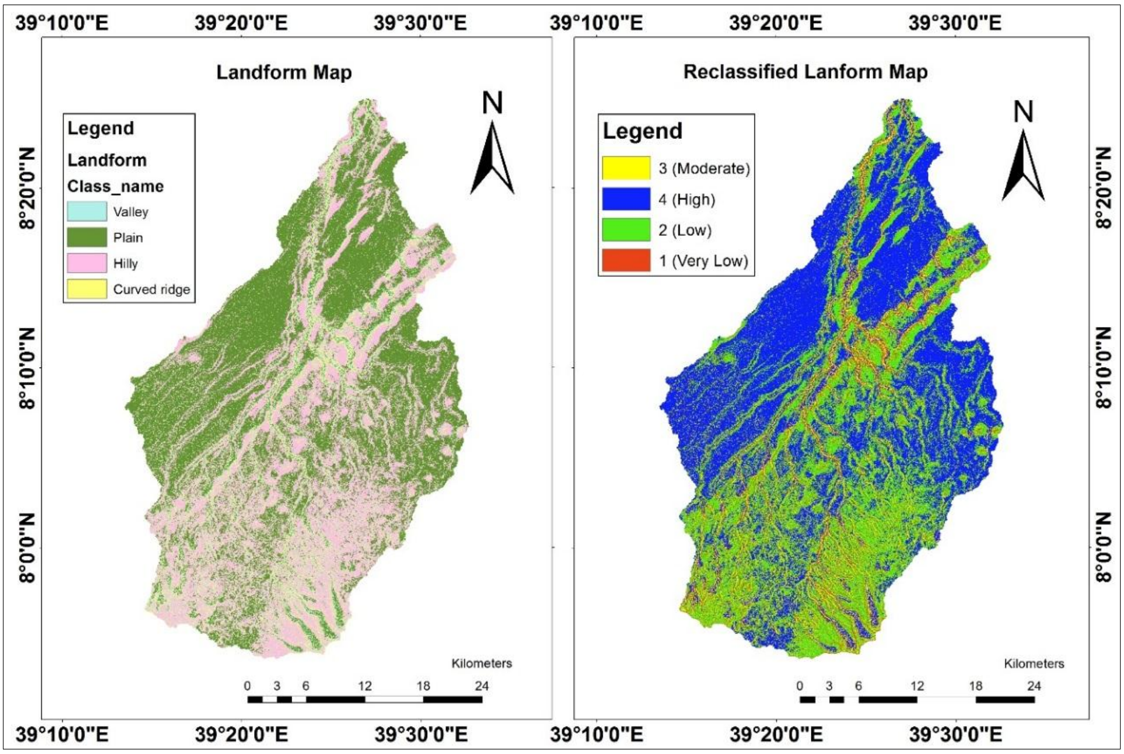


Figure 10. Landform and Reclassified landform map

### 4.2.5 Rainfall

Rainfall is another factor that governs the amount of water that would be available to infiltrate and joins into groundwater zones. Factors such as terrain, vegetation, and surface geology alter the link between rainfall and groundwater occurrence; all of these factors influence the amount of water that gets underground (Libasse, 2007). The amount of water that percolates into the ground, annual rainfall should be taken into account with varied surface conditions that determine the amount of water that flows to the ground system. The long-term mean annual rainfall map of the study area was prepared by IDW interpolation from five meteorological stations. Based on the mean annual rainfall and its contribution to groundwater recharge, the relative weights given for each rainfall class are presented in Table 11 below.

For the cause, an area where high mean annual rainfall has a greater tendency to occur high groundwater potential due to high infiltration rate rather than a low rainfall area. Based on the rainfall factor, most parts of the study area were suitable (33.80% in a very high and 38.22% in high suitability range) in which the high amount of rainfall can recharge into the groundwater system, whereas 10.48% was moderate and 17.55 % of the total area was poor suitable for groundwater potential.

Table 11. The assigned weights and classes for Rainfall

| Factor | Classes (mm) | Weight (%) | Area (%) | Suitability | Rank | CR (%) |
|---|---|---|---|---|---|---|
| | 988 - 1020 | 46.0 | 33.80 | Very high | 5 | |
| | 956 - 987 | 28.0 | 38.22 | High | 4 | 8.5 |
| Rainfall | 924 - 955 | 18.0 | 10.48 | Moderate | 3 | |
| | 891 - 923 | 8.0 | 17.55 | Low | 2 | |

The higher the rainfall, the more the volume available for percolating the soil and has been assigned a large weight and vice versa (Yusuf, 2013; Saranya and Saravanan, 2020). It was identified that an area having high mean annual rainfall was observed around the lower part whereas less rainfall was observed at the upper part of the watershed due to the altitude and, also the range of their classification were based on the above findings and agreed with them. In the present study, the weights of rainfall factors were given based on the contribution to groundwater recharge, the high rate was assigned for high rainfall and low rainfall areas were assigned the lowest rate for low groundwater potential.

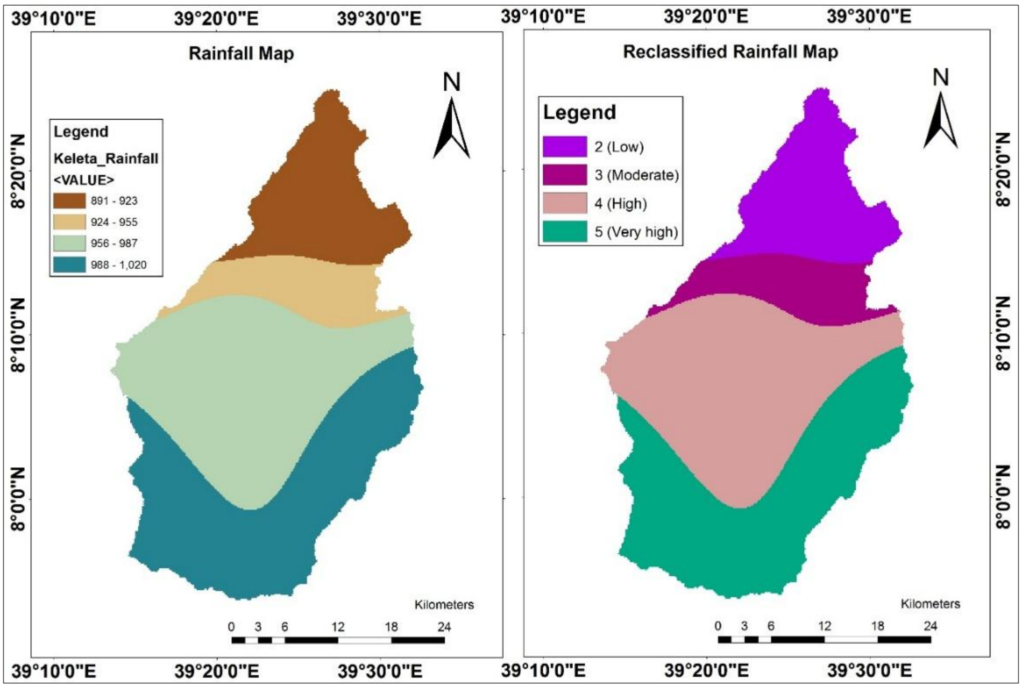


Figure 11. Rainfall and Reclassified rainfall map

### 4.2.6 Lithology

Lithology plays a major role in the availability and occurrence of groundwater and their types affect the recharge of groundwater as it controls the percolation. The storage of groundwater depends upon the type and porosity of rock formation. Types of rocks determine peculiarities of geological cross-section structure, type of porosity values, the nature of permeability, geological structure geomorphology, and character of spatial heterogeneity of flow and transport parameters (Lemessa, 2017). In the present study, the lithological stratigraphy of an area was done based on the previous data which was obtained from Minstry of water, irrigation and energy office. In general, Cenozoic lithological units such as tertiary volcanic and quaternary groups were found in the study area. The Cenozoic volcanic cover comes in monotonous and locally deformed and intruded by dykes. The occurrences of groundwater in this group are through in fractures and flow contacts. The details of each lithological unit based on their physical characteristics are described in Appendix Table A1.

According to the data, there are eight major lithological units founds in the study region, and from these, the chilalo formation (Nc) and nazareth groups (Nn) are most dominant whereas bofa basalt (Nb) and recent basalts (Qb) are less dominated one. In the study, bofa basalt and recent basalt have a very high rank to form groundwater potential whereas quaternary rhyolite volcanic center (Qr) have low rank. Due to the deep nature of vertical joints for bofa basalt units which have a high tendency of infiltration rate, and highly vesicular and fissure eruption for recent basalt which have high to moderate permeability. Further, the classes, the area coverage from the total, assigned weights with consistency ratio of each lithological unit were presented in Table 12 and Figure 12 below.

Table 12. The assigned weights and classes for Lithology

| Factor | Classes | Area (%) | Relative weight (%) | Suitability | Rank | CR (%) |
|---|---|---|---|---|---|---|
| Lithology | Nb | 0.89 | 26.0 | Very high | 5 | 8.7 |
| | Qb | 0.68 | 18.0 | | | |
| | Nn | 29.15 | 17.0 | High | 4 | |
| | Nc | 30.48 | 10.0 | | | |
| | Qd | 17.15 | 9.0 | Moderate | 3 | |
| | Q | 10.08 | 8.0 | | | |
| | Ncb | 6.45 | 6.0 | Low | 2 | |
| | Qr | 5.53 | 5.0 | Very low | 1 | |

The suitability level and classes of the lithological group for this study were found in the classes of another finding (Agumase et al., 2019; Lemessa, 2017) and consistent with them which were conducted on the hydrogeology and rock formation for groundwater occurrence.

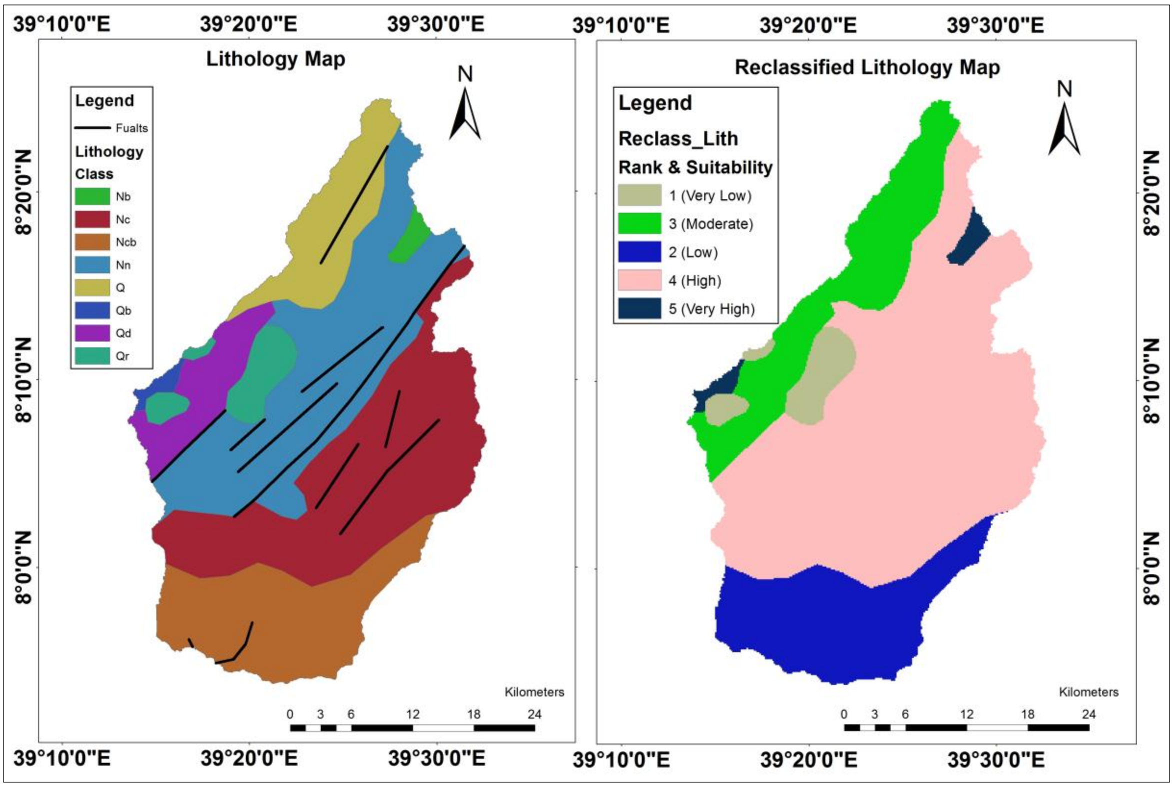


Figure 12. Lithology and Reclassified lithology map

### 4.2.7 Land use land cover

Land use land cover describes the surface of the earth cover. The land cover is the natural layer which includes features like water bodies, vegetation, mountain, and rock or bares while land use is the modified natural environment by human operation and comprising parameters like croplands, industry, plantations, built-up lands, and so on. Information on soil moisture, permeability, percolation, and amount of runoff is decided based on the land use type of the study. Therefore, land use/ cover influences either directly or indirectly or/and have a positive or negative impact on groundwater recharge. Trees may increase water loss by evapotranspiration or they may facilitate recharge by reducing runoff and by intercepting water and infiltrating its droplet slowly (Murthy, 2000).

For the issue being talked about, regardless of whether evapotranspiration and interception are accepted consistent and just constructive outcomes of vegetation are considered given a large portion of the vegetation's are involved in the ledge region and sloppy. From a water asset perspective, it has high runoff and a low likelihood to penetrate subsurface except especially along with the geographical constructions (Yusuf, 2013). In this way, vegetation covers are given as least position and agricultural terrains have the most noteworthy position for this study when compared them to each other.

The land use land cover pattern of the study area was categorized into cultivating land, forest, built-up land, shrubland, shrubland with exposed rock, and afro-alpine with grassland. Cultivated land was mostly dominated at central to western and eastern part of the region, shrubland with exposed rock found at upper part and afro-alpine with grassland was found in southern part of the study region (Figure 13). The Keleta watershed was mostly dominated by agricultural land which covers 54.61 % while less is covered by built-up land which has 6.64 % of the total area. The rating was assigned based on the quantity of water available for recharge according to the landform and slope of the area. The highest rating of 32.5 % was given for cultivating land due to having a nearly gentle to flat slope to increase infiltration rate while a very low rate (5.0 %) for built-up land (Table 13). Because an areas that are covered by houses and roads were leads to greater runoff rather than infiltration to the groundwater system.

Table 13. The assigned weights and classes for LULC

| Factor | Classes Name | Area (%) | Weight (%) | Suitability | Rank | CR (%) |
|---|---|---|---|---|---|---|
| | Cultivate land | 54.61 | 34.0 | Very high | 5 | |
| | Forest land | 6.89 | 26.0 | High | 4 | |
| LULC | Shrubland | 9.52 | 19.0 | Moderate | 3 | 8.9 |
| | Afro-alpine with grassland | 12.79 | 10.0 | Moderate | 3 | |
| | Shrubland with exposed rock | 9.70 | 6.0 | Low | 2 | |
| | Built-up land | 6.64 | 5.0 | Very low | 1 | |

Even an area is covered by vegetation and trees for the forest land, shrubland, and afro-alpine land; the given rate was less than that of agricultural land because they are located in and around high slope areas such that it made the higher runoff and the less infiltration rate on the area. The ability of dense forest areas and agricultural land to recharge and hold groundwater is high, whereas exposed bare rock and built-up areas are least favorable for infiltration and recharging groundwater (Dar et al., 2020). Similarly, Tolche (2021) reported that cultivated land, shrubland, and built-up land have very good, medium, and very poor respectively to occur groundwater potential that water to recharge the subsurface system.

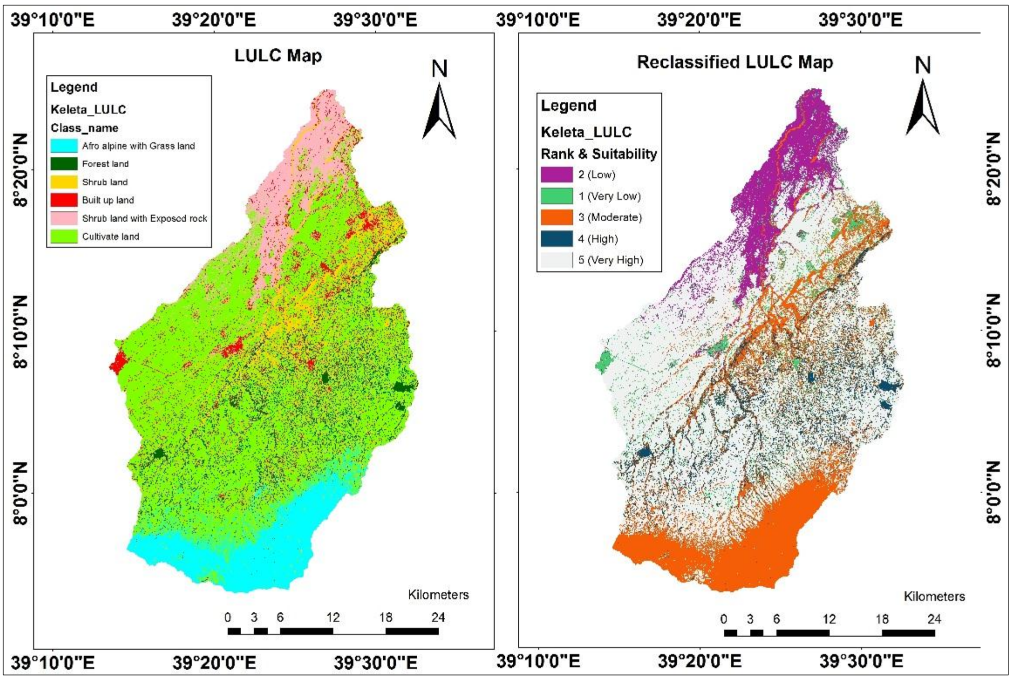


Figure 13. LULC and Reclassified LULC map

### 4.2.8 Soil

Soil is the loose surface material that consists of organic matter and inorganic particles through some natural process whether internal or external process as weathering and decomposition of parent materials, climate change, organisms, and human activities. It is one of the major important parameters that affect the occurrence and distribution of groundwater and plays a significant role in the infiltration of water into the ground. The rate of infiltration depends on the permeability and water holding capacity of the soil. The permeable area containing a large amount of sand or gravel permits high percent precipitation to infiltrate the ground and contribute to groundwater whereas less permeable areas have a little percent of water seeping in. The amount of water reaching the water table depends on the extent of the unconsolidated zone lying beneath the soil (Arivalagan et al., 2014).

The soil texture is a key criterion for the assessment of the physical characteristics of soil and is directly linked to the structure, porosity, and permeability of soil properties. The base data for the soil classification of the present study which has been obtained from the Ministry of Water, Irrigation and Energy represented that the eleven major soil-sub groups were found in watershed namely, Eutric and Chromic vertisols; Vertic and Eutric cambsols; Dystric and Eutric nitosols; Eutric regosols; Chromic and Orthic luvisols; Leptosols and Vitric andisols based on the FAO classification, and their detail descriptions were presented in Appendix Table A2.

The determination of weight for each soil unit was done based on the comparison and taking their clay contents, which was explained in FAO (1997a) for the present study. In terms of area coverage, Vertisols and Cambisols are the most dominant soil whereas Leptosols and andisols are very less dominant in the study area (Table 14). According to FAO (1997a), the textural classification of these soil groups are categorized into loam, clay loam, and clay classes and they have moderate to poor permeability which yields moderate to very low groundwater potential.

Table 14. The assigned weights and classes for Soil

| Factor | Soil Types | Soil Textures | Area (%) | Area Tot.(%) | Weight (%) | Suitability | Rank | CR (%) |
|---|---|---|---|---|---|---|---|---|
| Soil | Regosol | Loam | 8.12 | 8.12 | 28.0 | Moderate | 3 | 8.3 |
| | Leptosol | Loam | 1.84 | 1.84 | 25.0 | | | |
| | Luvisol | Loam | 10.30 | 17.80 | 18.0 | | | |
| | | Loam | 7.48 | | | | | |
| | Nitosol | Loam | 5.37 | 11.57 | 12.0 | | | |
| | | Loam | 6.20 | | | | | |
| | Andisol | Clay loam | 0.02 | 0.02 | 8.0 | Low | 2 | |
| | Cambsol | Clay loam | 19.9 | 29.55 | 5.0 | | | |
| | | Clay loam | 9.58 | | | | | |
| | Vertisol | Clay(heavy) | 22.90 | 30.75 | 4.0 | Very Low | 1 | |
| | | Clay(light) | 7.76 | | | | | |

Agumase et al. (2019) reported that Luvisols, Regosols, and Nitosols are moderately suitable for groundwater recharge based on their clay content, and Cambisols and Vertisols are low to very low suitable respectively due to their low infiltration rate. Similarly, Leptosols and Luvisols have moderate clay content and are moderately suitable whereas Cambisols and vertisols are less suitable due to containing clay and expensive clay in large volume which is not favorable for groundwater recharge (Libasse, 2007). The current study was agreed upon and accepted based on these findings and FAO classification.

For this study, the high rank were assigned for leptosols, regosols, Luvisols and Nitsols from the others as the result of moderate permeability and produce moderate groundwater potential, low rank and weight were assigned to soil having fine-grained texture (andosols; cambisols and vertisols) due to poor permeability and high water holding capacity. In general, 30.75% of the area was very poor, 29.57% of the area was poor, and 39.68% of the area was moderate suitable based on the influence of soil factor for groundwater potential evaluation (Table 14). This results in a less percentage of the area was moderately suitable for groundwater potential development.

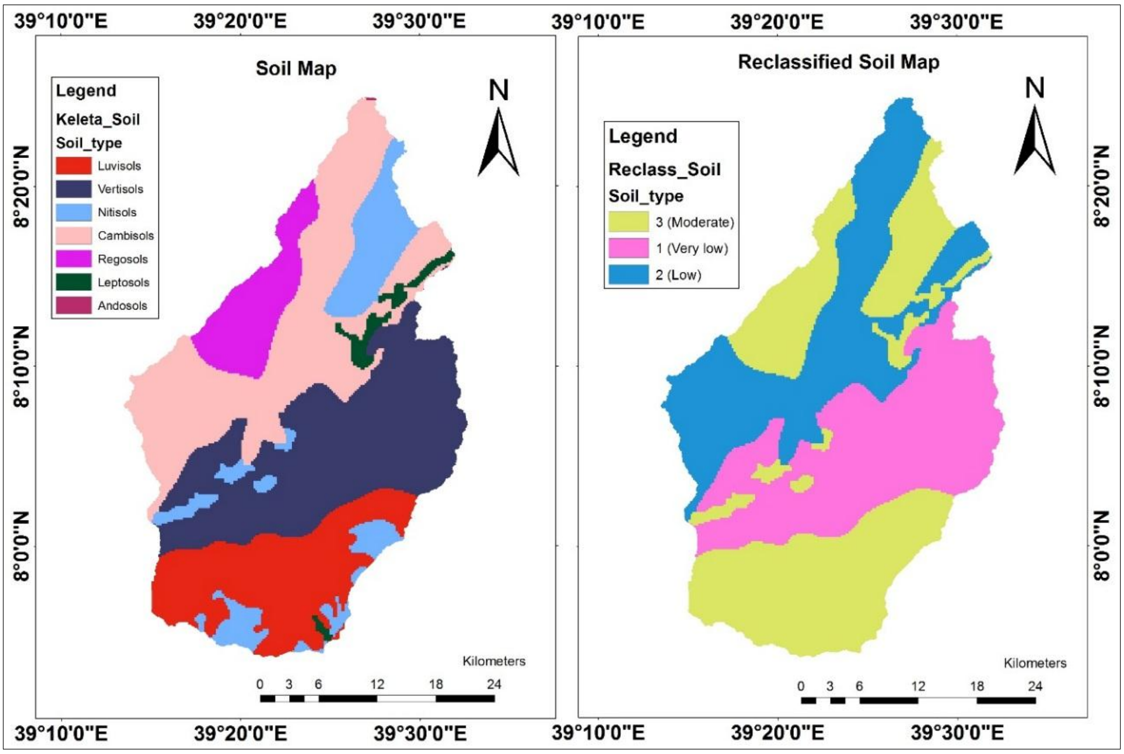


Figure 14. Soil and Reclassified soil map

## 4.3 Weight assignment for potential land suitability influencing factors

Irrigation land suitability model study was used to evaluate potentially irrigable land based on the given suitable criteria, which included weighing the values of all data sets such as soil type, soil depth, soil drainage, slope, and land use/cover of an area by assigning their weights. The relative importance factors were evaluated by Fuzzy-AHP pairwise comparison approaches to provide a series of pairwise factors in the matrix and the weightage value of each criterion was assigned by scores as per the Saaty (1980) scale in Table 15 below.

Table 15: Pair-wise comparison matrix of triangular fuzzy-AHP for LS evaluation

| Factors | ST | | | SDr | | | SDe | | | SL | | | LULC | | |
|---|---|---|---|---|---|---|---|---|---|---|---|---|---|---|---|
| ST | 1 | 1 | 1 | 2 | 3 | 4 | 3 | 4 | 5 | 1 | 1 | 1 | 4 | 5 | 6 |
| SDr | 1/4 | 1/3 | 1/2 | 1 | 1 | 1 | 2 | 3 | 4 | 1 | 1 | 1 | 3 | 4 | 5 |
| SDe | 1/5 | 1/4 | 1/3 | 1/4 | 1/3 | 1/2 | 1 | 1 | 1 | 1/4 | 1/3 | 1/2 | 2 | 3 | 4 |
| SL | 1 | 1 | 1 | 1 | 1 | 1 | 2 | 3 | 4 | 1 | 1 | 1 | 2 | 3 | 4 |
| LULC | 1/6 | 1/5 | 1/4 | 1/5 | 1/4 | 1/3 | 1/4 | 1/3 | 1/2 | 1/4 | 1/3 | 1/2 | 1 | 1 | 1 |

Where: ST represents Soil type; SDr represents Soil drainage; SDe represents Soil depth; SL represents Slope and LULC represents Land use/cover

### 4.3.1 Normalization of weightage and principal Eugen vector

An evaluation of the potential land suitability zone was computed by analyzing the percentage of each influencing factor. The percentage influences of each factor were calculated using Equation 3.8 and then, de-fuzzified from the membership function to generate non-fuzzy numbers for each criterion using Equation 3.9, and finally, the average value was taken as shown in Table 16 below.

Table 16. Calculation of geometric mean, relative and normalized weightage for PLS

| Factors | | ri | | | wi | | $W_{avg}$ | $W_{nor}$ | W (%) |
|---|---|---|---|---|---|---|---|---|---|
| ST | 1.90 | 2.30 | 2.60 | 0.30 | 0.37 | 0.50 | 0.38 | 0.37 | 36.80 |
| SDr | 1.10 | 1.30 | 1.60 | 0.20 | 0.22 | 0.30 | 0.23 | 0.22 | 21.80 |
| SDe | 0.50 | 0.60 | 0.80 | 0.10 | 0.10 | 0.20 | 0.11 | 0.14 | 10.40 |
| SL | 1.30 | 1.60 | 1.70 | 0.20 | 0.25 | 0.30 | 0.26 | 0.25 | 25.00 |
| LULC | 0.30 | 0.40 | 0.50 | 0.10 | 0.06 | 0.10 | 0.06 | 0.06 | 6.00 |
| Sum | 5.10 | 6.10 | 7.20 | 0.90 | 1.00 | 1.40 | 1.04 | 1.00 | 100.00 |

Where: ri denotes the geometric mean of fuzzy normalized values; wi denotes the relative fuzzy weights of each criterion; $W_{avg}$ denotes the average fuzzy weight and $W_{nor}$ denotes the normalized weight of each criterion

The consistency ratio was used to assess the pair-wise comparison judgments inside each thematic layer. It is believed that the consistency ratio will be nearly perfect to provide a decision that is close to valid, and it is linked to a comparison matrix. To circumvent the consistency ratio formula, the consistency index was determined using Equation 3.11, which gave (CI) = 0.095. According to Saaty (1980), the expert's consistency ratio was 0.084 (Table 17), which was calculated using Equation 3.10, which is less than 0.1, and the weight assigned was valid for further study.

Table 17. Calculation of Eugen vector and its value for PLS

| Factors | $R_i$ | | | $W_i$ | | | $\lambda$ |
|---|---|---|---|---|---|---|---|
| ST | 1.10 | 2.00 | 3.50 | 4.20 | 5.30 | 6.70 | 5.40 |
| SDr | 0.70 | 1.10 | 2.00 | 4.30 | 5.20 | 6.40 | 5.30 |
| SDe | 0.30 | 0.60 | 1.00 | 4.30 | 5.60 | 6.50 | 5.40 |
| SL | 0.80 | 1.30 | 2.20 | 4.40 | 5.20 | 6.30 | 5.30 |
| LULC | 0.20 | 0.30 | 0.60 | 4.40 | 5.60 | 6.30 | 5.40 |
| | | | Lambda max ($\lambda_{max}$) | | | | 5.40 |
| | | | Consistency Ratio (%) | | | | 8.40 |

Where: $R_i$ denotes fuzzy geometric mean for Eugen vector; $W_i$ denotes weights of fuzzy Eugen vector and $\lambda$ denotes Eugen values

### 4.4 Input thematic layers analysis for potential land suitability

The classification of land suitability for suitable use requires an understanding of conditions and processes controlling land characteristics in the area. Land evaluation for irrigated agriculture is mainly required to enhance agricultural productivity and it is necessary to forecast the farmer's benefits to sustain without any damage to the environment. For this study, the main irrigation suitability factors undertaken after a deep literature review were slope, soil type, soil drainage, soil depth and land use/cover. These factors are the principal parameters that influence land suitability assessment for surface irrigation development and they should be produced to prepare the thematic maps that were used to identify the suitability classes in the study area. According to FAO (1976), each aspect determining the suitability of the land for surface irrigation is classified into four classes, such as highly suitable (Class S1), moderately suitable (Class S2), marginally suitable (Class S3) and currently not suitable (Class N). And each of these maps as factors is described in more detail for a better understanding of their contribution to the assessment of potential land suitability for irrigated agriculture. The suitability of each factor should be analyzed and weighted to get the existing potential irrigable areas, which are presented as follows.

#### 4.4.1 Land use land cover

Land needs to be better matched for its users to increase production and the interaction between various physical, economic, and social factors is the key result of land use of an area. Land use/cover has been considered as one of the parameters for potential land suitability for surface irrigation. The study area is covered by different land use/cover types, namely, forest land, cultivated land, shrubland, afro-alpine with grassland, shrubland with exposed rock land, and built-up land. Land use/cover categories were assessed for their suitability for irrigation potential based on operating efficiency, land preparation costs, and environmental implications for the present study.

Megersa (2020) and Hussien et al. (2019) reported that cultivated land was classified as highly appropriate for irrigation, with the idea that certain land cover classes could be irrigated without or at a low cost for farm preparation, whereas water body and built-up land were not suitable for irrigation. Similarly, Halefom and Ulsido (2020) reported that forest land and shrubland are marginally suitable due to their land removal and preparation cost, whereas, cultivated land is highly suitable due to low limitation and built-up land is not suitable for surface irrigation assessment.

For this study, cultivated land was categorized as highly suitable for surface irrigation because cultivated land will be used to irrigate with very little limitation and gets the highest rank and also it covers most of the area. And due to the high requirement of initial investment for land preparation and location of unappropriated (rocky and gorge) areas, forest land, shrubland, shrubland with exposed rock, and afro-alpine with grassland were marginally suitable for surface irrigation while built-up land was not suitable at all. Based on the area coverage of the LULC factor that inferences land suitability, more than half of the total area (54.61%) was highly suitable, and 38.75% was marginally suitable and only 6.64% of the total area was not suitable for surface irrigation development (Table 18).

Table 18. Evaluation of LULC factor for land suitability analysis

| Factor | Classes Name | Area (%) | Weight (%) | Suitability Classes | Rank | CR (%) |
|---|---|---|---|---|---|---|
| LULC | Cultivate land | 54.61 | 57.0 | Highly (S1) | 4 | 9.4 |
| | Forest land | 6.89 | 15.0 | Marginally (S3) | 2 | |
| | Shrubland | 9.52 | 13.0 | | | |
| | Afro-alpine with grassland | 12.79 | 7.0 | | | |
| | Shrubland with exposed rock | 9.70 | 5.0 | | | |
| | Built-up land | 6.64 | 4.0 | Not (N) | 1 | |

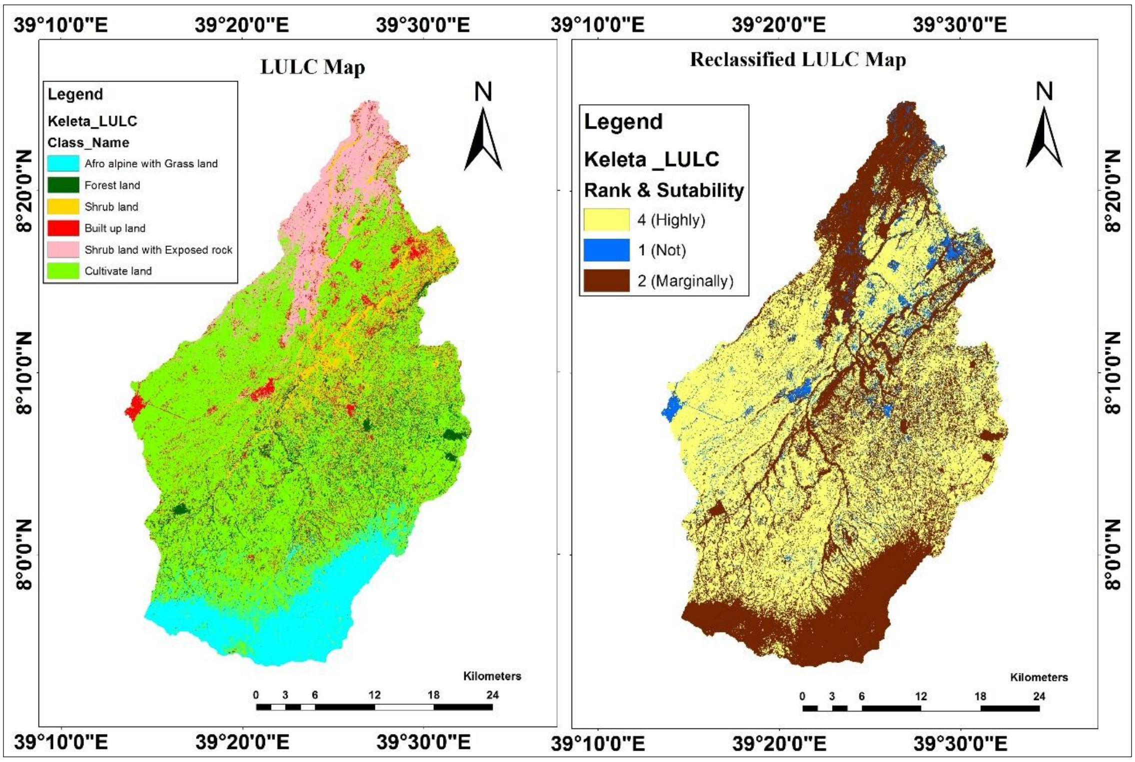


Figure 15. LULC map for irrigation land suitability analysis

### 4.4.2 Slope

The slope gradient of the land has a great influence on land capability and selection of the irrigation methods. Land suitability for surface irrigation is highly influenced by slope steepness than pressurized irrigation (drip and sprinkler irrigation) and should be critically considered for surface irrigation development. It influences land development, erosion hazard, method of irrigation, crop water use, drainage requirement, and other management and production costs. Therefore, for surface irrigation development, the study of the slope factor is a principal factor for land suitability. According to FAO standard guidelines in terms of slope gradient, slopes of less than 2% are ideal for surface irrigation, however slopes of more than 8% are generally not advised (FAO, 1999). Thus, the slope factor could be highly influenced on land suitability for surface irrigation through increasing or decreasing flow velocity.

Megersa (2020) and Hussien et al. (2019) reported that the influence of slope steepness for surface irrigation was highly suitable in the 0 to 2% class, moderately (2-5%) and marginally (5-8%) suitable. Based on the FAO framework and different reviews, the category ranges from 0 to 2% have highly suitable due to less occurrence of surface runoff, 2 to 5% class have moderately suitable, 5 to 8% class are marginally suitable and > 8% are not suitable for surface irrigation in the study area. For surface irrigation development of the study area, an unsuitable slope class was found around mountain ridges and the main drainage (highly gorge) area due to very high steepness. This indicates that 55.95% and 32.16% of the area were highly and moderately suitable for surface irrigation respectively whereas the remaining 9.78% and 2.11% were marginally and less suitable for surface irrigation development respectively based on the influence of slope factor for land suitability. Further, the slope factor for land suitability evaluation was presented in detail in Table 19 and Figure 16 as below.

Table 19. Evaluation of slope factor for land suitability analysis

| Factor | Classes (%) | Area (%) | Suitability Classes | Weight (%) | Rank | CR (%) |
|---|---|---|---|---|---|---|
| Slope | 0 – 2 | 55.95 | Highly (S1) | 62.0 | 4 | 8.7 |
| | 2 – 5 | 32.16 | Moderately (S2) | 23.0 | 3 | |
| | 5 – 8 | 9.78 | Marginally (S3) | 11.0 | 2 | |
| | > 8 | 2.11 | Not (N) | 4.0 | 1 | |

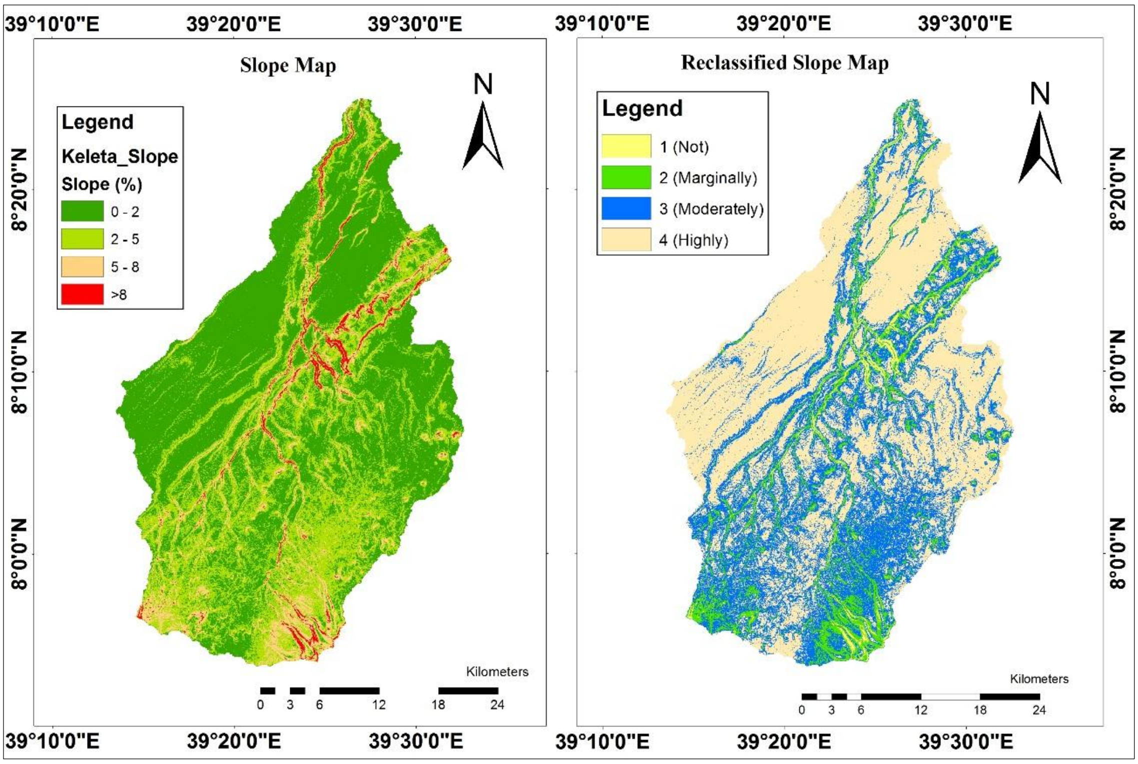


Figure 16. Slope map for irrigation land suitability analysis

### 4.4.3 Soil type

Soil type is one of the most important factors that influence the suitability for surface irrigation development and it was evaluated through its suitability potential for agricultural production. Based on the FAO guidelines for soil evaluation, the soil texture of the study area was evaluated and classified into loam soils (nitosol, leptisol, regosol, and luvisol); loam clay soils (cambisol and andisol), and clay soil classes (vertisol). Vertisols contain a large volume of organic matter and are useful for agricultural production when adaptive management is precondition because the heavy soil texture and domination of expanding clay minerals results in narrow soil moisture and is hindered for tillage when the soil is wet and hardness when it is dry and also plant roots are damaged when cracking of soils (FAO, 1985). Thus, without the adaptive management of the land, the direct usage of of vertisols for surface irrigation development for agricultural production is not acceptable and it may reduce the crop yield.

Halefom and Ulsido (2020) reported that loam soils are highly suitable for potential land suitability analysis whereas loam clay and clay soils are moderately and marginally suitable for land suitability respectively based on the availability of their pores space and infiltration rate. Nitosols and Luvisols are highly suitable whereas, Regosols and Leptosols are moderately suitable for potential land suitable for surface irrigation based on their fine-material content (Balew et al. 2021; FAO and UNESCO, 1988).

Based on these consistent and agreements Vertisols, Cambisols and Andisols have high water holding capacity due to their high content of porosity which results in marginally suitable for agricultural production and have low rank for this study. This indicates that around 60.43% of the study area was marginally suitable based on the soil type factor. Regosols and Leptosols are less suitable for surface irrigation which covers 19.64% of the total area, whereas Luvisols and Nitosols are highly suitable for surface irrigation due to their moderate infiltration rate and low surface runoff, which covers the remaining around 20% of the total area. This means that the most of study area was marginally suitable and from the total, only 20% of the area was highly suitable based on the influence of soil type factors for surface irrigation development.

Table 20. Soil type factor evaluation for land suitability analysis

| Factor | Soil Types | Area (%) | Weight (%) | Suitability | Rank | CR (%) |
|---|---|---|---|---|---|---|
| Soil type | Luvisols | 8.23 | 37.0 | Highly(S1) | 4 | 7.7 |
| | Nitosols | 11.57 | 24.0 | | | |
| | Regosols | 1.84 | 15.0 | Moderately(S2) | 3 | |
| | Leptosols | 17.80 | 12.0 | | | |
| | Andosols | 0.02 | 7.0 | Marginally(S3) | 2 | |
| | Cambisols | 29.66 | 5.0 | | | |
| | Vertisols | 30.75 | 4.0 | | | |

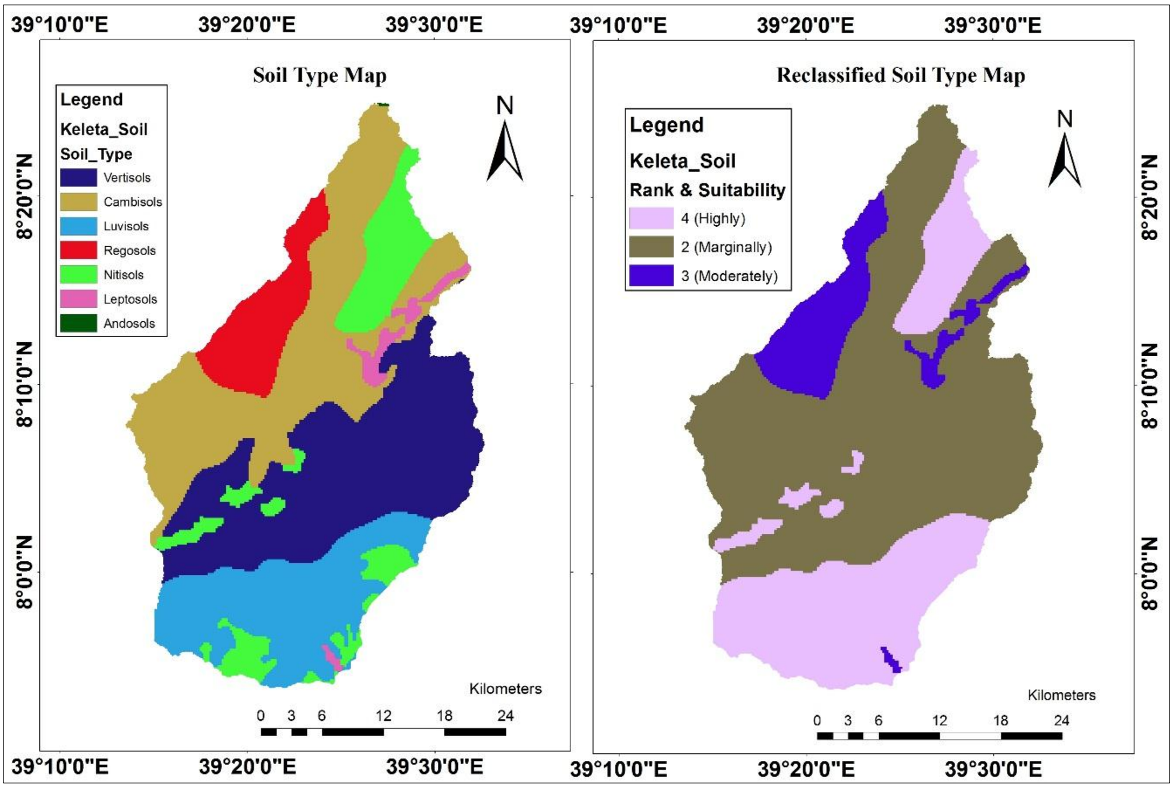


Figure 17. Soil type map for irrigation land suitability

### 4.4.4 Soil depth

The thickness of the soil materials that gives the structural support, nutrients, and water for plants is referred to as soil depth. Irrigation management decisions may be influenced by the depth of a contrasting soil layer. For irrigation development, the depth of the soil layer, the rooting depth, and the amount of available soil water for plants are mostly considering and investigating one for agricultural crop. Irrigation is required more frequently on soils with less available water for plants. The soil depth of the study area was classified into three groups such as deep (>100cm), moderately deep (50-100cm), and shallow depth (30-50cm) according to FAO (1997b) to surface irrigation suitability.

From a soil depth point of view, 49.59% of the study area was covered by highly suitable, 32.59% of the area was moderately suitable and 17.82% of the area was marginally suitable for surface irrigation based on the FAO classification of surface irrigation suitability and various review (Table 21). The reclassified soil depth map in Figure 18 below, the highly suitable soil depth was located in the study area of western and northern to northeastern part. In this area, crop production through surface irrigation is highly recommend based on the influence of soil depth factor because an area has a deep soil layer and the crop can grow with unlimited root depth to produce the yield. The moderately deep soil was found in the northeastern and central to the eastern part of the study area whereas, shallow depth soil was located at northeastern and in a small portion of the southern part (Figure 18). Normally, the shallow depth soil layer is not suitable for deep to moderately deep-rooted crop type because it influences direct growing of plant root in the soil, this cause the reduction of crop yield but it may suit for the vegetable crop because they have very shallow roots.

Table 21. Soil depth factor evaluation for land suitability analysis

| Factor | Soil Types | Area (%) | Weight (%) | Soil depth (cm) | Suitability Classes | Rank | CR (%) |
|---|---|---|---|---|---|---|---|
| Soil depth | Regosols | 1.84 | 35.0 | 150.0 | Highly(S1) | 4 | 8.4 |
| | Cambisols | 29.66 | 22.0 | 120.0 | | | |
| | Nitosols | 11.57 | 20.0 | 120.0 | | | |
| | Luvisols | 8.23 | 10.0 | 100.0 | Moderately(S2) | 3 | |
| | Vertisols | 30.75 | 6.0 | 70.0 | | | |
| | Andosols | 0.02 | 4.0 | 50.0 | Marginally(S3) | 2 | |
| | Leptosols | 17.80 | 3.0 | 30.0 | | | |

Scholars (Hussien et al., 2019; Girma et al., 2020) conducted that deep depth (>100cm) soil is highly suitable for agricultural production, and moderately deep (50-100cm) and shallow depth (10-50cm) soil are moderately and marginally suitable for surface irrigation because the volume of water extracted from the crop depends on the soil type and its root depth. Thus, the suitability classification of the soil depth of the study was acceptable as compared with this finding and agreed with the ranges

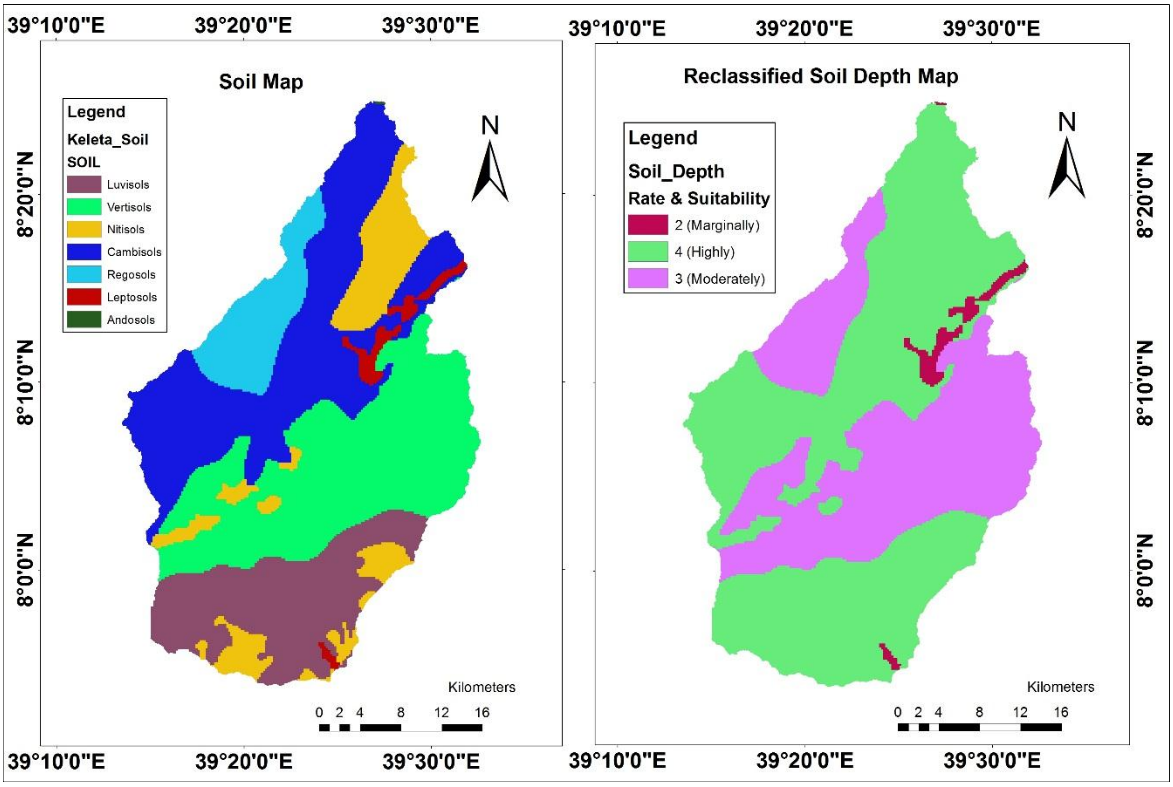


Figure 18. Soil depth map for irrigation land suitability

### 4.4.5 Soil drainage

One of the most important factors for land evaluation for surface irrigation is soil drainage. The condition of the soil drainage system is crucial for crop production because it regulates the flow of water and salt throughout the soil profile. Some amount of salt may accumulate in the root zone due to either over-irrigation/rainfall and or poor quality of water. Salt could build up to dangerous levels in the landscape and vegetation if this constant leaching does not occur. When some amount of salt adds to the soil regularly, the site's drainage must be adequate to allow water and salt to flow freely through the profile. According to FAO (1997b) soil permeability evaluation practices, the soil drainage of the study area was classified into three groups, namely, moderately well, imperfectly, and poorly drained.

For the study, a major portion (51.48%) of the study area was covered by moderately well-drained, 17.82% of the area was imperfectly and 30.75% of the area was poorly drained (Table 22). The moderately well-drained soil was found at the southern and northwestern to the northern part of the study area which is moderately suitable for surface irrigation development. The imperfectly drained was found in northeastern and a small portion of the southern part while poorly drained soil was located central to the eastern side of the study region (Figure 19). To develop and design surface irrigation for crop production on the poor and imperfectly soil drained study area, an adequate drainage system can be designed to remove excess water from the agricultural field because these areas are difficult for crop growth due to the development salt accumulation in the crop root, reduce crop soil aeration, and reduce/influence crop yield.

Table 22. Soil drainage factor evaluation for land suitability analysis

| Factor | Soil Types | Area (%) | Weight (%) | Soil drainage | Suitability Classes | Rank | CR (%) |
|---|---|---|---|---|---|---|---|
| Soil drainage | Nitosols | 11.57 | 24.0 | Mode-Well | Moderately(S2) | 3 | 9.2 |
| | Luvisols | 8.23 | 22.0 | | | | |
| | Regosols | 1.84 | 21.0 | | | | |
| | Cambisols | 29.66 | 16.0 | | | | |
| | Andosols | 0.02 | 10.0 | Imperfectly | Marginally(S3) | 2 | |
| | Leptosols | 17.80 | 4.0 | | | | |
| | Vertisols | 30.75 | 3.0 | Poor | Not(N) | 1 | |

Poor and excessively drained soils are not suitable for surface irrigation development whereas imperfectly and moderately well-drained soils are marginally and moderately suitable respectively (Balew et al., 2021). Similarly, Gonfa et al. (2021), Hussien et al. (2019) argued that poor and highly drained soils are currently unsuitable for surface irrigation development, and imperfectly and moderately well-drained soils are marginally and moderately suitable respectively. Based on this review, the current study was agreed and acceptable for evaluation of soil drainage factor for irrigation land suitability assessment in the study region.

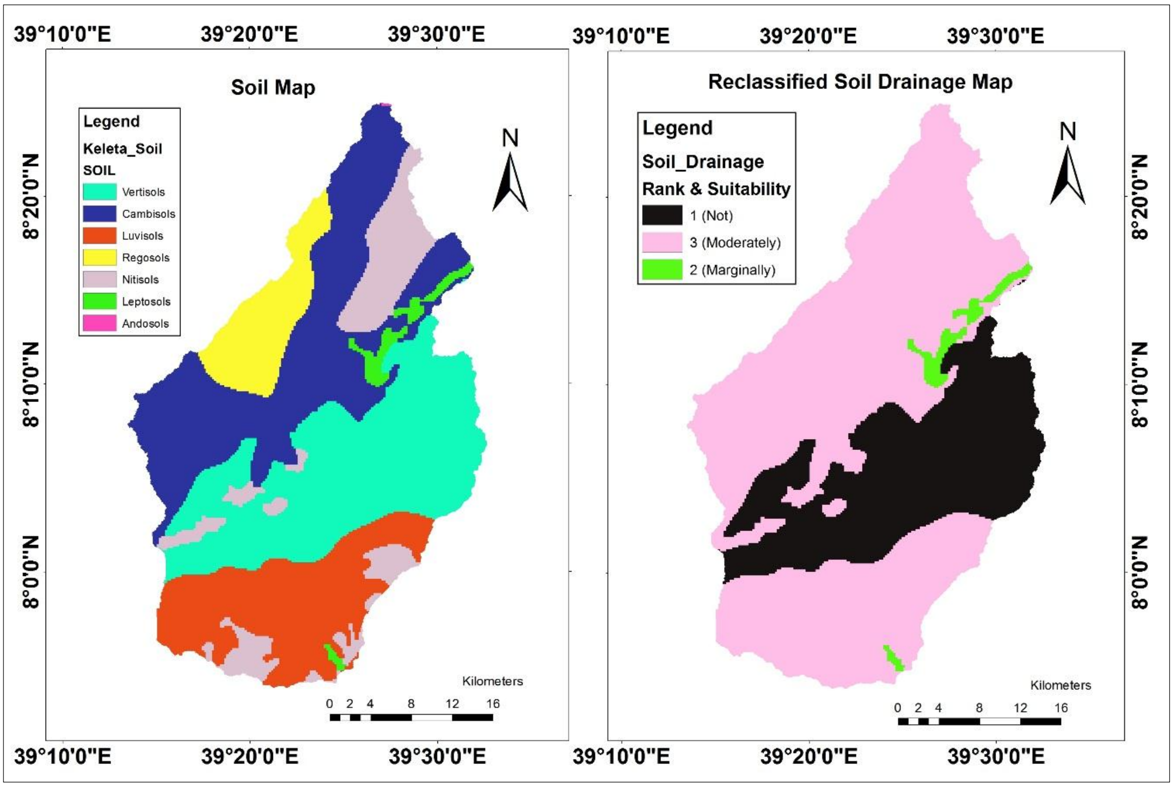


Figure 19. Soil drainage map for irrigation land suitability

### 4.5 Groundwater potential zone map

To identify the groundwater perspective zone, the different thematic maps were prepared and their degree of influences on groundwater occurrences have been derived. These thematic maps include drainage density, land use/cover, soil, lineament density, landform, slope, lithology, and rainfall map. The percentage influences of thematic layers and the rank for their parameters were assigned based on expert assessment of work carried out through a similar groundwater potential zone mapping study (Tesfaye, 2012). This is because none of those factors have the same effect on groundwater occurrence and movement (Saaty, 1980). The suitability level for each criterion was analyzed and discussed in section 4.1 by checking pair-wise comparison judgments inside each thematic layer using FAHP and assessing the consistency ratio.

The consistency ratio of the expert for this study was 0.068 from section 3.4, which is less than 0.1 and the given weight was valid for further analysis according to Saaty (1980). Table 5, presented that the top three factors influencing groundwater occurrence were landform (26.1 %), slope (22.5%), and lithology (17.1%), whereas rainfall, soil, drainage density, lineament density, and land use/cover, on the other hand, were the five least impacting parameters. Finally, the delineated groundwater potential zone of an area was computed by overlaying all thematic layers by linear combination using the following equation:

$$GWPZ = 26.1\% * LF + 22.5\% * SL + 17.1\% * LITH + 10.6\% * RF + 9.6\% * LD + 7.4\% * DD + 4.3\% * LULC + 2.2\% * SO \qquad (4.1)$$

Where, GWPZ represents Groundwater potential zone; LF represents Landform map; SL represents Slope map; RF represents Rainfall map; LITH represents Lithology map; LD represents Lineament density map; DD represents Drainage density map; LULC represents Land use/cover map and SO represents Soil map

Landform, slope, and lithology were taken as the principal factors for the occurrence and distribution of groundwater potential in the area and had given us the highest rank from the other. The landform is considered as the first main factor because the infiltration of water into the ground depends on terrain relief, slope characteristics, and permeability of bedrocks. The slope is the greater influence on groundwater potential due to increasing or decreasing of recharge into the sub-surface system, and lithology was also influenced through their permeability, faulting, and fracturing of aquifer characteristics. Whereas, the soil factor has less influence on the groundwater potential of the area due to the availability of highly porous soil which results in less infiltration of the water into the ground.

To identify the overall suitability of the area, the spatial analysis tool was used to overlay all theme layers using Arc map based on rates for the classes in each layer and the weight of thematic layers (percent of influences) derived from pairwise comparison. Finally, the groundwater potential can be assigned into three different potential zones, namely Low, Moderate, and High groundwater potential zones, after the integration of the interpreted layers (Table 23). From the combined features of all thematic layers, the majority of the area is covered by a moderate groundwater potential zone (61.51%), and the remaining areas are covered by high (33.45%) and low (5.04%) groundwater potential zone (Table 23).

Table 23. An area of groundwater potential zone

| Rate (Index values) | GW Potential Suitability classes | Area ($Km^2$) | Area (%) |
|---|---|---|---|
| 2 | Low | 59.18 | 5.04 |
| 3 | Moderate | 722.16 | 61.51 |
| 4 | High | 392.66 | 33.45 |
| | Total | 1174.00 | 100.00 |

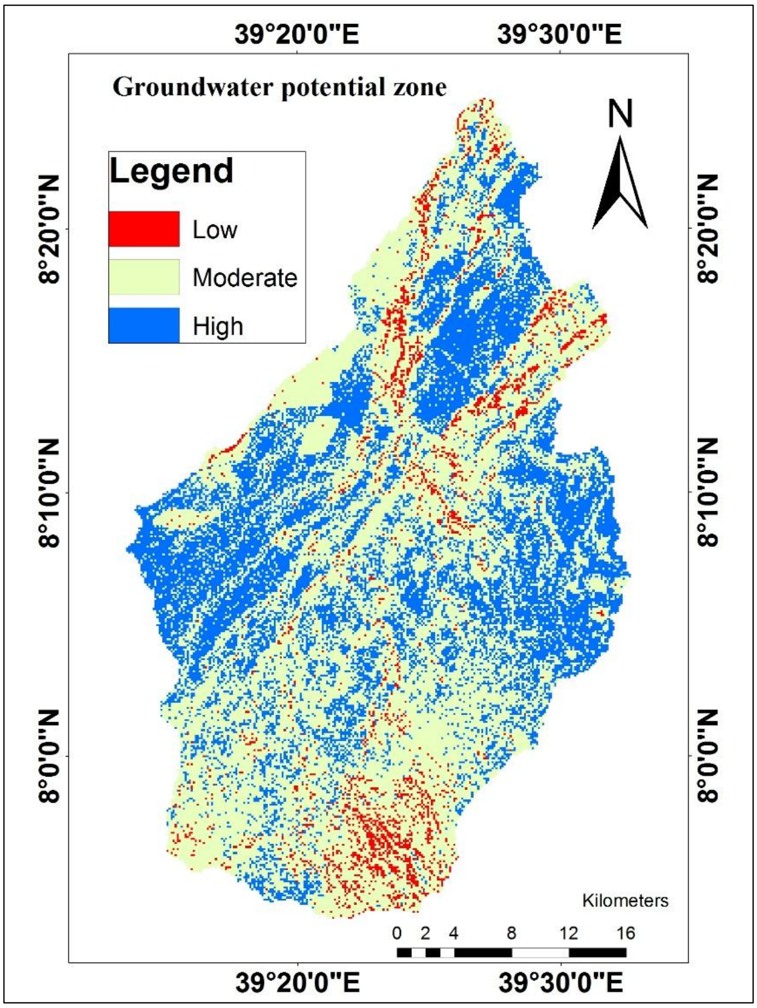


Figure 20. Groundwater potential zone map

The high groundwater potential zone is highly concentrated in the western, eastern, and the northeastern region of the study area (Figure 20). Which have the availability of nearly flat slope, plain landform, and cultivate land overlaid with the nazerat series (have high faulting), recent and bofa basalt of lithology which have the vesicular and fissure eruption, and deep level of vertical joint respectively that have an ability of high infiltration rate.

Similar studies have been reported that the high GW potential was present an area of having a low slope, flat topography, high porosity and permeability, and easily fracturing and faulting geological rock formation (Oikonomidis et al., 2015; Andualem and Demeke, 2019; Dar et al., 2020). The availability of groundwater in this area has high potential and is also recommended to use for crop production for this study.

Low groundwater potential is highly distributed in the southern and center to northern region of the areas, which have an area of hilly and volcanic landform, very steep slope, and high drainage density overlaid which resulted in a low groundwater potential zone. Scholars (Agumase et al., 2019; Tolche, 2021) conducted that low GW potential in the study region was found in a steep slope, low permeability and porosity, high drainage density, and curved ridge landform. Because the steep slope, volcanic landform, and high drainage density in the area result in low infiltration rate and higher runoff, which cause low groundwater potential occurrence. As a result, the groundwater potential in these locations can be insufficient for irrigation development for this study.

On other hand, the moderate GW potential zone is highly dominated in the southern, and center to the northwestern and northeastern part of the study area (Figure 20). These areas are observed in moderate slope with irregular plain of landform, moderate drainage to Holocene lithology that is a detritus deposit mainly along the base of escarpment slopes and piedmonts. Generally, the major portion of the study region has moderate to high groundwater potential, which will meet irrigation and other water demands. Hereon, the suitability classes assigned for each factor based on their influences for groundwater potential assessment are presented in Table 24 below.

Table 24. The factors suitability level to identify groundwater potential zone

| Criteria | Suitability Classes | | | | |
|---|---|---|---|---|---|
| | 5 | 4 | 3 | 2 | 1 |
| LF | - | Plain | Valley fill | Hill | Volcanic |
| SL | 0 - 3 | 3 - 8 | 8 - 15 | 15 - 30 | >30 |
| RF | 988 - 1020 | 956 - 987 | 924 - 955 | 891 - 923 | - |
| LD | 0.99 - 1.8 | 0.65 - 0.98 | 0.37 - 0.64 | 0.13 - 0.36 | 0 - 0.12 |
| LITH | Nb/Qb | Nn/Nc | Qd/Q | Ncb | Qr |
| DD | 0 - 11.9 | 12 - 31 | 31.1 - 55.1 | 55.2 - 85.8 | 85.9 - 168 |
| LULC | Cultivate land | Forest land | Shrub/Afro-alpine with grassland | Shrub with exposed rock land | Built-up land |
| SO | - | - | Medium | Medium to fine | Fine |

Where: LF; SL; RF; LD; LITH; DD; LULC and SO area described on above

## 4.6 Validation of groundwater perspective zone

The delineated groundwater perspective zone should be validated to check the performance level of the study. The results obtained from the weighted overlay were verified with the existing boreholes/dug-wells and spring sources of groundwater yield data (Yusuf, 2013; Agumase et al., 2019). The seventeen water inventory points data (boreholes and spring sources) was obtained from the OWWDSE office, which was based on the results of the groundwater perspective zone and coincided with the expected result. Inspite of the lack of general standared classification, groundwater yield data can be categorized into different zones with respect to site specific conditions. Scolars (Tuinhof et al., 2011) highlighted the aquifer yield classification in sub-saharan Africa and Enideg (2012) conducted the volcanic aquifer yield in central Ethiopia, the aquifer yield classification was categorized into five classes includes very high yield (> 20 l/s), high yield (5-20 l/s), moderate yield (2-5 l/s), low yield (0.5-2 l/s) and very low yield (<0.5 l/s).

Due to the variation of physographic characterstics and types of geology, groundwater yields vary from place to place and categorized into high yield (5-20 l/s), moderate yield (2-5 l/s), low yield (0.5-2 l/s) for this study. Thus, out of seventeen water invertory data in which eight of seven fall under high potential, five of four fall under medium potential and all low-yield invertory points are found under the low potential area (Table 25). This indicates, out of total, 88% were matched with their corresponding classes of groundwater perspective zones. This shows groundwater potential zones is relative to water invertory point data that were found in the watershed (Figure 21).

Table 25. The factors suitability level to identify groundwater potential zone

| S.No. | Expected GW perspective | GW perspective zone | | | |
|---|---|---|---|---|---|
| | | Low | Moderate | High | Total |
| 1 | Total number of validation under different GWP zone | 4.0 | 5.0 | 8.0 | 17.0 |
| 2 | No. of valid under agree | 4.0 | 4.0 | 7.0 | 15.0 |
| 3 | No. of valid under disagree | 0.0 | 1.0 | 1.0 | 2.0 |
| 4 | Average yield data (l/s) | 1.4 | 3.7 | 14.2 | |

$$\text{Prediction accuracy (\%)} = \frac{\text{No. of valid under agree}}{\text{Total No. of validation}} = \left(\frac{15}{17}\right) * 100 = 88\%$$

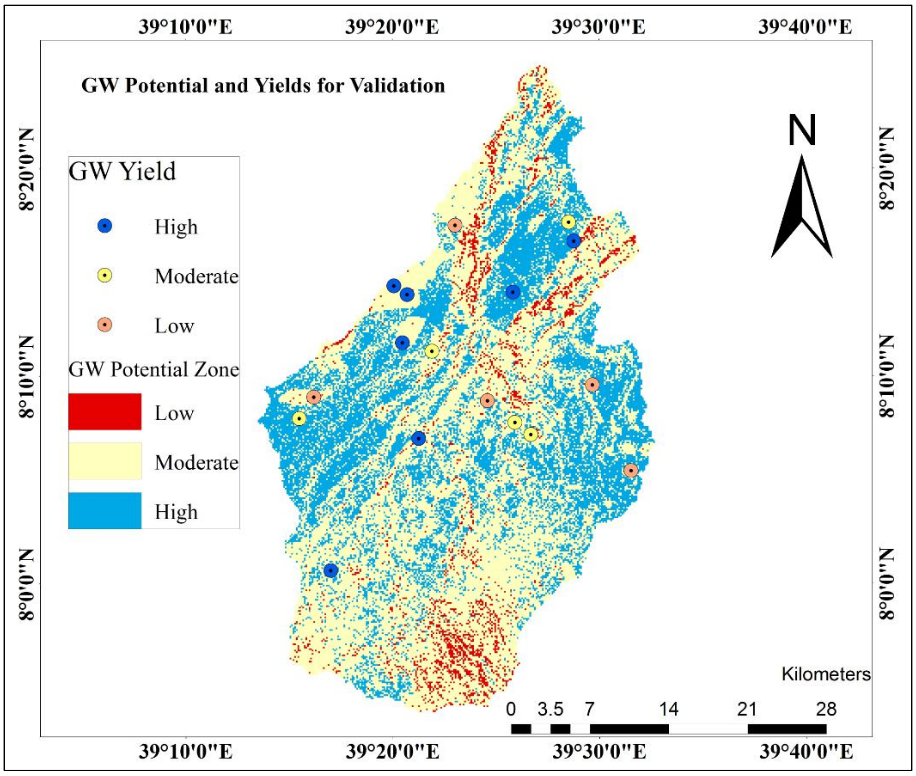


Figure 21. Groundwater potential and validation map

## 4.7 Potential land suitability zone map

The evaluation of potential site suitability is a crucial first step in the surface irrigation development process and should be assessed by considering different land suitability influencing factors. The physical characteristics of the land such as, land use/ cover and slope steepness, and the soil physical properties (types, depth, and drainage) were considered as the factor that influences land suitability for this study. After the identification, the thematic maps of each factor were prepared, and the influencing rates and consistency ratio were checked based on the Saaty scale and also the potential suitability level of each criterion was analyzed and discussed in section 4.3. According to Saaty (1980), the expert's consistency ratio was 0.084 in section 3.5, which is less than 0.1, and the weight assigned was valid for further study. Based on this valid CR, the weightage of each factor was determined (Table 16). Then, an integration of all criteria was done to determine the overall irrigable land suitability classes of the study area using the following equation:

$$PLSZ = 36.8\% * ST + 25\% * SL + 21.8\% * SDr + 10.4\% * SDe + 6\% * LULC \quad (4.2)$$

Where, PLSZ represents the Potential land suitability zone; ST represents Soil type map; SL represents Slope map; SDr represents Soil drainage map; SDe represents Soil depth map and LULC represents Land use/cover map.

The selected five parameters were most influential in determining land suitability for surface irrigation, however, soil type (36.8%), slope steepness (25%), and soil drainage (21.8%) were more influential than the rest. Because gravity is employed as a driving factor for surface irrigation, slope gradient can increase or decrease irrigation water flow velocity, causing soil erosion if it is not carefully designed during site suitability development. Soil type and drainage, on the other hand, are the major consideration because they have an impact on crop growth, irrigation water scheduling, and crop yield.

After identifying and analyzing each criterion, the weighted overlaying of the factors was done to get the overall suitability of land for surface irrigation using spatial analysis tool in Arc map. Thus, the overall suitability of the study area can be assigned into three different zones namely, Marginally suitable, Moderately suitable, and Highly suitable zones. The major portion of the study region is moderately suitable (68.94%), and 19.19% of the area is high and 11.87% of the area is marginally suitable for agricultural production through surface irrigation (Table 26 and Figure 22).

Table 26. An area of potential land suitability zone

| Rank (Index values) | Potential Land Suitability | Area ($Km^2$) | Area (%) |
|---|---|---|---|
| 2 | Marginally | 139.38 | 11.87 |
| 3 | Moderately | 809.37 | 68.94 |
| 4 | Highly | 225.25 | 19.19 |
| | Total | 1174.00 | 100.00 |

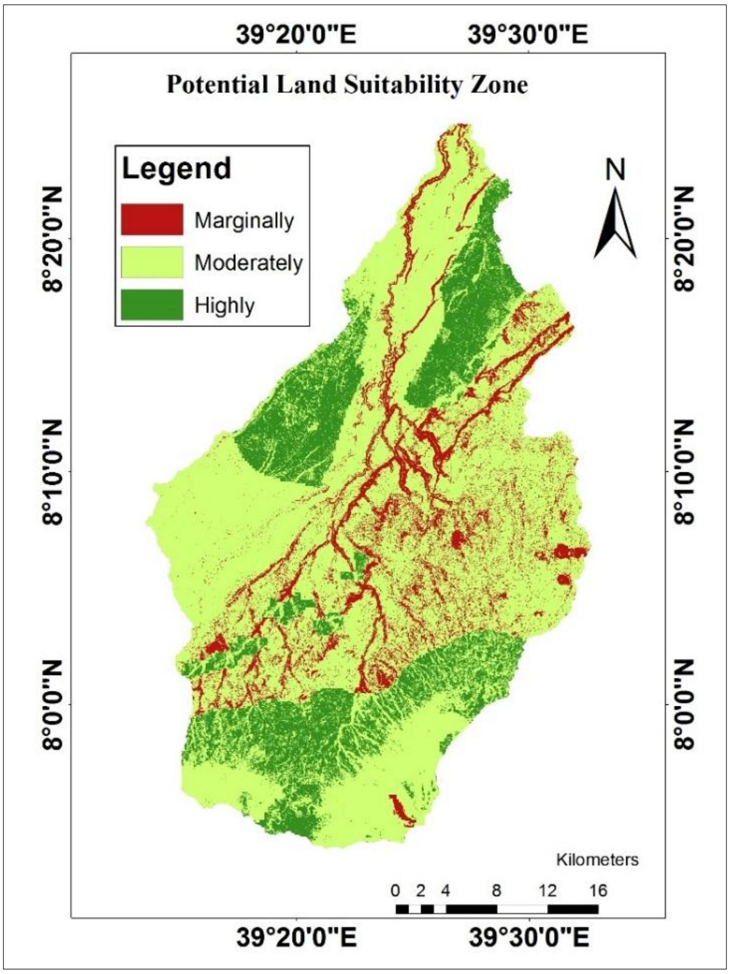


Figure 22. Potential land suitability zone map

The high agricultural land suitability class is concentrated in northwestern, northeastern and southern and also the small portion of the southwestern area (Figure 22). These areas are covered by highly drained and deep depth soil with medium-grained soil particles overlaid with nearly flat slopes and cultivated land. Scholars (Gonfa et al., 2021; Balew et al., 2021) reported that the high land suitability region was found in an area of cultivated land, deep depth soil, and highly drained soils. It is fact that the total available water in the root zone increase with an increase in the soil depth and medium-grained soil particle, and an area of nearly gentile slope should have highly suitable for irrigation water distribution, hence this area is highly suitable for arable land. This indicates, the area requires very less limitation of initial cost to develop and design the surface irrigation for agricultural production.

The moderate suitability class is distributed from the western to the eastern area, center to the northern part, and southern area to a low extent. This is due to an overlaid of the moderate slope, soil drainage and depth, and moderate to fine-grained soil size with small trees and rock-covered land. This indicates the moderate initial investment cost should be required to prepare the land for surface irrigation development. Marginally suitable areas are mainly distributed in the central part of the watershed. This class is located in a very steep slope, gorge areas, and poorly drained soil overlaid with shallow depth and fine-grained soil particles. Similarly, Shitu and Berhanu, (2020) reported that the marginally suitable zone was found in an area where the availability of high and poor drained soil, shallow depth soil, and the steep sloppy areas.

It is known that the fine soil particle requires the proper drainage system, a very steep slope should need land leveling and grading, and also the shallow depth soil affects the effective growing of crop root, hence the location of this area is marginally suitable for land suitability. Thus, it requires a high investment cost for surface irrigation development for agricultural crop production. Generally, the major portion of the study area is covered by a moderate land suitability class which will require moderate investment cost for surface irrigation development and only a small portion of the area will require very less investment cost because it is highly suitable for surface irrigation design.

Table 27. The factors suitability level to identify potential land suitability zone

| Criteria | Suitability Classes | | | |
|---|---|---|---|---|
| | 4 | 3 | 2 | 1 |
| Soil type | Luvisol/ Nitosol | Regosols/Leptosol | Andosol/Cambisol/ vertisol | - |
| Slope | 0 - 2% | 2 - 5% | 5 - 8% | >8% |
| Soil drainage | - | Moderately well | Imperfectly | Poor |
| Soil depth | >100cm | 50 - 100cm | 30 - 50cm | - |
| Land use/cover | Cultivated land | - | Forest/shrub/Afro-alpine with grass/ Shrub with exposed rock | Built-up land |

### 4.8 Sensitivity of factors influence GWP and irrigation land suitability

The map removing sensitivity analysis method was applied for this study using Equation 3.15 through removing each theme layer one by one for the testing output map. This indicates that the created output map was extremely sensitive to the theme layer with the greatest mean variation index. The statistics of variation index of map removal sensitivity analysis values were peresnted in Table 28.

Table 28. Statistics of the one-map removal sensitivity analysis for GW potential

| S.No. | Layer removed | Variation Index (%) | | | |
|---|---|---|---|---|---|
| | | Min | Max | Mean | SD |
| 1 | Lineament density | 0.12 | 3.59 | 0.75 | 1.52 |
| 2 | Slope | 0.68 | 8.40 | 1.89 | 3.56 |
| 3 | Drainage density | 0.00 | 2.76 | 0.66 | 1.17 |
| 4 | Landform | 1.23 | 7.80 | 1.46 | 3.37 |
| 5 | Rainfall | 0.01 | 4.03 | 1.03 | 1.39 |
| 6 | Lithology | 0.35 | 6.39 | 0.82 | 2.70 |
| 7 | Land use/cover | 0.92 | 1.61 | 0.09 | 0.68 |
| 8 | Soil type | 0.34 | 0.49 | 0.03 | 0.22 |

It shows the highest variation index, with a mean of 1.89%, was found in the removal of the slope layer to determine the output map of the GWP zone in the study area. Landform and rainfall were the second and third most prominent thematic layers, with 1.46% and 1.03%

of the variation index, respectively. This is essential due to the high theoretical weight assigned to these layers (Table 5). Land use/cover and soil, on the other hand, were the least variation index in determining this study's output map, accounting for 0.09% and 0.02%, respectively.

In addition, for the irrigation land suitability prospect map for the research region, slope was the top sensitive thematic layer (mean varation index of 1.58%), followed by soil depth and soil type, which accounted for 1.01% and 0.76% of the variation index, respectively. Land use/cover and soil drainage, on the other hand, were the least sensitive layers, accounting for 0.64% and 0.34% of the mean variation index, respectively (Table 29). Generally, these are relatively similar with theoretical weight assigned to the factors, which indicates the high variation indexes are identified for the higher theoretical weights were almost given and vice-versa for both studies.

Table 29. Statistics of the one-map removal sensitivity analysis for PL suitability

| S.No. | Layer removed | Variation Index (%) | | | |
|---|---|---|---|---|---|
| | | Min | Max | Mean | SD |
| 1 | Land use/cover | 0.07 | 1.72 | 0.64 | 0.76 |
| 2 | Slope | 0.76 | 3.13 | 1.58 | 0.32 |
| 3 | Soil type | 0.43 | 1.58 | 0.76 | 0.83 |
| 4 | Soil depth | 0.00 | 2.64 | 1.01 | 0.46 |
| 5 | Soil drainage | 0.18 | 2.17 | 0.34 | 0.25 |

### 4.9 Groundwater potential versus irrigation land suitability

The assessment of land suitability for surface irrigation development using groundwater potential through the spatial domain was the key study for this work. This study was conducted by identifying the various main parameters which influence the suitability for potentially irrigable land and groundwater potential, and finally, analyzed and weighted by suitability model in the spatial domain. Integration of all the thematic maps was carried out to get the suitability classes for both works, and which are classified and identified into the three suitability classes such as highly, moderately, and low (marginally) suitable. In both studies, the majority of a portion (722.165 $km^2$ for GWP and 809.37 $km^2$ for PLS) are covered by moderately suitable. The amount of high and low suitable classes are different when compared to each other (Table 30 and Figure 23).

Table 30. Suitability classes and their area coverage of GWP and PILS zone

| Rank (Index values) | Suitability Classes | GWP Area ($Km^2$) | PLS Area ($Km^2$) |
|---|---|---|---|
| 2 | Low (Marginally) | 59.18 | 139.38 |
| 3 | Moderately | 722.16 | 809.37 |
| 4 | Highly | 392.66 | 225.25 |
| | Total | 1174.00 | 1174.00 |

And also, the location of suitability classes for groundwater potential and irrigation land suitability zone of all sites are not founded in the same area in the study region (Figure 23). As presented in the figure, high groundwater potential is mainly distributed in the western, eastern, and northeastern parts, whereas high land suitability is located in southern, northeastern, and southwestern to a small extent. While moderate groundwater potential is highly distributed in southern, northwestern, and center to northeastern part, whereas moderate land suitability is a southern edge, southwestern to northern, and in the whole area to a small extent. And, low groundwater potential is located at southern, northern, and northeastern whereas marginal land suitability is highly distributed in the central part, and center to north part in small extent of the watershed.

Therefore, the northeastern and northwestern parts of the area having high suitabile land for surface irrigation also has high GWP in the same area. Hence, on-land surface irrigation development could be applied in this area with low investment on conveyance/distribution system. On the other hand, it can be possible to irrigate the crop in a moderately land-suitable area by pumping and distributing water from a high groundwater potential area where they aren't located in the same region. Generally, most areas of the watershed are covered by moderate to high GW potential and irrigation land suitability zone. Hence, this helps to produce the agricultural crop in the area using groundwater source irrigation as optional during the dry season without investing high initial cost.

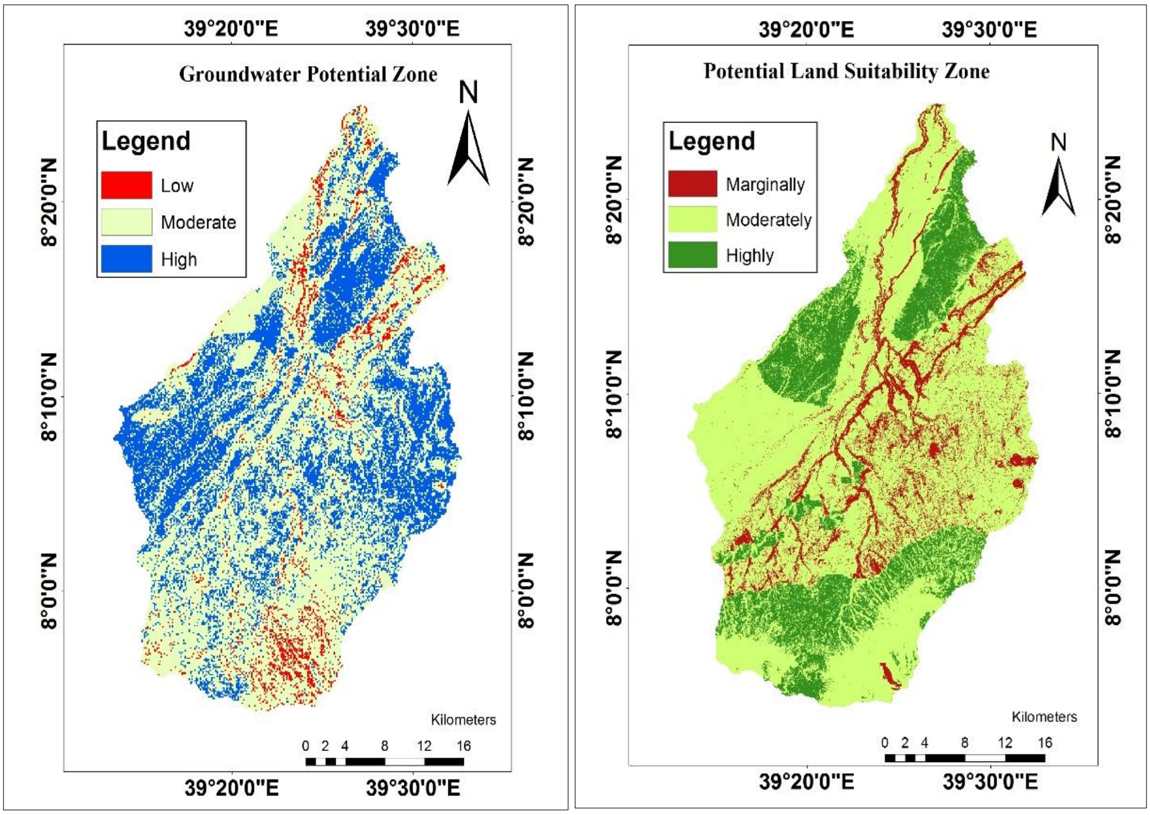


Figure 23. GWP zone and PILS zone map

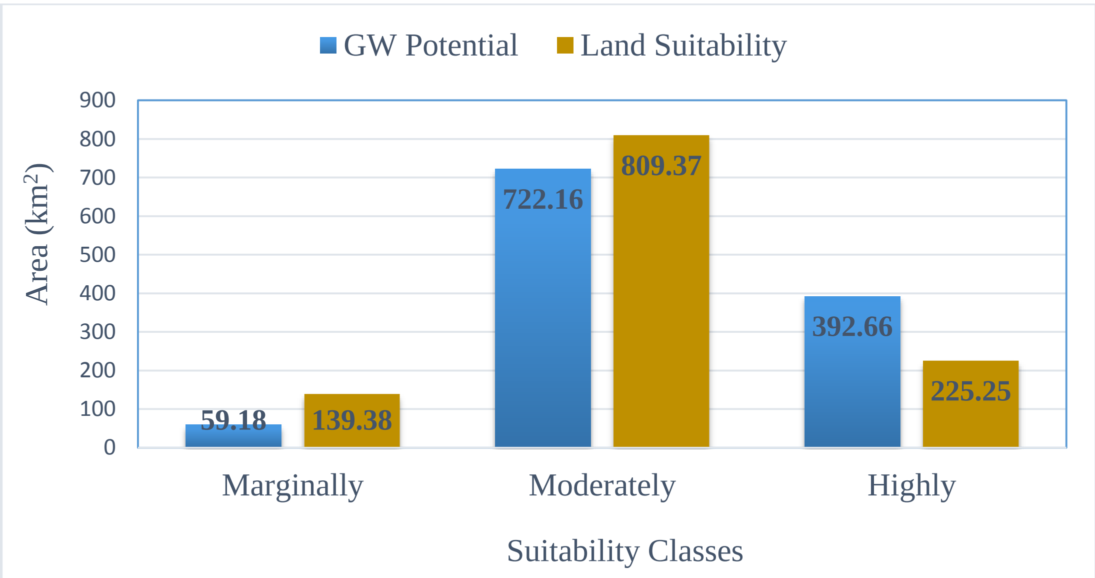


Figure 24. Area coverage for GWP and PLS zone

# 5. CONCLUSION AND RECOMMENDATION

## 5.1 Conclusion

GIS and remote sensing play an important role in the water resources development in the field of hydrogeology by providing and collecting different data. So that the present study has attempted to applied GIS-based multi-criteria analysis through the application of various spatial analysis tools to delineate potential groundwater and irrigation land suitability zone map of the Keleta watershed. The eight main influencing factors such as drainage density, land use/cover, soil, lineament density, landform, slope, lithology, and rainfall for groundwater potential and five main influencing factors such as land use/land cover, soil factors (types, depth, and drainage) and slope for irrigation land suitability were considered to generate the thematic maps. The FAHP method was adapted in a pair-wise comparison matrix to give the value of each factor based on their influences and the weighted comparison analysis was accepted after the consistency ratio was checked that was less than 0.1. The consistency ratio for the factors used to identify groundwater potential and irrigation land suitability zone in this study were 0.068 and 0.067, respectively.

For the study, landform, slope, lithology, and rainfall were highly influencing factors for groundwater potential zone whereas soil type, slope, and soil drainage were considered as the most influencing factors for irrigation land suitability zone. After overlaying these all factors, the result of the study revealed that the delineated zone was classified into three namely, low, moderate, and high suitable for groundwater potential and marginal, moderate, and high suitable for irrigation land suitability. The result indicates that from the total area, low suitable was 5.04%, moderately suitable was 61.51%, and highly suitable was 33.45% for GW potential, and marginally suitable was 11.87%, moderately suitable was 68.94%, and highly suitable was 19.19% for irrigation land suitability. Finally, groundwater potential was verified with the existing water invertory point data in which 88% were matched with its corresponding groundwater potential zones. The sensitivity analysis for both studies were done and hence, the slope was the top sensitive thematic layer for GW potential and irrigation land suitability which has the mean variation index of 1.89% and 1.58%, respectively followed by landform and rainfall for GWP and, soil depth and type for PLS.

High groundwater potential was found in western, eastern, and northeastern parts, this was because of the characterization by plain landform, nearly flat slope, low drainage density, and high faulting and fissure eruption of the lithological areas. High land suitability was located in southern, northeastern, northwestern and southwestern to a small extent due to medium soil particles, nealy flat slope, and moderately well-drained soil in the areas. In contrast, low groundwater potential was found in southern, northern, and northeastern parts, this was because of the steep slope, hill and volcanic landform, high drainage density, and low lineament density which contributes to high runoff and low infiltration rate. Whereas, marginal land suitability was mainly distributed in the center part and the small extent in the center to the northern part which coincides with fine soil particles, poor soil drainage, shallow depth soil, and steep slope areas.

This study was conducted that the identified groundwater potential was used for agricultural production through surface irrigation. The study has delineated areas that will allow the proper crops to be grown at the right location for the optimum yield and return on investment for the crop using groundwater potential through surface irrigation. In the northeast and northweast parts of the area, the high GWP and PLS were found in the same area, therefore on-land surface irrigation development will be used in this area with minimum cost of the conveyance or a distribution systems. It should be possible to irrigate a crop in a somewhat an appropriate location by pumping and distributing water from a highly favorable groundwater potential area that was used for not matching to each area through the conveyance and distributed system.

## 5.2 Recommendation

The following three points are recommended based on the this finding and the obstacles encountered during this work:

- Use the most recent conventional existing data with high resolution for groundwater potential mapping, and use field sampleed and laboratory tested soil data for each soil factor to delineate the irrigation land suitability map for the further study.
- It is recommended that use and drill wells in highly favorable groundwater potential area to irrigate the crop in the moderate to the high land suitable area through conveyance system for the unmatched area by considering initial investment cost.
- Soil and water conservation methods, as well as integrated watershed management should be used in area of low groundwater and marginal land suitable locations to promote groundwater recharge and agricultural land suitability.

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# APPENDICES

## Tables in the Appendix

Table A1: Description of Lithological group in the study area

| No. | Lithological group | Description |
|---|---|---|
| 1 | Bofa Basalts (Nb) | The rift floor basalts are locally vesicular and fresh with several flows separated by palaeosols and coriaceous horizons. Bofa Basalts are found in the small area of the upper part and form a wedge between the Nazareth group (Gedion, 2009). It consists of basalt lavas and basaltic pyroclastic and has Pliocene age. It has the deep nature of the vertical joints and most of the precipitation infiltrates into the groundwater, and generally, Bofa basalts are expected to have high to medium permeability (Seaton et al., 2014). |
| 2 | Nazareth Series (Nn) | The name of the Nazareth series was given mainly ignimbrites, rhyolites, and un-welded tuffs that cover the middle to the upper part of the watershed. It is thicker in the escarpment tends to thin out on the plateau margins and is affected by faulting. In the composition of the ignimbrites are sub-alkaline rhyolites and trachyte with rare per-alkaline varieties. This group has a late Miocene to Pliocene age and has high permeability due to high faulting. |
| 3 | Chilalo Formations (Nc) | This is the dominant lithology of the silicic group (rhyolite and trachytic volcanic group) and is found in the middle to lower part of the watershed. It has late Miocene to Pliocene age. |
| 4 | Holocene Sediments (Q) | Includes pediment or detritus deposits generally gravelly, mainly along the base of escarpment slopes and piedmonts. This sediment mainly consists of gravel and sand, and it is found in the upper edge of the study area. |
| 5 | Recent Basalts (Qb) | Basalts (typical pahoehoe), scoria cones, and hyaloclastite deposits covered in the western edge at the middle area of the watershed; partly make up the axial and marginal volcanic ranges. It has a Pleistocene to recent age. These units are the result of highly vesicular and fissure eruption. It can store a high quantity of groundwater and is considered to have high to moderate permeability. The basaltic lava flows are vesicular in texture and some of them are filled with secondary minerals (Haile et al., 2002). |

| No. | Lithological group | Description |
|---|---|---|
| 6 | Dino formation (Qd) | This group of lithology units is predominately ignimbrites, un-welded pyroclastic, water lain pyroclastic occasionally intercalated with aspheric basalts and lacustrine beds. Since the unit is very loose, the surface runoff has formed deep gullies all over the farmlands. Covers the western edge of the middle part of the study area and has Pleistocene age. |
| 7 | Volcanic Center (Quaternary Rhyolite Qr) | The major lithological group is known as silicic centers (rhyolites and trachytes) and is covered along the axial area of the middle part of the study area. This group is associated with ignimbrite, tuff, and rare coriaceous basalts and has Pleistocene age. |

Table A2: Description of Soil group in the study area

| No. | Soil group | Description |
|---|---|---|
| 1 | Vertisols | are churning heavy clay soils with a high proportion of swelling clays. These soils form deep wide cracks from the surface downward when they dry out and are imperfect to poorly drain (ISRIC, 2001). It has a uniform particle size distribution throughout the slum but the texture may changes sharply where the substratum is reached. The infiltration of water in dry (cracked) vertisols with surface mulch are initially rapid. However, once the surface soil is thoroughly wetted and cracks have closed, the rate of water infiltration becomes almost nil. And it has good water-holding properties and has low water percolation to groundwater. |
| 2 | Cambisols | are medium and fine-textured materials derived from a wide range of rocks, mostly alluvial deposits, and have high porosity, a good water holding capacity, and good internal drainage (ISRIC, 2014). It has loamy to clayey soil textural groups and contains at least some weather-able minerals in the silt and sand fractions. Changes in structure, color, clay concentration, or carbonate content indicate the beginnings of horizon differentiation in the subsurface. Cambisols are distinguished by the absence of significant amounts of alleviated clay and organic materials, as well as minor or moderate weathering of the parent material. |
| 3 | Nitisols | it accommodates deep, well-drained, tropical soils with diffuse horizon boundaries and moderate to strong angular blocky structure element and fair water-holding properties (Spaargaren, 2008). Nitisols are strong weathered soils and red or reddish-brown clayey soils. It is hard when dry, very friable to the firm when moist and sticky, and plastic when wet. It has relatively high contents of weathering minerals and surface soils may consist of several percent of organic matter. |

| No. | Soil group | Description |
|---|---|---|
| 4 | Luvisols | these soils have mixed mineralogy, high nutrient content, and good drainage of these soils make them suitable for a wide range of agriculture. Luvisols form on flat or gently sloping landscapes and are generally characterized by a surface accumulation of humus overlying an extensively leached layer that is nearly devoid of clay, has good permeability, and iron-bearing minerals (Young, 2016). It has deep in-depth and is generally well to moderately well-drained. Clay content differentiation (particularly clay migration) with a lower content in the topsoil and a higher content in the subsoil without significant base cation leaching or advanced weathering of high-activity clays. The majority of Luvisols are productive soils that can be used for a variety of agricultural purposes. |
| 5 | Regosols | are characterized by medium to fine-textured, unconsolidated parent material that may be of alluvial origin and by lack of significant soil layer. It has a low water-holding capacity their high permeability to water makes them sensitive to drought. Regosols is a deep, well-drained, non-differential mineral soil that has minimal expression of diagnostic horizons. Many regosols in colluvial materials are prone to slaking in particular those in the loss. This makes it sensitive to erosion in wet periods. It forms a hard surface crust early in the dry season; the crust hinders the emergences of seedling and infiltration of rain and irrigation water in the dry season. |
| 6 | Leptosols | are soils with a very shallow profile depth (indicating little influence of the soil-forming process), and they often contain large amounts of gravel (FAO, 2016). They typically remain under natural vegetation, being especially susceptible to erosion, desiccation, or waterlogging, depending on topography and distributed in high mountain areas. Terracing, or the manual removal of stones and their use as terrace fronts, can transform steep slopes with shallow and stony soils into cultivable land. Drought can occur even in humid environments due to high internal drainage and shallowness of many leptosols. |
| 7 | Andosols | these soils are highly porous, dark-colored soils developed from parent material of volcanic origin, such as volcanic ash, tuff, and pumice (FAO, 2016). Although the soils have excellent water holding and nutrient capacity. In general, its soil is formed from materials rich in volcanic glass and having dark surface horizons. Andosols are easy to grow, have strong portability, and can store a lot of water. It can support soils that form in volcanic ejecta or glasses in nearly any climate. Because of their low bearing capacity and stickiness, strongly hydrated Andosols are difficult to till. |

Table A3: Fifteen year mean monthly rainfall data for the Huruta weather station

| Year | Jan | Feb | Mar | Apr | May | Jun | Jul | Aug | Sep | Oct | Nov | Dec |
|---|---|---|---|---|---|---|---|---|---|---|---|---|
| 2005 | 52.1 | 0.0 | 154.0 | 167.4 | 130.0 | 138.0 | 144.8 | 119.4 | 94.9 | 29.7 | 18.0 | 0.0 |
| 2006 | 6.4 | 25.3 | 62.4 | 107.1 | 53.4 | 110.0 | 236.2 | 148.6 | 154.0 | 64.1 | 0.0 | 36.0 |
| 2007 | 25.3 | 26.9 | 77.5 | 87.4 | 66.0 | 84.6 | 137.2 | 184.9 | 408.0 | 26.1 | 11.7 | 0.0 |
| 2008 | 2.5 | 0.3 | 0.0 | 71.7 | 115.0 | 95.7 | 239.9 | 239.8 | 143.0 | 125.0 | 64.4 | 0.0 |
| 2009 | 38.5 | 0.0 | 22.7 | 71.0 | 22.2 | 21.1 | 170.2 | 186.9 | 45.8 | 69.0 | 1.0 | 9.1 |
| 2010 | 0.0 | 96.2 | 61.5 | 153.5 | 89.2 | 104.0 | 175.7 | 92.8 | 116.0 | 28.4 | 24.7 | 3.1 |
| 2011 | 8.5 | 9.1 | 76.5 | 14.8 | 95.6 | 119.0 | 135.4 | 132.1 | 174.0 | 4.4 | 32.1 | 0.0 |
| 2012 | 0.0 | 0.0 | 18.6 | 129.1 | 35.4 | 49.3 | 179.7 | 126.8 | 146.0 | 19.0 | 3.6 | 0.4 |
| 2013 | 15.5 | 0.0 | 47.6 | 82.3 | 113.0 | 97.7 | 198.0 | 130.6 | 92.3 | 47.3 | 22.8 | 0.0 |
| 2014 | 2.5 | 9.9 | 13.9 | 27.0 | 91.4 | 66.3 | 168.4 | 185.3 | 162.0 | 132.0 | 10.3 | 1.8 |
| 2015 | 1.1 | 0.0 | 5.1 | 3.3 | 201.0 | 93.6 | 118.1 | 191.9 | 129.0 | 3.1 | 21.9 | 2.8 |
| 2016 | 3.3 | 1.5 | 29.5 | 88.3 | 102.0 | 104.0 | 135.2 | 75.3 | 184.0 | 6.2 | 0.0 | 0.0 |
| 2017 | 0.0 | 21.0 | 4.5 | 10.0 | 148.0 | 8.5 | 71.0 | 128.4 | 186.0 | 1.4 | 0.0 | 0.0 |
| 2018 | 0.0 | 11.3 | 17.0 | 49.2 | 125.0 | 26.4 | 24.7 | 18.9 | 8.3 | 0.0 | 0.0 | 0.0 |
| 2019 | 0.0 | 16.1 | 10.8 | 29.6 | 8.6 | 17.5 | 47.9 | 73.6 | 97.1 | 0.7 | 0.0 | 0.0 |

Table A4: Fifteen year mean monthly rainfall data for the Kulumsa weather station

| Year | Jan | Feb | Mar | Apr | May | Jun | Jul | Aug | Sep | Oct | Nov | Dec |
|---|---|---|---|---|---|---|---|---|---|---|---|---|
| 2005 | 0.0 | 44.9 | 113 | 128.5 | 71.9 | 63.9 | 62.7 | 86.5 | 86.4 | 19.2 | 25.8 | 0.31 |
| 2006 | 4.7 | 20.2 | 79.4 | 131.4 | 65.9 | 80.6 | 161.6 | 99.7 | 86.2 | 62.1 | 2.0 | 6.5 |
| 2007 | 11.0 | 59.6 | 49.4 | 89.9 | 144.7 | 121.0 | 130.5 | 97.2 | 79.8 | 20.2 | 6.6 | 0.0 |
| 2008 | 0.5 | 2.3 | 1.4 | 41.5 | 81.1 | 44.3 | 160.6 | 228.5 | 101.6 | 77.8 | 65.6 | 0.0 |
| 2009 | 20.3 | 10.8 | 37.2 | 50.2 | 61.7 | 61.0 | 150.2 | 199.8 | 95.0 | 68.3 | 0.9 | 30.0 |
| 2010 | 4.5 | 127.0 | 96.7 | 107.2 | 93.5 | 116.0 | 148.2 | 82.0 | 123.5 | 3.3 | 3.5 | 4.5 |
| 2011 | 1.2 | 25.6 | 135.0 | 58.3 | 119.2 | 68.7 | 113.9 | 153.6 | 167.4 | 5.0 | 4.0 | 0.0 |
| 2012 | 1.4 | 2.5 | 24.9 | 101.3 | 72.7 | 78.2 | 188.3 | 184.3 | 272.1 | 3.8 | 4.0 | 13.3 |
| 2013 | 7.5 | 0.0 | 84.7 | 36.1 | 130.1 | 56.1 | 173.2 | 75.1 | 114.9 | 36.0 | 6.3 | 0.0 |
| 2014 | 2.6 | 29.7 | 66.0 | 65.5 | 110.7 | 43.8 | 40.8 | 127.8 | 159.7 | 215 | 1.5 | 0.0 |
| 2015 | 0.0 | 2.2 | 31.0 | 17.9 | 136.8 | 144.0 | 59.0 | 72.8 | 121.2 | 12.7 | 28.4 | 0.3 |
| 2016 | 20.4 | 1.9 | 40.2 | 250.1 | 125.8 | 123.0 | 136.3 | 55.5 | 102.9 | 26.4 | 12.2 | 0.0 |
| 2017 | 0.0 | 29.1 | 88.6 | 25.3 | 164.5 | 64.2 | 130.2 | 106.6 | 131.2 | 17.4 | 0.0 | 0.0 |
| 2018 | 10.2 | 15.5 | 64.4 | 137.7 | 145.2 | 125.0 | 120.6 | 192.2 | 72.3 | 15.8 | 22.9 | 0.6 |
| 2019 | 0.0 | 22.3 | 76.5 | 81.5 | 123.2 | 94.4 | 125.4 | 149.4 | 101.8 | 16.6 | 11.4 | 0.3 |

Table A5: Fifteen year mean monthly rainfall data for the Diksis weather station

| Year | Jan | Feb | Mar | Apr | May | Jun | Jul | Aug | Sep | Oct | Nov | Dec |
|---|---|---|---|---|---|---|---|---|---|---|---|---|
| 2005 | 4.08 | 43.7 | 88.7 | 153.0 | 28.5 | 39.2 | 185.8 | 215.3 | 74.6 | 6.8 | 3.9 | 20.2 |
| 2006 | 5.45 | 29.2 | 59.2 | 110.0 | 15.9 | 56.5 | 226.3 | 182.0 | 92.6 | 13.7 | 0.0 | 36.4 |
| 2007 | 2.7 | 58.3 | 118.0 | 195.0 | 41.2 | 21.8 | 145.3 | 248.5 | 56.5 | 0.0 | 7.8 | 3.9 |
| 2008 | 8.2 | 0.0 | 0.0 | 50.7 | 22.8 | 35.7 | 293.7 | 225.9 | 71.7 | 93.7 | 71.2 | 0.0 |
| 2009 | 64.0 | 0.0 | 42.7 | 5.5 | 19.5 | 147.0 | 80.9 | 170.8 | 40.9 | 67.7 | 0.0 | 17.6 |
| 2010 | 0.0 | 229.4 | 150.0 | 94.9 | 18.0 | 133.0 | 99.5 | 96.6 | 55.6 | 0.0 | 0.0 | 0.0 |
| 2011 | 0.0 | 5.5 | 5.6 | 9.8 | 27.5 | 73.6 | 92.2 | 146.8 | 190.0 | 0.0 | 46.0 | 1.9 |
| 2012 | 0.0 | 0.0 | 0.0 | 12.7 | 20.4 | 41.5 | 402.8 | 228.9 | 124.0 | 2.5 | 2.0 | 0.0 |
| 2013 | 5.2 | 0.0 | 99.0 | 40.3 | 23.5 | 58.1 | 396.7 | 179.4 | 122.0 | 18.7 | 11.3 | 0.0 |
| 2014 | 0.0 | 4.6 | 118.0 | 4.8 | 36.2 | 4.9 | 132.0 | 196.5 | 143.0 | 92.8 | 20.4 | 0.0 |
| 2015 | 0.0 | 0.0 | 1.2 | 1.7 | 117.2 | 183.0 | 78.3 | 155.1 | 83.1 | 6.5 | 26.8 | 9.9 |
| 2016 | 0.0 | 14.3 | 20.2 | 112.0 | 70.5 | 180.0 | 287.7 | 108.4 | 62.9 | 0.0 | 4.3 | 0.0 |
| 2017 | 0.0 | 14.8 | 59.4 | 87.4 | 67.6 | 19.9 | 319.9 | 193.1 | 110.0 | 2.0 | 4.3 | 0.0 |
| 2018 | 0.0 | 14.5 | 39.8 | 99.9 | 69.0 | 100.0 | 303.8 | 150.8 | 86.3 | 1.0 | 4.3 | 0.0 |
| 2019 | 0.0 | 0.0 | 44.8 | 93.6 | 68.3 | 60.0 | 311.9 | 171.9 | 98.0 | 1.5 | 4.3 | 0.0 |

Table A6: Fifteen year mean monthly rainfall data for the Sire weather station

| Year | Jan | Feb | Mar | Apr | May | Jun | Jul | Aug | Sep | Oct | Nov | Dec |
|---|---|---|---|---|---|---|---|---|---|---|---|---|
| 2005 | 1.6 | 6.7 | 49.0 | 124.9 | 13.0 | 26.7 | 114.5 | 81.1 | 40.5 | 19.2 | 10.5 | 0.1 |
| 2006 | 0.5 | 2.4 | 78.4 | 108.9 | 52.9 | 56.1 | 214.8 | 143.0 | 74.0 | 64.9 | 4.3 | 0.0 |
| 2007 | 0.0 | 0.1 | 54.4 | 92.9 | 87.5 | 56.5 | 173.8 | 141.4 | 86.1 | 41.5 | 3.7 | 0.0 |
| 2008 | 2.8 | 1.2 | 1.7 | 47.8 | 41.0 | 43.5 | 202.0 | 195.3 | 94.9 | 65.7 | 7.3 | 2.0 |
| 2009 | 0.0 | 5.2 | 31.7 | 69.3 | 21.0 | 47.0 | 172.0 | 129.9 | 98.1 | 108.5 | 7.8 | 4.4 |
| 2010 | 1.2 | 8.3 | 109.0 | 106.6 | 86.6 | 93.5 | 199.2 | 179.3 | 149.4 | 28.1 | 12.8 | 7.7 |
| 2011 | 0.0 | 3.5 | 31.1 | 55.9 | 77.8 | 49.1 | 97.7 | 74.8 | 40.7 | 20.9 | 1.8 | 0.0 |
| 2012 | 0.2 | 0.6 | 6.0 | 105.2 | 30.8 | 39.9 | 190.2 | 236.2 | 96.4 | 17.3 | 5.4 | 8.5 |
| 2013 | 0.7 | 1.1 | 53.6 | 123.9 | 56.9 | 75.7 | 236.0 | 192.3 | 84.5 | 57.2 | 10.7 | 1.7 |
| 2014 | 1.1 | 19.6 | 43.8 | 73.8 | 70.4 | 42.4 | 145.9 | 134.8 | 98.2 | 111.1 | 31.0 | 0.8 |
| 2015 | 0.8 | 18.7 | 3.1 | 8.6 | 155.0 | 213.4 | 80.1 | 146.8 | 90.4 | 41.1 | 0.2 | 0.0 |
| 2016 | 0.4 | 17.8 | 2.5 | 12.4 | 331.0 | 97.1 | 201.7 | 130.1 | 273.2 | 44.1 | 4.4 | 2.1 |
| 2017 | 0.0 | 0.0 | 0.0 | 34.4 | 207.0 | 43.3 | 237.5 | 504.7 | 456.1 | 47.2 | 8.5 | 4.3 |
| 2018 | 0.1 | 1.5 | 2.2 | 6.4 | 2.8 | 3.4 | 3.4 | 6.2 | 2.1 | 1.9 | 4.4 | 0.2 |
| 2019 | 0.0 | 0.3 | 1.7 | 3.0 | 1.8 | 3.4 | 3.0 | 7.6 | 7.0 | 2.9 | 0.0 | 0.0 |

Table A7: Fifteen year mean monthly rainfall data for the Dera weather station

| Year | Jan | Feb | Mar | Apr | May | Jun | Jul | Aug | Sep | Oct | Nov | Dec |
|---|---|---|---|---|---|---|---|---|---|---|---|---|
| 2005 | 9.2 | 6.5 | 48.8 | 103.9 | 118.2 | 30.9 | 134.7 | 95.2 | 46.3 | 20.3 | 6.7 | 0.0 |
| 2006 | 11.7 | 8.1 | 75.4 | 100.9 | 50.5 | 70.8 | 242.2 | 156.5 | 80.5 | 57.6 | 7.6 | 0.6 |
| 2007 | 9.2 | 0.8 | 56.3 | 81.3 | 89.6 | 68.3 | 191.9 | 159.8 | 100.3 | 34.1 | 25.9 | 0.0 |
| 2008 | 0.0 | 1.6 | 2.0 | 45.1 | 39.5 | 51.2 | 216.8 | 205.2 | 105.1 | 57.5 | 2.4 | 1.9 |
| 2009 | 1.9 | 3.6 | 29.3 | 58.7 | 23.3 | 50.7 | 177.8 | 142.5 | 99.2 | 99.3 | 5.9 | 8.0 |
| 2010 | 1.2 | 76.0 | 90.0 | 97.2 | 85.2 | 108.0 | 209.1 | 174.8 | 140.3 | 24.1 | 10.4 | 9.5 |
| 2011 | 3.2 | 4.7 | 33.1 | 48.1 | 78.3 | 62.2 | 106.0 | 84.2 | 48.7 | 16.9 | 34.5 | 0.9 |
| 2012 | 0.2 | 0.5 | 7.7 | 97.4 | 28.1 | 47.2 | 215.6 | 248.4 | 103.6 | 14.9 | 3.3 | 8.0 |
| 2013 | 5.2 | 1.2 | 54.6 | 117.5 | 67.9 | 98.4 | 238.8 | 188.7 | 92.0 | 58.7 | 7.8 | 0.0 |
| 2014 | 0.0 | 2.6 | 41.0 | 65.1 | 73.4 | 53.6 | 152.8 | 146.9 | 105.3 | 100.2 | 25.9 | 0.5 |
| 2015 | 0.0 | 4.5 | 15.4 | 19.7 | 104.0 | 128.0 | 95.3 | 160.2 | 66.5 | 37.2 | 5.5 | 6.5 |
| 2016 | 9.9 | 20.3 | 49.8 | 221.3 | 133.7 | 67.9 | 163.1 | 181.0 | 101.5 | 48.6 | 6.1 | 7.9 |
| 2017 | 0.0 | 8.9 | 61.8 | 45.7 | 153.3 | 70.5 | 174.3 | 188.3 | 210.7 | 54.5 | 31.8 | 3.2 |
| 2018 | 0.1 | 1.5 | 1.8 | 5.6 | 2.9 | 3.6 | 3.3 | 5.9 | 1.9 | 1.4 | 2.8 | 0.0 |
| 2019 | 0.0 | 0.3 | 1.6 | 2.9 | 1.7 | 3.9 | 3.4 | 7.2 | 6.9 | 2.5 | 1.9 | 1.5 |

Table A8: Mean monthly temperatures (15 years) for the five weather stations

| Station | T ($^{o}$C) | Jan | Feb | Mar | Apr | May | Jun | Jul | Aug | Sep | Oct | Nov | Dec |
|---|---|---|---|---|---|---|---|---|---|---|---|---|---|
| | $T_{max}$ | 25.4 | 24.7 | 29.0 | 27.8 | 28.2 | 27.3 | 26.0 | 25.5 | 25.0 | 26.1 | 24.6 | 25.0 |
| Huruta | $T_{min}$ | 9.7 | 9.9 | 12.8 | 13.8 | 14.7 | 14.3 | 13.8 | 13.9 | 13.2 | 12.4 | 10.3 | 9.0 |
| | $T_{mean}$ | 17.6 | 17.3 | 20.9 | 20.8 | 21.5 | 20.8 | 19.9 | 19.7 | 19.1 | 19.2 | 17.4 | 17.0 |
| | $T_{max}$ | 24.0 | 23.8 | 26.4 | 25.6 | 24.7 | 23.8 | 21.8 | 21.7 | 22.0 | 23.5 | 23.2 | 22.7 |
| Kulumsa | $T_{min}$ | 8.1 | 8.7 | 10.7 | 11.6 | 11.3 | 10.7 | 10.8 | 10.9 | 10.3 | 10.7 | 9.6 | 8.1 |
| | $T_{mean}$ | 16.1 | 16.2 | 18.5 | 18.6 | 18.0 | 17.3 | 16.3 | 16.3 | 16.1 | 17.1 | 16.4 | 15.4 |
| | $T_{max}$ | 24.5 | 23.8 | 26.5 | 26.2 | 26.0 | 25.2 | 23.8 | 23.6 | 23.5 | 24.5 | 23.6 | 23.1 |
| Sire | $T_{min}$ | 9.7 | 10.1 | 12.3 | 13.5 | 13.9 | 12.8 | 13.3 | 12.8 | 12.1 | 12.4 | 10.7 | 9.3 |
| | $T_{mean}$ | 17.1 | 17.0 | 19.4 | 19.8 | 19.9 | 19.0 | 18.5 | 18.2 | 17.8 | 18.4 | 17.1 | 16.2 |
| | $T_{max}$ | 26.1 | 27.5 | 27.9 | 26.2 | 26.4 | 26.8 | 24.6 | 23.9 | 24.1 | 24.1 | 24.1 | 24.6 |
| Diksis | $T_{min}$ | 11.1 | 12.6 | 14.0 | 14.7 | 14.9 | 14.7 | 14.3 | 13.9 | 13.8 | 12.8 | 11.5 | 10.4 |
| | $T_{mean}$ | 18.6 | 20.1 | 20.9 | 20.4 | 20.7 | 20.8 | 19.4 | 18.9 | 18.9 | 18.4 | 17.8 | 17.5 |
| | $T_{max}$ | 25.9 | 27.4 | 28.0 | 26.5 | 26.5 | 26.1 | 23.5 | 22.8 | 23.4 | 24.0 | 24.2 | 24.5 |
| Dera | $T_{min}$ | 10.2 | 11.9 | 13.4 | 14.3 | 14.8 | 14.6 | 14.0 | 13.7 | 13.5 | 11.8 | 10.5 | 9.4 |
| | $T_{mean}$ | 18.1 | 19.6 | 20.7 | 20.4 | 20.6 | 20.3 | 18.8 | 18.2 | 18.4 | 17.9 | 17.3 | 16.9 |

Table A9: FAHP value, assigned weights, $\lambda_{max}$ and their CR for GWP analysis

**1) Landform (Geomorphology) factor**

| LF | Plains | | | Valley fill | | | Hills | | | Curved ridges | | |
|---|---|---|---|---|---|---|---|---|---|---|---|---|
| Plains | 1 | 1 | 1 | 2 | 3 | 4 | 6 | 7 | 8 | 6 | 7 | 8 |
| Valley fill | 1/4 | 1/3 | 1/2 | 1 | 1 | 1 | 4 | 5 | 6 | 6 | 7 | 8 |
| Hills | 1/8 | 1/7 | 1/6 | 1/6 | 1/5 | 1/4 | 1 | 1 | 1 | 1 | 1 | 1 |
| C. Ridges | 1/8 | 1/7 | 1/6 | 1/8 | 1/7 | 1/6 | 1 | 1 | 1 | 1 | 1 | 1 |

| LF | $r_i$ | | | $w_i$ | | | $W_{avg}$ | $W_{nor}$ | $R_i$ | | | $W_i$ | | | $\lambda$ |
|---|---|---|---|---|---|---|---|---|---|---|---|---|---|---|---|
| Plains | 2.91 | 3.48 | 4.00 | 0.41 | 0.57 | 0.77 | 0.58 | 0.57 | 1.48 | 2.38 | 3.79 | 3.59 | 4.18 | 4.93 | 4.20 |
| Valley fill | 1.57 | 1.85 | 2.21 | 0.22 | 0.30 | 0.42 | 0.32 | 0.31 | 0.84 | 1.26 | 1.96 | 3.79 | 4.17 | 4.60 | 4.20 |
| Hills | 0.38 | 0.41 | 0.45 | 0.05 | 0.07 | 0.09 | 0.07 | 0.07 | 0.19 | 0.27 | 0.4 | 3.58 | 4.03 | 4.60 | 4.10 |
| Ridges | 0.35 | 0.38 | 0.41 | 0.05 | 0.06 | 0.08 | 0.06 | 0.06 | 0.18 | 0.25 | 0.36 | 3.66 | 4.10 | 4.64 | 4.10 |
| Sum | 5.21 | 6.12 | 7.07 | 0.74 | 1.00 | 1.36 | 1.03 | 1.00 | | Lambda max ($\lambda_{max}$) | | | | | 4.20 |
| | | | | | | | | | | Consistency Ratio (%) | | | | | 5.80 |

## 2) Slope factor

| SL (%) | 0 - 3 | | | 3 - 8 | | | 8 - 15 | | | 15 - 30 | | | >30 | | |
|---|---|---|---|---|---|---|---|---|---|---|---|---|---|---|---|
| 0 - 3 | 1 | 1 | 1 | 2 | 3 | 4 | 4 | 5 | 6 | 6 | 7 | 8 | 9 | 9 | 9 |
| 3 - 8 | 1/4 | 1/3 | 1/2 | 1 | 1 | 1 | 2 | 3 | 4 | 4 | 5 | 6 | 6 | 7 | 8 |
| 8 - 15 | 1/6 | 1/5 | 1/4 | 1/4 | 1/3 | 1/2 | 1 | 1 | 1 | 3 | 4 | 5 | 4 | 5 | 6 |
| 15 - 30 | 1/8 | 1/7 | 1/6 | 1/6 | 1/5 | 1/4 | 1/3 | 1/4 | 1/5 | 1 | 1 | 1 | 1 | 2 | 3 |
| > 30 | 1/9 | 1/9 | 1/9 | 1/8 | 1/7 | 1/6 | 1/6 | 1/5 | 1/4 | 1/3 | 1/2 | 1 | 1 | 1 | 1 |

| SL (%) | ri | | | wi | | | $W_{avg}$ | $W_{nor}$ | Ri | | | Wi | | | λ |
|---|---|---|---|---|---|---|---|---|---|---|---|---|---|---|---|
| 0 - 3 | 3.29 | 3.94 | 4.54 | 0.36 | 0.51 | 0.71 | 0.53 | 0.50 | 1.54 | 2.69 | 4.63 | 4.30 | 5.29 | 6.53 | 5.40 |
| 3 - 8 | 1.64 | 2.04 | 2.49 | 0.18 | 0.26 | 0.39 | 0.28 | 0.27 | 0.77 | 1.37 | 2.44 | 4.31 | 5.20 | 6.28 | 5.30 |
| 8 - 15 | 0.87 | 1.06 | 1.30 | 0.10 | 0.14 | 0.20 | 0.15 | 0.14 | 0.42 | 0.73 | 1.28 | 4.45 | 5.30 | 6.27 | 5.30 |
| 15 - 30 | 0.37 | 0.43 | 0.48 | 0.04 | 0.06 | 0.07 | 0.06 | 0.05 | 0.17 | 0.29 | 0.49 | 4.27 | 5.18 | 6.62 | 5.40 |
| > 30 | 0.23 | 0.28 | 0.35 | 0.03 | 0.04 | 0.05 | 0.04 | 0.04 | 0.11 | 0.18 | 0.33 | 4.44 | 5.19 | 6.11 | 5.20 |
| Sum | 6.41 | 7.73 | 9.16 | 0.70 | 1.00 | 1.43 | 1.04 | 1.00 | | Lambda max ($\lambda_{max}$) | | | | | 5.30 |
| | | | | | | | | | | Consistency Ratio (%) | | | | | 7.00 |

**3) Lithology (Geology) factor**

| LITH | Nb | | | Qb | | | Nn | | | Nc | | | Qd | | | Q | | | Ncb | | | Qr | | |
|---|---|---|---|---|---|---|---|---|---|---|---|---|---|---|---|---|---|---|---|---|---|---|---|---|
| Nb | 1 | 1 | 1 | 1 | 2 | 3 | 1 | 2 | 3 | 2 | 3 | 4 | 2 | 3 | 4 | 2 | 3 | 4 | 2 | 3 | 4 | 3 | 4 | 5 |
| Qb | 1/3 | 1/2 | 1 | 1 | 1 | 1 | 1 | 2 | 3 | 2 | 3 | 4 | 1 | 1 | 1 | 2 | 3 | 4 | 1 | 2 | 3 | 3 | 4 | 5 |
| Nn | 1/3 | 1/2 | 1 | 1/3 | 1/2 | 1 | 1 | 1 | 1 | 1 | 2 | 3 | 1 | 2 | 3 | 2 | 3 | 4 | 2 | 3 | 4 | 2 | 3 | 4 |
| Nc | 1/4 | 1/3 | 1/2 | 1/4 | 1/3 | 1/2 | 1 | 1/2 | 1/3 | 1 | 1 | 1 | 2 | 3 | 4 | 1 | 1 | 1 | 1 | 2 | 3 | 2 | 3 | 4 |
| Qd | 1/4 | 1/3 | 1/2 | 1 | 1 | 1 | 1/3 | 1/2 | 1 | 1/4 | 1/3 | 1/2 | 1 | 1 | 1 | 1 | 1 | 1 | 1 | 2 | 3 | 2 | 3 | 4 |
| Q | 1/4 | 1/3 | 1/2 | 1/4 | 1/3 | 1/2 | 1/4 | 1/3 | 1/2 | 1 | 1 | 1 | 1 | 1 | 1 | 1 | 1 | 1 | 1 | 2 | 3 | 1 | 2 | 3 |
| Ncb | 1/4 | 1/3 | 1/2 | 1/3 | 1/2 | 1 | 1/4 | 1/3 | 1/2 | 1/3 | 1/2 | 1 | 1/3 | 1/2 | 1 | 1/3 | 1/2 | 1 | 1 | 1 | 1 | 1 | 1 | 1 |
| Qr | 1/5 | 1/4 | 1/3 | 1/5 | 1/4 | 1/2 | 1/4 | 1/3 | 1/2 | 1/4 | 1/3 | 1/2 | 1/4 | 1/3 | 1/2 | 1/3 | 1/2 | 1 | 1 | 1 | 1 | 1 | 1 | 1 |

| LITH | | $r_i$ | | | $w_i$ | | $W_{avg}$ | $W_{nor}$ | | $R_i$ | | | $W_i$ | | $\lambda$ |
|---|---|---|---|---|---|---|---|---|---|---|---|---|---|---|---|
| Nb | 1.62 | 2.45 | 3.22 | 0.13 | 0.26 | 0.48 | 0.29 | 0.26 | 0.79 | 2.17 | 5.49 | 6.08 | 8.24 | 11.35 | 8.60 |
| Qb | 1.19 | 1.71 | 2.28 | 0.10 | 0.18 | 0.34 | 0.21 | 0.18 | 0.62 | 1.61 | 4.16 | 6.48 | 8.78 | 12.17 | 9.10 |
| Nn | 0.99 | 1.51 | 2.21 | 0.08 | 0.16 | 0.33 | 0.19 | 0.17 | 0.49 | 1.36 | 3.69 | 6.23 | 8.34 | 11.12 | 8.60 |
| Nc | 0.84 | 1.00 | 1.19 | 0.07 | 0.11 | 0.18 | 0.12 | 0.10 | 0.44 | 0.96 | 2.29 | 6.62 | 8.91 | 12.84 | 9.50 |
| Qd | 0.67 | 0.87 | 1.15 | 0.05 | 0.09 | 0.17 | 0.11 | 0.09 | 0.36 | 0.82 | 2.08 | 6.70 | 8.76 | 12.07 | 9.20 |
| Q | 0.59 | 0.79 | 1.01 | 0.05 | 0.08 | 0.15 | 0.09 | 0.08 | 0.30 | 0.70 | 1.74 | 6.41 | 8.23 | 11.41 | 8.70 |
| Ncb | 0.41 | 0.54 | 0.84 | 0.03 | 0.06 | 0.13 | 0.07 | 0.06 | 0.20 | 0.48 | 1.47 | 6.14 | 8.32 | 11.65 | 8.70 |
| Qr | 0.35 | 0.43 | 0.62 | 0.03 | 0.05 | 0.09 | 0.06 | 0.05 | 0.17 | 0.38 | 1.04 | 6.17 | 8.21 | 11.29 | 8.60 |
| Sum | 6.66 | 9.29 | 12.5 | 0.53 | 1.00 | 1.88 | 1.14 | 1.00 | | Lambda max ($\lambda_{max}$) | | | | | 8.90 |
| | | | | | | | | | | Consistency Ratio (%) | | | | | 8.70 |

**4) Lineament density factor**

| LD (km/km$^2$) | 0.99-1.8 | | | 0.65-0.98 | | | 0.37-0.64 | | | 0.13-0.36 | | | 0-0.12 | | |
|---|---|---|---|---|---|---|---|---|---|---|---|---|---|---|---|
| 0.99-1.80 | 1 | 1 | 1 | 3 | 4 | 5 | 4 | 5 | 6 | 6 | 7 | 8 | 7 | 8 | 9 |
| 0.65-0.98 | 1/5 | 1/4 | 1/3 | 1 | 1 | 1 | 1 | 2 | 3 | 4 | 5 | 6 | 6 | 7 | 8 |
| 0.37-0.64 | 1/6 | 1/5 | 1/4 | 1/3 | 1/2 | 1 | 1 | 1 | 1 | 2 | 3 | 4 | 4 | 5 | 6 |
| 0.13-0.36 | 1/8 | 1/7 | 1/6 | 1/6 | 1/5 | 1/4 | 1/2 | 1/3 | 1/4 | 1 | 1 | 1 | 2 | 3 | 4 |
| 0-0.12 | 1/9 | 1/8 | 1/7 | 1/8 | 1/7 | 1/6 | 1/6 | 1/5 | 1/4 | 1/4 | 1/3 | 1/2 | 1 | 1 | 1 |

| LD (km/km$^2$) | $r_i$ | | | $w_i$ | | | $W_{avg}$ | $W_{nor}$ | $R_i$ | | | $W_i$ | | | $\lambda$ |
|---|---|---|---|---|---|---|---|---|---|---|---|---|---|---|---|
| 0.99-1.80 | 3.47 | 4.07 | 4.64 | 0.38 | 0.53 | 0.73 | 0.55 | 0.52 | 1.69 | 2.88 | 4.88 | 4.41 | 5.43 | 6.70 | 5.50 |
| 0.65-0.98 | 1.37 | 1.77 | 2.17 | 0.15 | 0.23 | 0.34 | 0.24 | 0.23 | 0.67 | 1.20 | 2.15 | 4.46 | 5.21 | 6.31 | 5.30 |
| 0.37-0.64 | 0.85 | 1.08 | 1.43 | 0.09 | 0.14 | 0.22 | 0.15 | 0.15 | 0.41 | 0.72 | 1.37 | 4.36 | 5.13 | 6.12 | 5.20 |
| 0.13-0.36 | 0.46 | 0.49 | 0.53 | 0.05 | 0.06 | 0.08 | 0.07 | 0.06 | 0.22 | 0.33 | 0.54 | 4.33 | 5.23 | 6.52 | 5.40 |
| 0-0.12 | 0.23 | 0.26 | 0.31 | 0.02 | 0.03 | 0.05 | 0.04 | 0.03 | 0.11 | 0.18 | 0.31 | 4.61 | 5.39 | 6.27 | 5.40 |
| Sum | 6.38 | 7.68 | 9.09 | 0.70 | 1.00 | 1.42 | 1.04 | 1.00 | | Lambda max ($\lambda_{max}$) | | | | | 5.40 |
| | | | | | | | | | | Consistency Ratio (%) | | | | | 8.20 |

## 5) Rainfall factor

| RF (mm) | 988-1020 | | | 956-987 | | | 924-955 | | | 891-923 | | |
|---|---|---|---|---|---|---|---|---|---|---|---|---|
| 988-1020 | 1 | 1 | 1 | 1 | 2 | 3 | 2 | 3 | 4 | 4 | 5 | 6 |
| 956-987 | 1/3 | 1/2 | 1 | 1 | 1 | 1 | 1 | 2 | 3 | 2 | 3 | 4 |
| 924-955 | 1/4 | 1/3 | 1/2 | 1/3 | 1/2 | 1 | 1 | 1 | 1 | 2 | 3 | 4 |
| 891-923 | 1/6 | 1/5 | 1/4 | 1/4 | 1/3 | 1/2 | 1/2 | 1/3 | 1/4 | 1 | 1 | 1 |

| RF (mm) | ri | | | wi | | | $W_{avg}$ | $W_{nor}$ | Ri | | | Wi | | | λ |
|---|---|---|---|---|---|---|---|---|---|---|---|---|---|---|---|
| 988-1020 | 1.68 | 2.34 | 2.91 | 0.26 | 0.48 | 0.81 | 0.52 | 0.46 | 0.84 | 1.93 | 4.38 | 3.20 | 4.03 | 5.42 | 4.20 |
| 956-987 | 0.90 | 1.32 | 1.86 | 0.14 | 0.27 | 0.52 | 0.31 | 0.28 | 0.45 | 1.09 | 2.78 | 3.17 | 4.05 | 5.39 | 4.20 |
| 924-955 | 0.64 | 0.84 | 1.19 | 0.10 | 0.17 | 0.33 | 0.20 | 0.18 | 0.33 | 0.70 | 1.72 | 3.32 | 4.09 | 5.20 | 4.20 |
| 891-923 | 0.38 | 0.39 | 0.42 | 0.06 | 0.08 | 0.12 | 0.09 | 0.08 | 0.19 | 0.32 | 0.66 | 3.17 | 4.07 | 5.65 | 4.30 |
| Sum | 3.60 | 4.88 | 6.38 | 0.56 | 1.00 | 1.77 | 1.11 | 1.00 | | Lambda max ($\lambda_{max}$) | | | | | 4.20 |
| | | | | | | | | | | Consistency Ratio (%) | | | | | 8.50 |

### 6) Drainage density factor

| DD (km/km$^2$) | 0-12 | | | 12-31 | | | 31-55 | | | 55-85 | | | 85-168 | | |
|---|---|---|---|---|---|---|---|---|---|---|---|---|---|---|---|
| 0-12 | 1 | 1 | 1 | 2 | 3 | 4 | 4 | 5 | 6 | 6 | 7 | 8 | 9 | 9 | 9 |
| 12-31 | 1/4 | 1/3 | 1/2 | 1 | 1 | 1 | 3 | 4 | 5 | 4 | 5 | 6 | 6 | 7 | 8 |
| 31-55 | 1/6 | 1/5 | 1/4 | 1/5 | 1/4 | 1/3 | 1 | 1 | 1 | 2 | 3 | 4 | 4 | 5 | 6 |
| 55-85 | 1/8 | 1/7 | 1/6 | 1/6 | 1/5 | 1/4 | 1/2 | 1/3 | 1/4 | 1 | 1 | 1 | 2 | 3 | 4 |
| 85-168 | 1/9 | 1/9 | 1/9 | 1/8 | 1/7 | 1/6 | 1/6 | 1/5 | 1/4 | 1/4 | 1/3 | 1/2 | 1 | 1 | 1 |

| DD (km/km$^2$) | $r_i$ | | | $w_i$ | | | $W_{avg}$ | $W_{nor}$ | $R_i$ | | | $W_i$ | | | $\lambda$ |
|---|---|---|---|---|---|---|---|---|---|---|---|---|---|---|---|
| 0-12 | 3.37 | 3.94 | 4.44 | 0.37 | 0.51 | 0.67 | 0.52 | 0.50 | 1.64 | 2.68 | 4.34 | 4.40 | 5.30 | 6.45 | 5.40 |
| 12-31 | 1.78 | 2.16 | 2.61 | 0.20 | 0.28 | 0.39 | 0.29 | 0.28 | 0.90 | 1.48 | 2.44 | 4.56 | 5.32 | 6.19 | 5.40 |
| 31-55 | 0.77 | 0.94 | 1.15 | 0.09 | 0.12 | 0.17 | 0.13 | 0.12 | 0.39 | 0.64 | 1.06 | 4.57 | 5.31 | 6.12 | 5.30 |
| 55-85 | 0.46 | 0.49 | 0.53 | 0.05 | 0.06 | 0.08 | 0.06 | 0.06 | 0.22 | 0.33 | 0.51 | 4.37 | 5.22 | 6.41 | 5.30 |
| 85-168 | 0.23 | 0.25 | 0.30 | 0.02 | 0.03 | 0.04 | 0.03 | 0.03 | 0.12 | 0.17 | 0.27 | 4.73 | 5.32 | 5.98 | 5.30 |
| Sum | 6.60 | 7.78 | 9.02 | 0.73 | 1.00 | 1.37 | 1.03 | 1.00 | | Lambda max ($\lambda_{max}$) | | | | | 5.30 |
| | | | | | | | | | | Consistency Ratio (%) | | | | | 7.80 |

## 7) Soil type factor

| SOIL | Re | | | Lv | | | Nt | | | Lp | | | An | | | Cm | | | Vr | | |
|---|---|---|---|---|---|---|---|---|---|---|---|---|---|---|---|---|---|---|---|---|---|
| Re | 1 | 1 | 1 | 1 | 2 | 3 | 1 | 2 | 3 | 2 | 3 | 4 | 2 | 3 | 4 | 3 | 4 | 5 | 4 | 5 | 6 |
| Lv | 1/3 | 1/2 | 1 | 1 | 1 | 1 | 1 | 2 | 3 | 2 | 3 | 4 | 3 | 4 | 5 | 3 | 4 | 5 | 4 | 5 | 6 |
| Nt | 1/3 | 1/2 | 1 | 1/3 | 1/2 | 1 | 1 | 1 | 1 | 1 | 2 | 3 | 3 | 4 | 5 | 2 | 3 | 4 | 3 | 4 | 5 |
| Lp | 1/4 | 1/3 | 1/2 | 1/4 | 1/3 | 1/2 | 1 | 1/2 | 1/3 | 1 | 1 | 1 | 2 | 3 | 4 | 2 | 3 | 4 | 3 | 4 | 5 |
| An | 1/4 | 1/3 | 1/2 | 1/5 | 1/4 | 1/3 | 1/5 | 1/4 | 1/3 | 1/4 | 1/3 | 1/2 | 1 | 1 | 1 | 2 | 3 | 4 | 2 | 3 | 4 |
| Cm | 1/5 | 1/4 | 1/3 | 1/5 | 1/4 | 1/3 | 1/4 | 1/3 | 1/2 | 1/4 | 1/3 | 1/2 | 1/4 | 1/3 | 1/2 | 1 | 1 | 1 | 1 | 2 | 3 |
| Vr | 1/6 | 1/5 | 1/4 | 1/6 | 1/5 | 1/4 | 1/5 | 1/4 | 1/3 | 1/5 | 1/4 | 1/3 | 1/4 | 1/3 | 1/2 | 1/3 | 1/2 | 1 | 1 | 1 | 1 |

| SOIL | $r_i$ | | | $w_i$ | | | $W_{avg}$ | $W_{nor}$ | $R_i$ | | | $W_i$ | | | $\lambda$ |
|---|---|---|---|---|---|---|---|---|---|---|---|---|---|---|---|
| Re | 1.74 | 2.56 | 3.31 | 0.15 | 0.29 | 0.51 | 0.31 | 0.28 | 0.81 | 2.13 | 5.15 | 5.45 | 7.39 | 10.1 | 7.70 |
| Lv | 1.57 | 2.19 | 2.92 | 0.13 | 0.25 | 0.45 | 0.27 | 0.25 | 0.75 | 1.81 | 4.39 | 5.61 | 7.37 | 9.78 | 7.60 |
| Nt | 1.10 | 1.57 | 2.26 | 0.09 | 0.18 | 0.35 | 0.20 | 0.18 | 0.53 | 1.30 | 3.32 | 5.63 | 7.34 | 9.58 | 7.50 |
| Lp | 0.96 | 1.10 | 1.31 | 0.08 | 0.12 | 0.20 | 0.14 | 0.12 | 0.46 | 0.92 | 2.07 | 5.65 | 7.43 | 10.3 | 7.80 |
| An | 0.52 | 0.67 | 0.89 | 0.04 | 0.08 | 0.14 | 0.09 | 0.08 | 0.25 | 0.59 | 1.42 | 5.71 | 7.75 | 10.4 | 7.90 |
| Cm | 0.35 | 0.46 | 0.64 | 0.03 | 0.05 | 0.10 | 0.06 | 0.05 | 0.16 | 0.39 | 0.96 | 5.51 | 7.39 | 9.88 | 7.60 |
| Vr | 0.27 | 0.33 | 0.45 | 0.02 | 0.04 | 0.07 | 0.04 | 0.04 | 0.13 | 0.27 | 0.66 | 5.56 | 7.31 | 9.59 | 7.50 |
| Sum | 6.51 | 8.89 | 11.8 | 0.55 | 1.00 | 1.81 | 1.12 | 1.00 | | Lambda max ($\lambda_{max}$) | | | | | 7.70 |
| | | | | | | | | | | Consistency Ratio (%) | | | | | 8.30 |

**8) Land use land cover factor**

| LULC | CL | | | FR | | | SHR | | | AFR-G | | | SH-R | | | BL | | |
|---|---|---|---|---|---|---|---|---|---|---|---|---|---|---|---|---|---|---|
| CL | 1 | 1 | 1 | 1 | 2 | 3 | 2 | 3 | 4 | 2 | 3 | 4 | 4 | 5 | 6 | 4 | 5 | 6 |
| FR | 1/3 | 1/2 | 1 | 1 | 1 | 1 | 1 | 2 | 3 | 2 | 3 | 4 | 4 | 5 | 6 | 4 | 5 | 6 |
| SHR | 1/4 | 1/3 | 1/2 | 1/3 | 1/2 | 1 | 1 | 1 | 1 | 2 | 3 | 4 | 3 | 4 | 5 | 4 | 5 | 6 |
| AFR-G | 1/4 | 1/3 | 1/2 | 1/4 | 1/3 | 1/2 | 1/2 | 1/3 | 1/4 | 1 | 1 | 1 | 2 | 3 | 4 | 1 | 2 | 3 |
| SH-R | 1/6 | 1/5 | 1/4 | 1/6 | 1/5 | 1/4 | 1/5 | 1/4 | 1/3 | 1/4 | 1/3 | 1/2 | 1 | 1 | 1 | 1/3 | 1/2 | 1 |
| BL | 1/6 | 1/5 | 1/4 | 1/6 | 1/5 | 1/4 | 1/6 | 1/5 | 1/4 | 1/3 | 1/2 | 1 | 1 | 2 | 3 | 1 | 1 | 1 |

| LULC | | $r_i$ | | | $w_i$ | | $W_{avg}$ | $W_{nor}$ | | $R_i$ | | | $W_i$ | | $\lambda$ |
|---|---|---|---|---|---|---|---|---|---|---|---|---|---|---|---|
| CL | 2.00 | 2.77 | 3.46 | 0.2 | 0.35 | 0.59 | 0.38 | 0.34 | 0.93 | 2.28 | 5.10 | 4.73 | 6.47 | 8.62 | 6.60 |
| FR | 1.48 | 2.05 | 2.75 | 0.15 | 0.26 | 0.47 | 0.29 | 0.26 | 0.69 | 1.66 | 3.82 | 4.72 | 6.34 | 8.14 | 6.40 |
| SHR | 1.12 | 1.47 | 1.98 | 0.11 | 0.19 | 0.34 | 0.21 | 0.19 | 0.55 | 1.24 | 2.77 | 4.96 | 6.62 | 8.19 | 6.60 |
| AFR-G | 0.63 | 0.78 | 0.95 | 0.06 | 0.10 | 0.16 | 0.11 | 0.10 | 0.29 | 0.65 | 1.41 | 4.70 | 6.61 | 8.63 | 6.60 |
| SH-R | 0.28 | 0.34 | 0.47 | 0.03 | 0.04 | 0.08 | 0.05 | 0.06 | 0.13 | 0.27 | 0.64 | 4.87 | 6.27 | 8.04 | 6.40 |
| BL | 0.34 | 0.45 | 0.6 | 0.03 | 0.06 | 0.10 | 0.06 | 0.05 | 0.16 | 0.40 | 0.85 | 4.69 | 6.99 | 8.33 | 6.70 |
| Sum | 5.85 | 7.86 | 10.2 | 0.57 | 1.00 | 1.74 | 1.11 | 1.00 | | Lambda max ($\lambda_{max}$) | | | | | 6.60 |
| | | | | | | | | | | Consistency Ratio (%) | | | | | 8.90 |

Table A10: FAHP value, assigned weights, $\lambda_{max}$ and their CR for PILS analysis

**1) Soil type factor**

| ST | Lv | | | Nt | | | Re | | | Lp | | | An | | | Cm | | | Vr | | |
|---|---|---|---|---|---|---|---|---|---|---|---|---|---|---|---|---|---|---|---|---|---|
| Lv | 1 | 1 | 1 | 2 | 3 | 4 | 3 | 4 | 5 | 3 | 4 | 5 | 3 | 4 | 5 | 4 | 5 | 6 | 4 | 5 | 6 |
| Nt | 1/4 | 1/3 | 1/2 | 1 | 1 | 1 | 2 | 3 | 4 | 2 | 3 | 4 | 3 | 4 | 5 | 3 | 4 | 5 | 4 | 5 | 6 |
| Re | 1/5 | 1/4 | 1/3 | 1/4 | 1/3 | 1/2 | 1 | 1 | 1 | 1 | 2 | 3 | 2 | 3 | 4 | 3 | 4 | 5 | 3 | 4 | 5 |
| Lp | 1/5 | 1/4 | 1/3 | 1/4 | 1/3 | 1/2 | 1 | 1/2 | 1/3 | 1 | 1 | 1 | 2 | 3 | 4 | 2 | 3 | 4 | 3 | 4 | 5 |
| An | 1/5 | 1/4 | 1/3 | 1/5 | 1/4 | 1/3 | 1/4 | 1/3 | 1/2 | 1/4 | 1/3 | 1/2 | 1 | 1 | 1 | 1 | 2 | 3 | 1 | 2 | 3 |
| Cm | 1/6 | 1/5 | 1/4 | 1/5 | 1/4 | 1/3 | 1/5 | 1/4 | 1/3 | 1/4 | 1/3 | 1/2 | 1/3 | 1/2 | 1 | 1 | 1 | 1 | 1 | 1 | 1 |
| Vr | 1/6 | 1/5 | 1/4 | 1/6 | 1/5 | 1/4 | 1/5 | 1/4 | 1/3 | 1/5 | 1/4 | 1/3 | 1/3 | 1/2 | 1 | 1 | 1 | 1 | 1 | 1 | 1 |

| ST | $r_i$ | | | $w_i$ | | | $W_{avg}$ | $W_{nor}$ | $R_i$ | | | $W_i$ | | | $\lambda$ |
|---|---|---|---|---|---|---|---|---|---|---|---|---|---|---|---|
| Lv | 2.63 | 3.36 | 4.05 | 0.24 | 0.37 | 0.58 | 0.40 | 0.37 | 1.40 | 2.89 | 5.78 | 5.96 | 7.73 | 9.94 | 7.90 |
| Nt | 1.67 | 2.19 | 2.75 | 0.15 | 0.24 | 0.39 | 0.26 | 0.24 | 0.87 | 1.84 | 3.80 | 5.84 | 7.54 | 9.62 | 7.70 |
| Re | 0.99 | 1.35 | 1.75 | 0.09 | 0.15 | 0.25 | 0.16 | 0.15 | 0.51 | 1.12 | 2.39 | 5.79 | 7.45 | 9.52 | 7.60 |
| Lp | 0.93 | 1.06 | 1.24 | 0.08 | 0.12 | 0.18 | 0.13 | 0.12 | 0.48 | 0.88 | 1.79 | 5.77 | 7.44 | 10.1 | 7.80 |
| An | 0.42 | 0.60 | 0.82 | 0.04 | 0.07 | 0.12 | 0.07 | 0.07 | 0.22 | 0.49 | 1.10 | 5.72 | 7.32 | 9.37 | 7.50 |
| Cm | 0.34 | 0.41 | 0.54 | 0.03 | 0.05 | 0.08 | 0.05 | 0.05 | 0.18 | 0.34 | 0.71 | 5.86 | 7.26 | 9.19 | 7.40 |
| Vr | 0.32 | 0.38 | 0.49 | 0.03 | 0.04 | 0.07 | 0.05 | 0.04 | 0.17 | 0.31 | 0.65 | 5.89 | 7.30 | 9.26 | 7.50 |
| Sum | 6.98 | 8.96 | 11.2 | 0.65 | 1.04 | 1.67 | 1.07 | 1.00 | | Lambda max ($\lambda_{max}$) | | | | | 7.60 |
| | | | | | | | | | | Consistency Ratio (%) | | | | | 7.70 |

2) **Slope factor**

| Slope (%) | 0 - 2 | | | 2 - 5 | | | 5 - 8 | | | >8 | | |
|---|---|---|---|---|---|---|---|---|---|---|---|---|
| 0-2 | 1 | 1 | 1 | 3 | 4 | 5 | 6 | 7 | 8 | 9 | 9 | 9 |
| 2-5 | 1/5 | 1/4 | 1/3 | 1 | 1 | 1 | 2 | 3 | 4 | 6 | 7 | 8 |
| 5-8 | 1/8 | 1/7 | 1/6 | 1/4 | 1/3 | 1/2 | 1 | 1 | 1 | 4 | 5 | 6 |
| >8 | 1/9 | 1/9 | 1/9 | 1/8 | 1/7 | 1/6 | 1/6 | 1/5 | 1/4 | 1 | 1 | 1 |

| Slope (%) | ri | | | wi | | | $W_{avg}$ | $W_{nor}$ | Ri | | | Wi | | | λ |
|---|---|---|---|---|---|---|---|---|---|---|---|---|---|---|---|
| 0 - 2 | 3.57 | 3.98 | 4.36 | 0.50 | 0.63 | 0.79 | 0.64 | 0.62 | 1.75 | 2.64 | 4.00 | 3.53 | 4.21 | 5.09 | 4.30 |
| 2 - 5 | 1.19 | 1.46 | 1.75 | 0.17 | 0.23 | 0.32 | 0.24 | 0.23 | 0.58 | 0.94 | 1.53 | 3.53 | 4.12 | 4.84 | 4.20 |
| 5 - 8 | 0.55 | 0.66 | 0.80 | 0.08 | 0.10 | 0.14 | 0.11 | 0.11 | 0.28 | 0.43 | 0.70 | 3.63 | 4.18 | 4.82 | 4.20 |
| >8 | 0.24 | 0.26 | 0.29 | 0.03 | 0.04 | 0.05 | 0.04 | 0.04 | 0.13 | 0.17 | 0.25 | 3.85 | 4.26 | 4.75 | 4.30 |
| Sum | 5.55 | 6.36 | 7.20 | 0.77 | 1.00 | 1.30 | 1.02 | 1.00 | | Lambda max ($\lambda_{max}$) | | | | | 4.20 |
| | | | | | | | | | | Consistency Ratio (%) | | | | | 8.70 |

### 3) Soil depth factor

| SDe | Re | | | Ca | | | Nt | | | Lv | | | Ve | | | An | | | Le | | |
|---|---|---|---|---|---|---|---|---|---|---|---|---|---|---|---|---|---|---|---|---|---|
| Re | 1 | 1 | 1 | 2 | 3 | 4 | 2 | 3 | 4 | 3 | 4 | 5 | 4 | 5 | 6 | 5 | 6 | 7 | 5 | 6 | 7 |
| Ca | 1/4 | 1/3 | 1/2 | 1 | 1 | 1 | 1 | 1 | 1 | 3 | 4 | 5 | 4 | 5 | 6 | 5 | 6 | 7 | 5 | 6 | 7 |
| Nt | 1/4 | 1/3 | 1/2 | 1 | 1 | 1 | 1 | 1 | 1 | 2 | 3 | 4 | 3 | 4 | 5 | 4 | 5 | 6 | 5 | 6 | 7 |
| Lv | 1/5 | 1/4 | 1/3 | 1/5 | 1/4 | 1/3 | 1/2 | 1/3 | 1/4 | 1 | 1 | 1 | 2 | 3 | 4 | 3 | 4 | 5 | 4 | 5 | 6 |
| Ve | 1/6 | 1/5 | 1/4 | 1/6 | 1/5 | 1/4 | 1/5 | 1/4 | 1/3 | 1/4 | 1/3 | 1/2 | 1 | 1 | 1 | 2 | 3 | 4 | 3 | 4 | 5 |
| An | 1/7 | 1/6 | 1/5 | 1/7 | 1/6 | 1/5 | 1/6 | 1/5 | 1/4 | 1/5 | 1/4 | 1/3 | 1/4 | 1/3 | 1/2 | 1 | 1 | 1 | 1 | 2 | 3 |
| Le | 1/7 | 1/6 | 1/5 | 1/7 | 1/6 | 1/5 | 1/7 | 1/6 | 1/5 | 1/6 | 1/5 | 1/4 | 1/5 | 1/4 | 1/3 | 1/3 | 1/2 | 1 | 1 | 1 | 1 |

| SDe | ri | | | wi | | | $W_{avg}$ | $W_{nor}$ | Ri | | | Wi | | | λ |
|---|---|---|---|---|---|---|---|---|---|---|---|---|---|---|---|
| Re | 2.75 | 3.50 | 4.21 | 0.23 | 0.35 | 0.52 | 0.37 | 0.35 | 1.42 | 2.72 | 4.96 | 6.18 | 7.75 | 9.60 | 7.80 |
| Ca | 1.85 | 2.19 | 2.57 | 0.15 | 0.22 | 0.31 | 0.23 | 0.22 | 0.96 | 1.65 | 2.88 | 6.19 | 7.53 | 9.16 | 7.60 |
| Nt | 1.63 | 1.98 | 2.37 | 0.14 | 0.20 | 0.29 | 0.21 | 0.20 | 0.82 | 1.45 | 2.58 | 6.02 | 7.29 | 8.89 | 7.40 |
| Lv | 0.90 | 1.03 | 1.19 | 0.08 | 0.10 | 0.15 | 0.11 | 0.10 | 0.45 | 0.79 | 1.43 | 6.03 | 7.61 | 9.85 | 7.80 |
| Ve | 0.50 | 0.63 | 0.80 | 0.04 | 0.06 | 0.10 | 0.07 | 0.06 | 0.26 | 0.48 | 0.92 | 6.12 | 7.62 | 9.40 | 7.70 |
| An | 0.29 | 0.37 | 0.47 | 0.02 | 0.04 | 0.06 | 0.04 | 0.04 | 0.15 | 0.27 | 0.52 | 6.06 | 7.40 | 9.10 | 7.50 |
| Le | 0.23 | 0.27 | 0.35 | 0.02 | 0.03 | 0.04 | 0.03 | 0.03 | 0.12 | 0.21 | 0.39 | 6.42 | 7.67 | 9.14 | 7.70 |
| SUM | 8.15 | 9.98 | 12.00 | 0.68 | 1.00 | 1.47 | 1.05 | 1.00 | | Lambda max ($\lambda_{max}$) | | | | | 7.70 |
| | | | | | | | | | | Consistency Ratio (%) | | | | | 8.40 |

**4) Soil drainage factor**

| SDr | Nt | | | Lv | | | Rg | | | Ca | | | An | | | Le | | | Ve | | |
|---|---|---|---|---|---|---|---|---|---|---|---|---|---|---|---|---|---|---|---|---|---|
| Nt | 1 | 1 | 1 | 1 | 1 | 1 | 1 | 2 | 3 | 1 | 2 | 3 | 2 | 3 | 4 | 3 | 4 | 5 | 4 | 5 | 6 |
| Lv | 1 | 1 | 1 | 1 | 1 | 1 | 1 | 1 | 1 | 1 | 2 | 3 | 2 | 3 | 4 | 3 | 4 | 5 | 4 | 5 | 6 |
| Rg | 1/3 | 1/2 | 1 | 1 | 1 | 1 | 1 | 1 | 1 | 1 | 2 | 3 | 2 | 3 | 4 | 3 | 4 | 5 | 4 | 5 | 6 |
| Ca | 1/3 | 1/2 | 1 | 1/3 | 1/2 | 1 | 1 | 1/2 | 1/3 | 1 | 1 | 1 | 2 | 3 | 4 | 3 | 4 | 5 | 4 | 5 | 6 |
| An | 1/4 | 1/3 | 1/2 | 1/4 | 1/3 | 1/2 | 1/4 | 1/3 | 1/2 | 1/4 | 1/3 | 1/2 | 1 | 1 | 1 | 3 | 4 | 5 | 4 | 5 | 6 |
| Le | 1/5 | 1/4 | 1/3 | 1/5 | 1/4 | 1/3 | 1/5 | 1/4 | 1/3 | 1/5 | 1/4 | 1/3 | 1/5 | 1/4 | 1/3 | 1 | 1 | 1 | 4 | 5 | 6 |
| Ve | 1/6 | 1/5 | 1/4 | 1/6 | 1/5 | 1/4 | 1/6 | 1/5 | 1/4 | 1/6 | 1/5 | 1/4 | 1/6 | 1/5 | 1/4 | 1/6 | 1/5 | 1/4 | 1 | 1 | 1 |

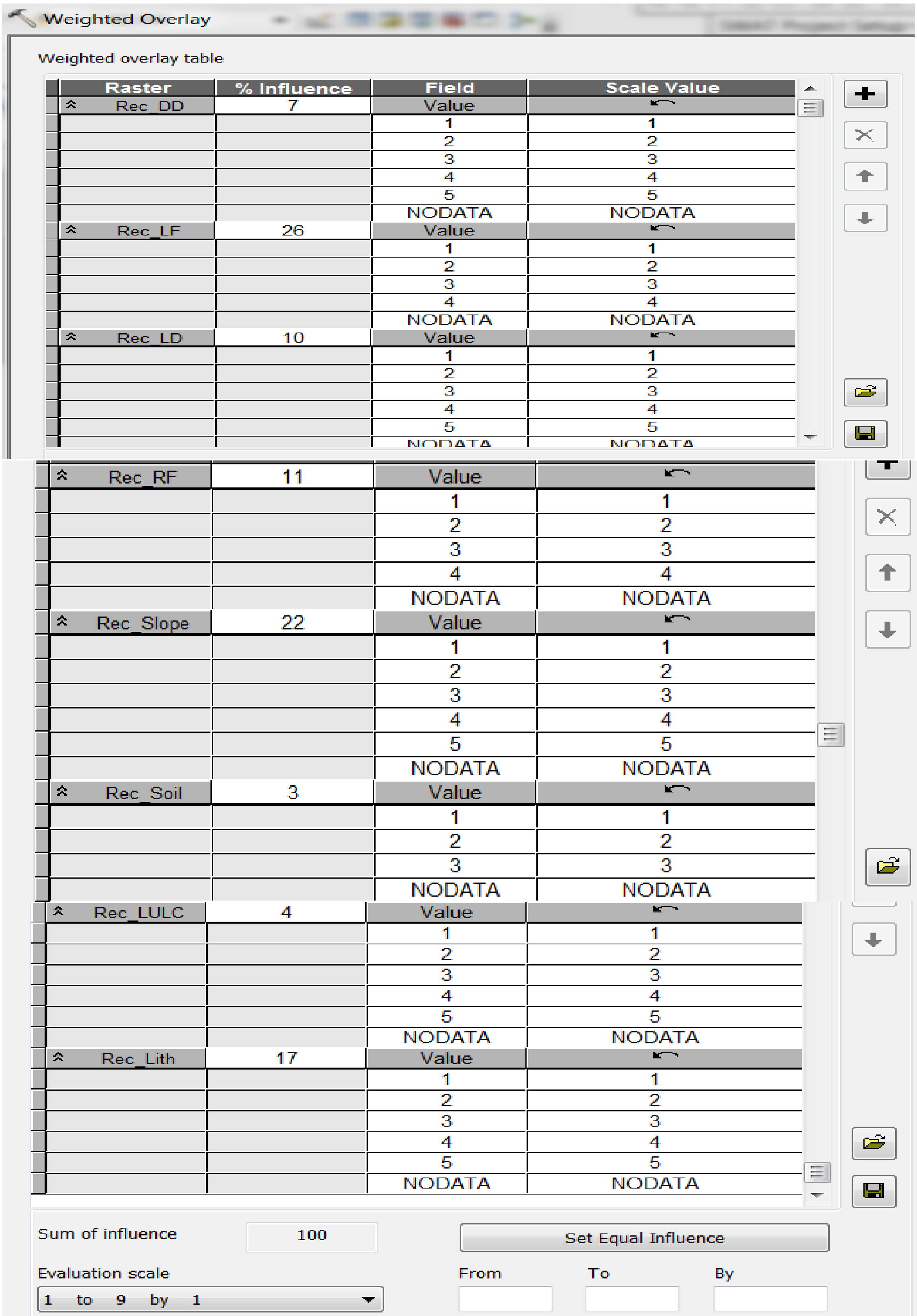
| SDr | $r_i$ | | | $w_i$ | | | $W_{avg}$ | $W_{nor}$ | $R_i$ | | | $W_i$ | | | $\lambda$ |
|---|---|---|---|---|---|---|---|---|---|---|---|---|---|---|---|
| Nt | 1.57 | 2.19 | 2.71 | 0.14 | 0.25 | 0.39 | 0.26 | 0.24 | 0.81 | 1.81 | 3.80 | 5.69 | 7.32 | 9.67 | 7.60 |
| Lv | 1.57 | 1.98 | 2.32 | 0.14 | 0.22 | 0.34 | 0.23 | 0.22 | 0.81 | 1.61 | 3.13 | 5.69 | 7.17 | 9.31 | 7.40 |
| Rg | 1.35 | 1.79 | 2.32 | 0.12 | 0.20 | 0.34 | 0.22 | 0.21 | 0.72 | 1.49 | 3.13 | 5.87 | 7.31 | 9.31 | 7.50 |
| Ca | 1.15 | 1.33 | 1.69 | 0.10 | 0.15 | 0.25 | 0.17 | 0.16 | 0.62 | 1.12 | 2.42 | 5.96 | 7.42 | 9.83 | 7.70 |
| An | 0.65 | 0.82 | 1.09 | 0.06 | 0.09 | 0.16 | 0.10 | 0.10 | 0.37 | 0.72 | 1.51 | 6.31 | 7.79 | 9.50 | 7.90 |
| Le | 0.39 | 0.47 | 0.59 | 0.04 | 0.05 | 0.09 | 0.06 | 0.05 | 0.23 | 0.42 | 0.84 | 6.49 | 8.03 | 9.84 | 8.10 |
| Ve | 0.22 | 0.25 | 0.30 | 0.02 | 0.03 | 0.04 | 0.03 | 0.03 | 0.12 | 0.22 | 0.43 | 6.17 | 7.82 | 9.80 | 7.90 |
| Sum | 6.89 | 8.84 | 11.00 | 0.62 | 1.00 | 1.60 | 1.08 | 1.00 | | Lambda max ($\lambda_{max}$) | | | | | 7.70 |
| | | | | | | | | | | Consistency Ratio (%) | | | | | 9.20 |

### 5) Land use land cover factor

| LULC | CL | | | FR | | | SH | | | SHR-R | | | AFR-G | | | BLT | | |
|---|---|---|---|---|---|---|---|---|---|---|---|---|---|---|---|---|---|---|
| CL | 1 | 1 | 1 | 6 | 7 | 8 | 6 | 7 | 8 | 7 | 8 | 9 | 9 | 9 | 9 | 9 | 9 | 9 |
| FR | 1/8 | 1/7 | 1/6 | 1 | 1 | 1 | 1 | 2 | 3 | 1 | 2 | 3 | 2 | 3 | 4 | 4 | 5 | 6 |
| SHR | 1/8 | 1/7 | 1/6 | 1/3 | 1/2 | 1 | 1 | 1 | 1 | 2 | 3 | 4 | 2 | 3 | 4 | 4 | 5 | 6 |
| AFR-G | 1/9 | 1/8 | 1/7 | 1/3 | 1/2 | 1 | 1/4 | 1/3 | 1/2 | 1 | 1 | 1 | 1 | 2 | 3 | 1 | 2 | 3 |
| SH-R | 1/9 | 1/9 | 1/9 | 1/4 | 1/3 | 1/2 | 1/4 | 1/3 | 1/2 | 1/3 | 1/2 | 1 | 1 | 1 | 1 | 1 | 1 | 1 |
| BLT | 1/9 | 1/9 | 1/9 | 1/6 | 1/5 | 1/4 | 1/6 | 1/5 | 1/4 | 1/3 | 1/2 | 1 | 1 | 1 | 1 | 1 | 1 | 1 |

| LULC | | $r_i$ | | | $w_i$ | | $W_{avg}$ | $W_{nor}$ | | $R_i$ | | | $W_i$ | | $\lambda$ |
|---|---|---|---|---|---|---|---|---|---|---|---|---|---|---|---|
| CL | 5.23 | 5.63 | 6.00 | 0.46 | 0.58 | 0.72 | 0.59 | 0.57 | 2.31 | 3.76 | 6.08 | 5.01 | 6.49 | 8.41 | 6.60 |
| FR | 1.00 | 1.43 | 1.82 | 0.09 | 0.15 | 0.22 | 0.15 | 0.15 | 0.45 | 0.98 | 1.83 | 5.04 | 6.64 | 8.36 | 6.70 |
| SHR | 0.93 | 1.21 | 1.59 | 0.08 | 0.12 | 0.19 | 0.13 | 0.13 | 0.43 | 0.85 | 1.56 | 5.17 | 6.78 | 8.15 | 6.70 |
| AFR-G | 0.46 | 0.66 | 0.93 | 0.04 | 0.07 | 0.11 | 0.07 | 0.07 | 0.20 | 0.46 | 0.89 | 4.99 | 6.80 | 7.92 | 6.60 |
| SH-R | 0.36 | 0.43 | 0.55 | 0.03 | 0.04 | 0.07 | 0.05 | 0.05 | 0.17 | 0.27 | 0.52 | 5.22 | 6.13 | 7.79 | 6.40 |
| BLT | 0.32 | 0.36 | 0.44 | 0.03 | 0.04 | 0.05 | 0.04 | 0.04 | 0.15 | 0.23 | 0.41 | 5.47 | 6.30 | 7.86 | 6.50 |
| Sum | 8.30 | 9.72 | 11.3 | 0.73 | 1.00 | 1.36 | 1.03 | 1.00 | | Lambda max ($\lambda_{max}$) | | | | | 6.60 |
| | | | | | | | | | | Consistency Ratio (%) | | | | | 9.40 |

## Figures in the Appendix




| Raster | % Influence | Field | Scale Value |
|---|---|---|---|
| Rec_DD | 7 | Value | |
| | | 1 | 1 |
| | | 2 | 2 |
| | | 3 | 3 |
| | | 4 | 4 |
| | | 5 | 5 |
| | | NODATA | NODATA |
| Rec_LF | 26 | Value | |
| | | 1 | 1 |
| | | 2 | 2 |
| | | 3 | 3 |
| | | 4 | 4 |
| | | NODATA | NODATA |
| Rec_LD | 10 | Value | |
| | | 1 | 1 |
| | | 2 | 2 |
| | | 3 | 3 |
| | | 4 | 4 |
| | | 5 | 5 |
| | | NODATA | NODATA |
| Rec_RF | 11 | Value | |
| | | 1 | 1 |
| | | 2 | 2 |
| | | 3 | 3 |
| | | 4 | 4 |
| | | NODATA | NODATA |
| Rec_Slope | 22 | Value | |
| | | 1 | 1 |
| | | 2 | 2 |
| | | 3 | 3 |
| | | 4 | 4 |
| | | 5 | 5 |
| | | NODATA | NODATA |
| Rec_Soil | 3 | Value | |
| | | 1 | 1 |
| | | 2 | 2 |
| | | 3 | 3 |
| | | NODATA | NODATA |
| Rec_LULC | 4 | Value | |
| | | 1 | 1 |
| | | 2 | 2 |
| | | 3 | 3 |
| | | 4 | 4 |
| | | 5 | 5 |
| | | NODATA | NODATA |
| Rec_Lith | 17 | Value | |
| | | 1 | 1 |
| | | 2 | 2 |
| | | 3 | 3 |
| | | 4 | 4 |
| | | 5 | 5 |
| | | NODATA | NODATA |

Figure A1. Weighted overlay workspace in ArcGIS for GW potential evaluation

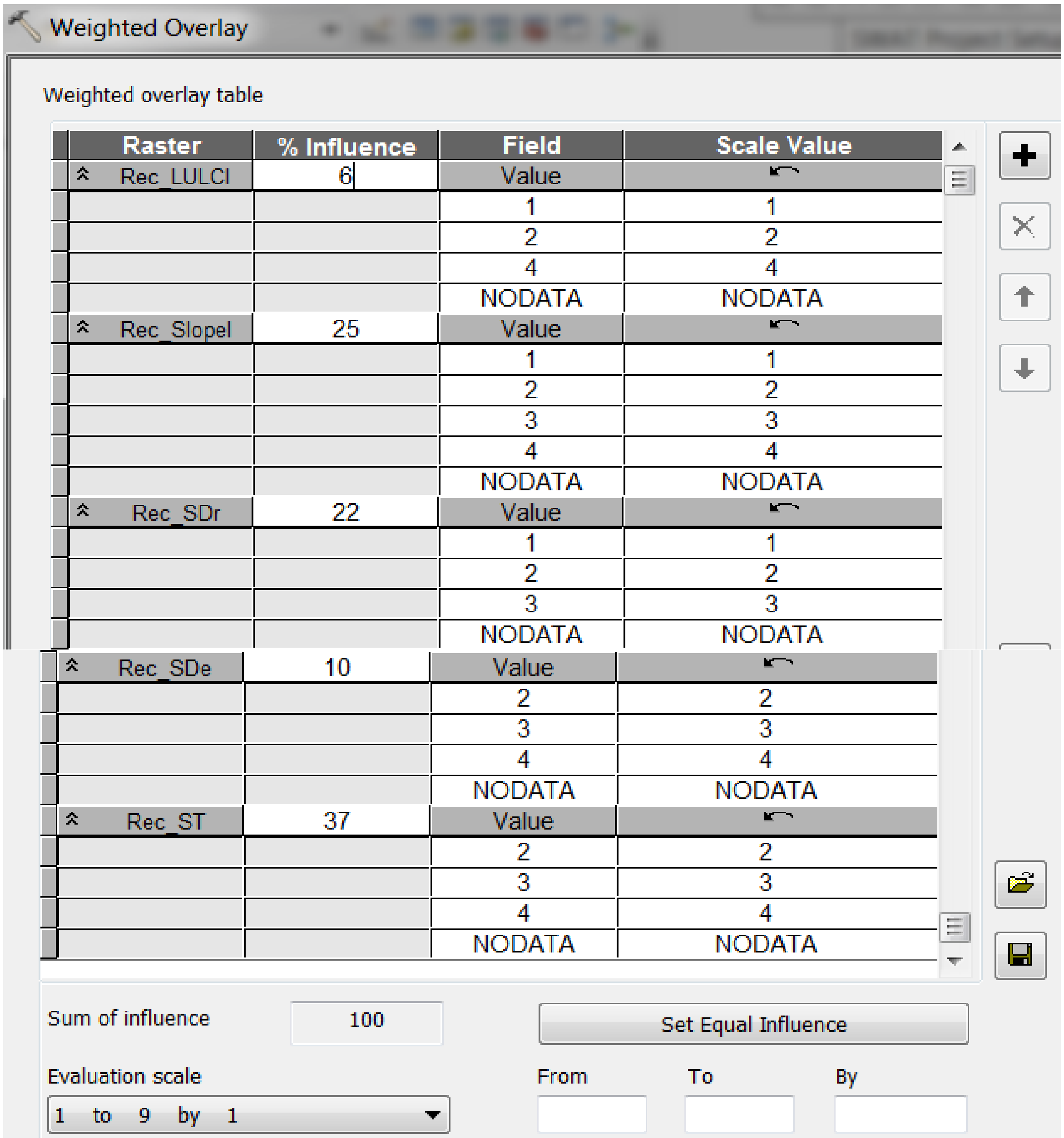



Figure A2. Weighted overlay workspace in ArcGIS for land suitability evaluation