GROUNDWATER POTENTIAL MAPPING USING SWAT MODEL AND GIS BASED MULTI-CRITERIA DECISION ANALYSIS: A CASE STUDY IN GIDABO WATERSHED, RIFT VALLEY LAKES BASIN, ETHIOPIA

M.Sc. THESIS

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HAWASSA UNIVERSITY, HAWASSA, ETHIOPIA

NOVEMBER, 2022

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HAWASSA UNIVERSITY ADVISORS' APPROVAL SHEET

This is to certify that the thesis entitled "**Groundwater Potential Mapping Using SWAT and GIS Based Multi-Criteria Decision Analysis: A Case Study in Gidabo River Catchment, Rift Valley Lakes Basin, Ethiopia**" submitted in partial fulfillment of the requirements for the degree of **Master of Science** in **Hydraulic Engineering**, the graduate program of the department of Hydraulic and Water Resources Engineering has been carried out by **Biruk Tamiru Tadele** Id.No. (**GPHydrW/0002/12**) under our supervision and guidance. Therefore, we recommend that the student has fulfilled the requirements and hence hereby he can submit the thesis to the department.

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We, the undersigned, members of the board of examiners of the final open defense by **Biruk Tamiru Tadele** have read and evaluated his thesis entitled "**Groundwater Potential Mapping Using SWAT And GIS based Multi-Criteria Decision Analysis: A Case Study in Gidabo River Catchment, Rift Valley Lakes Basin, Ethiopia**", and examined the candidate. This is, therefore, to certify that the thesis has been accepted in the partial fulfillment of the requirements for the degree of masters in "hydraulic engineering".

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LISTS OF ACRONYMS AND ABBREVTIONS

AHP	Analytic Hierarchy Process
BCM	Billion Cubic Meter
BCK	Billion Cubic Kilometer
CI	Consistency Index
CR	Consistency Ratio
EMA	Ethiopia Mapping Agency
ERDAS	Earth Resource Data Analysis System
FAO	Food and Agriculture Organization
GIS	Geographic Information System
GLC-Share	The Global Land Cover-SHARE
GWP	Groundwater Potential
GWPZ	Groundwater potential zones
HRU	Hydrological Response Unit
IDW	Inverse Distance Weighted
LU/LC	Land-use/land-cover
MCDA	Multi-Criteria Decision Analysis
MCDM	Multi-Criteria Decision Making
MoWIE	Ministry of Water, Irrigation and Energy
MoWR	Ministry of Water Resources
SRTM DEM	Shuttle Radar Topography Mission Digital Elevation Model
SWAT	Soil Water Assessment Tool
TPI	Topographic Position Index
TWI	Topographic Wetness Index
UNESCO	United Nations Educational, Scientific and Cultural Organization
USGS	United States Geological Survey
UTM	Universal Transverse Mercator

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DECLARATION

I undersigned and declared that this M.Sc. thesis entitled "Groundwater Potential Mapping using SWAT and GIS based MCDA: A case study in Gidabo River Catchment, Rift Valley Lakes basin, Ethiopia'' is my original work and has not been presented for a degree in any other university, and all sources of material used for this thesis have been duly acknowledged.

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

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ABSTRACT

Groundwater is the water that is located in the subsurface and saturates the rocks and soil beneath the ground surface. Groundwater is the most valuable natural resources for mankind for drinking, industrialization and irrigation in present day, but the availability is reduced gradually due to over exploitation and lack of management. However, identifying the groundwater potential zones in certain areas of Ethiopia is still challenging in terms of time and cost for resolving water scarcity problems and the management system of groundwater. A systematic assessment and identification of groundwater is essential for proper utilization and management of this precious natural resource. In recent years, Geographic information system based studies have gained much prominence in groundwater exploration, because it is rapid and will provide first-hand information on the resource for further developments. Therefore, the present study was conducted with an objective to identify the groundwater potential of Gidabo catchment, Rift Valley Lakes Basin of Ethiopia using SWAT and GIS-based MCDA techniques. Thematic maps were developed, for ten major parameters (recharge, soil, lineament density, lithology, land-us/ land-cover, geomorphology, slope, drainage density, Roughness and Topographic wetness index (TWI)) that affect the occurrence and movements of groundwater. Recharge was simulated by using SWAT model, the rest thematic layers were developed using ArcGIS 10.4 and Weights assigned to each thematic maps were based on their characteristics and water potential capacity through analytic hierarchy approach (AHP). The thematic layers were subjected to weight sum overlay in ArcGIS spatial analysis tool box, to delineate groundwater potential zone map. The resulted groundwater potential zone was categories in to four classes, namely high, moderate, low and very low. Generally Low and very low groundwater potential zones were found around highland area which coincide with structural hills, peak of the mountain and hard geological formation. The accuracy of the output was cross-validated with information on groundwater prospects of the catchment. Finally, it can be concluded that SWAT and GIS-based MCDA-AHP techniques is very effective and useful for the delineation and identification of groundwater potential zones in the study area.

Key word: AHP, GIS, Groundwater Flow Direction, Groundwater Potential, and Gidabo Catchment

1. INTRODUCTION

1.1. Background of the Study

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

Harvesting groundwater involves capturing shallow subsurface water from several sources including rivers, lakes and underground aquifers. Aquifers are regions of porous rocks and materials such as sand and gravel that hold a significant volume of water below the land surface. Groundwater reservoirs form naturally or through artificial means like building dams (Dukes & Kotecki, 2018). In arid climates and areas with less rain, many countries have turned to using fossil aquifers to fulfill their water needs since these aquifers have held large volumes of stable water for thousands of years. Groundwater can also be treated to combat pollution from natural contaminants as well as prevent deterioration caused by human activities like agriculture (Makkar & Kumar, 2020).

Due to recent advances in technology coupled with an enhanced understanding of geology, existing studies indicated improved estimations for actual volumes of stored groundwater than those estimated during previous decades (Rowland & Kooi, 2021). As a result, this raises potential new targets for future useable groundwater resources throughout global case studies. With access to affordable advanced pumping devices gets easier each day it becomes possible for people living in arid climates to extract viable levels underground water pressure providing a steady supply particularly in situations where periodic drought trouble surface supplies (Briscoe, Pletch & Jones 2017).

Monitoring programs can also be undertaken to provide rapid updates on changes in local hydrology or identify any associated risks due to extraction or pollutants found within drinking source waters. Governments around the world are beginning projects wherein long-term monitoring occurs at several depths within study sites allowing them adequate time to analyze seasonal data indices before taking critical decisions regarding groundwater harvesting policies (Guiliani et al., 2021). These studies have laid out projections on increasing global demands for drinking quality freshwaters contributing significantly towards its initial assessment process during decision making surroundings policy decisions related to future harvestable potentials associated with characterizing particular rural settings.

However, integration of geospatial tools (soil and water assessment tool (SWAT) and geographical information system (GIS) has established to be more convenient (powerful-tool), time-saving and cost effective techniques to assess and manage groundwater resource than that of conventional method in producing valuable database and map groundwater potential on the area (Murasingh and Jha, 2013; Arulbalaji *et al.,* 2019). It also helps to check the accuracy and reduce the bias on any single factor. In addition to SWAT and GIS techniques, multi-criteria decision analysis (MCDA) approach of Analytic Hierarchy Process (AHP) method is used to evaluate the level of influence (importance) of each factor governing groundwater and prioritize accordingly. Additionally, it's suitable to evaluate the consistency of the weight assigned through pairwise comparison in order to reduce the bias on decision making process (Manna *et al.,* 2017).

1.2. Statement of the Problem

Worldwide, the availability of groundwater is reduced gradually due to over exploitation, and the lack of groundwater management. Proper GWP investigation, and site selection done by geophysical and hydrological method is still more difficult/ laborious, time taking and cost ineffective. Improper groundwater potential site selection often leads an economic and time wastage for exploration, and unsustainable utilization resource is becoming increasingly an evident problem or challenging, and the key concern for many developing countries (Tesfaye, 2015; Abdul-Aziz *et al*., 2017). The population has no adequate clean water supply; this is partly due to lack of efficient, equitable and optimum utilization of available water resources of the country for significant socio economic development on sustainable basis (MoWIE, 2007).

Groundwater potential studies explore the subsurface environment, as well as hydrogeological and geophysical conditions, to provide insights into the availability of groundwater resources. The analysis usually comprises two stages: the initial regional exploration and the subsequent local investigation. During the regional exploration, site-specific parameters such as surface water runoff and infiltration rate are used in conjunction with geological data to identify high-potential areas for aquifers (Voss et al., 2018). In addition, soil type, topography, climate and ground elevation may also be taken into account (Munkner et al., 2018). During local investigation, more detailed information on a specific location is obtained by drilling boreholes or conducting geophysical surveys (Franke et al., 2016). By combining these two stages of investigations, a comprehensive picture of groundwater resource availability can be obtained. To solve such identified problems the current study is designed to provide groundwater information (database), distribution and map of potential site of Groundwater. Therefore, it is better to understand spatial dynamics of groundwater resource and identifying the Groundwater potential zones areas even in large and inaccessible areas and to prepare proper plan and management for the sustainable utilization of water resource with short time and minimum cost.

1.3. Objectives of the Study

1.3.1 General Objective

The general objective of the study was to map groundwater potential and recharge zone using integrated approach of SWAT and GIS based MCDA method in Gidabo Catchment, Rift Valley Lakes Basin of Ethiopia.

1.3.2. Specific Objectives

The specific objectives of the study were to:-

- Prepare thematic maps of factors influencing groundwater potential and recharge zone.
- Delineate groundwater potential zone through zone integration of thematic layers.
- Validate groundwater potential zone map.
- Demonstrate groundwater flow direction of the study area.

1.4. Research Questions

The following questions have been formulated to achieve the research objectives.

- What are the main factors affecting the occurrence and movements of groundwater in Gidabo Catchment?
- How the parameters are weighted according to groundwater potential affecting?
- How accurate is the developed groundwater potential zone map of the Gidabo Catchment?
- What is groundwater flow direction of the study area?

1.5. Scope of the Study

This research covered the mapping of groundwater potential by assessing the groundwater influencing parameters such as groundwater recharge, slope, land use/cover, geological formations (lithology, lineament density and drainage density), geomorphology, soil, TWI and Roughness within the Gidabo Watershed. Thematic maps were prepared for the above listed groundwater controlling parameters**.**

1.6. Significance of the Study

Ethiopia is the tower of water in east Africa but till there is water scarcity due to improper management, planning and use. Therefore, Mapping groundwater potential zone is important to understand groundwater occurrence and distribution in space and time of the area, which used for proper plan, management and utilization and/or may give better information for the success in selecting the favorable sites for efficient exploration (boreholes, hand dug wells and tube well drilling), and for the construction of artificial structure (check dam, recharge pit, recharge well, etc.) in efficient and effective way. (Sreenivasa *et al*., 2011, Badamasi *et al*., 2016).

Specifically, the main beneficiary of this study includes

- The communities are benefited from this study when the government or non-government bodies take action to develop and explore groundwater resource community development without cost and time constraint.

- When the government and non-government organization take an action or decision on suitable development, plan, management and utilization easily, and reduces the time and cost for selecting potential sites.

1.7. Limitation of the Study

The limitations of this research were lack of detail groundwater inventory point data especially well yield (discharge) data and unevenly distribution of point data. This study specifically focuses on mapping the groundwater potential zone of Gidabo Sub-basin. As it was a qualitative study the groundwater storage was not quantified.

2. LITERATURE REVIEW

2.1 Groundwater Potential Mapping

2.1.1. Groundwater Potential

Groundwater is the most valuable global resource, comprising 96% of the earth's unfrozen freshwater, as well as being the main water source in many water-scarce areas (Kidanu, 2018). It is the only underground water that is available to supply wells and springs, and supports wetlands. About 70% of the world's population depends on groundwater for basic domestic water services. The spatial distribution of GWPZ showed regional patterns related to geologic, physiographic and hydrologic characteristics of the area (Mamo, 2007).

2.1.2 Groundwater Potential of Ethiopia

Ethiopia is home to a large amount of groundwater resources. According to a study conducted by the International Water Management Institute (IWMI) in 2018, Ethiopia has an estimated 1.2 trillion cubic meters of renewable groundwater potential that is stored in aquifers and comprises 17% of the country's total internal renewable water resources (TIRWR). This large potential is largely untapped due to lack of awareness, limited financial resources and poor access to effective management technologies. Furthermore, out of the 1.2 trillion cubic meters only 872 million cubic meters are estimated as available for use due to poor assessment methods (Mulugeta et al., 2019). This indicates that there massive potential for development in Ethiopia if improved usage through appropriate policies were implemented. A recent study report indicates that most parts in the highland part possess sufficient volumes of fractional and renewable water reserves suitable for small-scale exploitation. Due to its high elevation with abundant rainfall and elevated drainage basin capacity most regions have a large current recharge rate often exceeding the available storage capacity. This has enabled Ethiopia to utilize precipitation not only as runoff but also as an infiltration recharge which is applicable for exploitation through artificial means (Gebremeskel, S.G., et al., 2017).

2.1.3 Groundwater Assessment

Assessment of the groundwater potential involves the analysis of groundwater flow and its interaction with the stream network, hydrological balance and forecasting the future use of water resources based on various exploitation alternatives (Groundwater assessment and management, 1989). It is essential for protection of water quality and management of groundwater systems (Waikar and Nilawar, 2014).

2.1.3.1 Groundwater Exploration

The water resources available in the basins remain almost constant, while the water demand continues to increase, due to the human population explosion, a rapid industrial development, urbanization and increase in agricultural production (Kassahun and Mohamed, 2018). Hence, the groundwater exploration is a typical task of a hydro-geologist or an engineer. Several geological, hydrogeological and geophysical methods are employed to target the groundwater potential zones (Balsubramanian, 2007).

The interpretation of satellite images and aerial photographs also help more in this process (Werz, 2006). Groundwater exploration is attempted through either by direct or indirect methods. Test drilling is the direct approach to find out the resource. This is an expensive affair (Sharma, 2021). During the last two centuries, more and more techniques have been developed to explore the groundwater. They are classified into surface and sub-surface methods. The surface methods are easy to operate and implement (Balsubramanian, 2007; Sharma, 2021). These require minimum facilities like topo-sheets, maps, reports, some field measurements and interpretations of data in the laboratories.

The surface methods of groundwater exploration include; esoteric methods, geomorphologic methods, geological and structural methods, soil and micro-biological methods, Remote Sensing techniques and surface geophysical methods (Epuh et al., 2020). The subsurface methods of groundwater exploration include both test drilling and borehole geophysical logging techniques (Coatfs, 1988).

When compared to the surface methods, the subsurface methods are very expensive and accurate. It is done at the government level projects where large scale investigations are carried out to ascertain the results of surface surveys (Balsubramanian, 2007).

2.1.3.2 Estimation of Groundwater Recharge

Groundwater recharge is an important process in many hydrogeological systems and it is essential to estimate groundwater recharge accurately for sustainable water resources management. Several approaches have been developed to estimate the recharge (Lachir et al., 2019). Lakshmipathy et al. (2017) used the stage-discharge relationship and surface runoff measurements to assess the open channel system-recharge contribution for an ungauged region of India. Richards (1945) proposed a simple mass balance approach, in which detected changes in groundwater levels over a period of time are used for estimating volumetric pumping or recharge. Infiltration rate methods such as Thiem equation, Soil Moisture Balance Based methods and Soil Water Budget Area Ratio methods are also applied in many arid or semi-arid regions (Ghezzehei & Asadi, 2010).

Bhargava et al. (2018), analyzed artificial groundwater recharge techniques by computing the monthly renewable groundwater potential over different Recharge Structures (RSs) models in situ sources through piezometeric analysis including shallow and deep bore wells. Recent advances on geospatial technology tools can help also to estimate groundwater recharge with more accuracy. These tools include Geographic Information Systems (GIS), Remote Sensing (RS) derived inputs, Global Positioning System (GPS), geo-statistical interpolations with satellite radar projections, etc.(Karmakar et al., 2015; Nivia et al., 2017; Elhag & Osman, 2018).

The water balance techniques which developed by Thornthwaite is another physical methods. In this method the water input and output/discharge are compared and the difference in the two is the estimated recharge. The hydrograph separation, river channel water budget, water table fluctuation and saturated volume fluctuation departure methods are included in these techniques (Walker et al., 2019). The tracer method involves the introduction of dissolved substances or solutions into the water cycle and tracing the movement of water using their concentrations. Common tracer methods are chloride mass balance and groundwater dating (Al-Sudani, 2018; Wu et al., 2016).

The recharge is the primary way through which water joins the aquifer and thus quantifying it is vital for integrated, sustainable management, and use of groundwater and surface water resources (Githui *et al*., 2012). SWAT model has been applied to estimate recharge (water balance in general) all over the world (Awan and Ismaeel, 2014; Githui *et al*., 2012; Jin *et al* 2015; Eshtawi *et al*., 2016; Putthividhya and Laonamsai, 2017).

SWAT is a physically-based hydrologic/water quality, and hydrologic response units (HRU) based large area Catchment model (Abbaspour *et al*., 2007; Arnold *et al*., 2012).

SWAT uses spatiotemporal data to simulate water flow in soil and groundwater, erosion, nutrient cycling, and others (Arnold *et al.*, 1998). There are different versions of SWAT with different interfaces; here version 2012 with ArcGIS interface (SWAT) was employed.

HRU is the smallest segment of a Catchment representing a diverse LULC, soil, and landscape characteristics within the sub basins. Flow is calculated for each segment of the Catchment separately. The general equation of the SWAT model is the following (Arnold *et al*., 1998).

$$SWt = SWo + \sum_{i=1}^{t} (\mathrm{Rday} - \mathrm{Qsurf} - \mathrm{ET} - \mathrm{Wper} - \mathrm{Qgw})$$

Where SW_o and SWt are the quantity of initial and final soil water (mm/day); t is the time (days); R_{day} is the precipitation (mm/day); Q_{surf} is the surface runoff (mm/day); ET is the evapotranspiration (mm/day); W_{perc} is the percolation (mm/day); Q_w is the flow from aquifer (mm/day).

SWAT simulates two aquifers for individual subasin: a shallow unconfined aquifer that donates water to the main stream or reaches of the subasin and a confined aquifer (Arnold *et al.*, 1993). The total recharge is computed using the following equation:

$$Wrch,i = \left(1 - \mathrm{e}\frac{-1}{\sigma gw}\right)Wseep + \mathrm{e}\frac{-1}{\sigma gw}\ Wrch,i-1$$

Where W*rch,i* and W*rch,i-1* are water flowing to the aquifer on day *i*, on day *i-1*, σgw the drainage delay time of the top formation (days), and Wseep is the water leaving from the soil profile at the bottom delay (day *i)* which can be calculated using the following relationship:

$$\mathrm{W}seep = Wperc + Wcrk,btm$$

Where W*perc* is the water escaping from the second layer(*mm/day*), and W*crk,btm* is the bypass flow from the soil profile at the lower boundary*(day i).*

The deep aquifer obtains some portion of the total recharge approximated with the following formula:

$$W_{deep} = \beta_{deep} * W_{rch}$$

Where W*perc* is the water moving from shallow to deep aquifer (*day i), βdeep* is the percolation coefficient.

2.1.3.3 Groundwater Flow Modelling

Effective management of groundwater requires the ability to predict subsurface flow and transport of solutes and the response of fluid and solute flux to changes in natural or human-induced stresses. Hence, the use of groundwater models is prevalent in the field of environmental science (Kumar, 2002). One popular type of tool that has been evolving since the mid-1960s is the deterministic, distributed-parameter, computer simulation model for analyzing flow and solute-transport in groundwater systems (Jacques, 1999; Konikow and Mercer, 1988).

The applicability or usefulness of a model depends on how closely the mathematical equations approximate the physical system being modeled (Kumar, 2002). Deterministic models are based on conservation of mass, momentum, and energy and describe cause and effect relations. The following typical topics shows the need for modelling and (lead to) describe the current groundwater flow modelling techniques.

I. Finite-difference methods

Finite-difference methods approximate the first derivatives in the partial differential equations as difference quotients (the differences between values of the independent variable at adjacent nodes with respect to the distance between the nodes, and at two successive time levels with respect to the duration of the time-step increment).

In general, the finite-difference methods are simpler conceptually and mathematically, and are easier to program. They are typically keyed to a relatively simple, rectangular grid, which also eases data entry.

II. Finite-element methods

Finite-element methods use assumed functions of the dependent variable and parameters to evaluate equivalent integral formulations of the partial differential equations. These equations can then be solved using either iterative or direct matrix methods. In direct methods, a sequence of operations is performed only once to solve the matrix equation, providing a solution that is exact, except for machine round-off error. Iterative methods arrive at a solution by a process of successive approximation. They involve making an initial guess at the solution, then improving this guess by some iterative process until an error criterion is satisfied. More recently, a semi-iterative method, or class of methods, known as conjugate-gradient methods, has gained popularity. One advantage of the conjugate-gradient method is that it does not require the use or specification of iteration parameters, thereby eliminating this partly subjective procedure.

Finite-element methods generally require the use of more sophisticated mathematics but, for some problems, may be more accurate numerically than standard finite-difference methods. A major advantage of the finite-element methods is the flexibility of the finite-element grid, which allows a close spatial approximation of irregular boundaries of the aquifer and (or) of parameter zones within the aquifer when they are considered. However, the construction and specification of an input data set are much more difficult for an irregular finite-element grid than for a regular rectangular finite-difference grid.

The method of characteristics was also developed to solve hyperbolic differential equations (advectively dominated transport equations). A major advantage is that the method minimizes numerical dispersion (Reddell and Sunada, 1970; Garder et al., 1964; Zheng and Bennett, 1995). Although finite-difference and finite-element models are commonly applied to transport problems, other types of numerical methods have also been applied to transport problems, including the method of characteristics, random walk, Eulerian-Lagrangian methods, and adaptive grid methods. All of these methods have the ability to track sharp fronts accurately with a minimum of numerical dispersion. A documented models based on variants of these approaches include Konikow and Bredehoeft (1978), Sanford and Konikow (1985), Prickett et al. (1981), and Zheng (1990).

No single one of the standard numerical methods is ideal for a wide range of transport problems and conditions. Thus, there is currently still much research on developing better mixed or adaptive methods that aim to minimize numerical errors and combine the best features of alternative standard numerical approaches.

This chapter provides a review of some important definition and theoretical bases for groundwater potential zone mapping, factor influence GW potential, SWAT and GIS application in hydrology empirical research were reviewed and finally, conceptual framework of the study formulated.

2.1.3.4. Models Review

Existing GIS software are extremely diverse in functionality, database structure and hardware requirements. Some of the popular GIS software is Arc/Info, ArcView, MapInfo, MGE (Modular GIS Environment), Genasys, ERDAS, GRASS, IDRISI and Atlas. These software are sophisticated and have a variety of functionalities for GIS applications and analyses. Most of these software come with capabilities to handle data in various formats, thereby facilitating data transfer between GIS software. Some of the above software is hardware specific and others run on a variety of platforms. A large number of generic deterministic groundwater models, based on a variety of numerical methods and a variety of conceptual models, are available.

GIS can facilitate the development, calibration, and verification of models as well as the display of model parameters and results in modeling groundwater movement. Spatial statistics and grid design capabilities of GIS can improve the modeling effort and aid in reliability assessment. A GIS-MODFLOW interface is an example of a groundwater finite-difference model linked with a GIS. The selection of a numerical method or generic model for a particular field problem depends on several factors, including accuracy, efficiency/cost, and usability. A large number and variety of generic groundwater models are documented and available at the present times are the following.

2.1.4. Groundwater Potential Mapping using SWAT and GIS based MCDA

Before the incorporation of SWAT and GIS based MCDA techniques, groundwater potential study was only done by using the data from field observations. In developing countries like Ethiopia, most of the hydrogeological investigations have been done using conventional techniques.

The conventional approaches for groundwater investigation like ground-based surveys and exploratory drilling are understood to be time-consuming, uneconomical and able to cover small areas of land (Mamo, 2007; Marghany et al., 2009).

Groundwater potential mapping using SWAT (Soil and Water Assessment Tool) combined with GIS (Geographical Information System) based Multi-Criteria Decision Analysis is one of the most effective methods for assessing the groundwater resources in a given region. This approach combines physical, climatic, and hydrogeological criteria to assess the suitability of an area for use as a groundwater resource. SWAT-GIS based Multi-Criteria Decision Analysis involves a series of steps including defining the criteria relevant to the site, determining their spatial patterns and weighing the criteria by which decision makers can determine suggested land uses. This technique has been used in many parts of the world to identify suitable sites where potential groundwater recharge can occur, helping to manage an area's subsequent water availability (Rasti et al., 2017). The combination of these two approaches helps to significantly improve our ability to better predict water availability by considering factors such as land use type, topography, climate variables and geologic settings. In addition, this model also allows for economic considerations in decision making processes; making it a more cost-effective strategy for evaluating future water supply needs (Yousefi et al., 2020).

2.1.6 Factors Affecting Groundwater Potential

The occurrence of groundwater potential zone is affected by many different geophysical and climatic factors like geology, topography and environmental conditions. Some of major factors influence or responsible for groundwater resource identification and locate potential site are discussed below.

2.1.6.1. Groundwater Recharge

Groundwater recharge or deep drainage or deep percolation is a hydrologic process, where water moves downward from surface water to groundwater. Recharge is the primary method through which water enters an aquifer. This process usually occurs in the vadose zone below plant roots and is often expressed as a flux to the water table surface. Groundwater recharge also encompasses water moving away from the water table farther into the saturated zone. Recharge occurs both naturally (through the water cycle) and through anthropogenic processes (i.e., "artificial groundwater recharge"), where rainwater and or reclaimed water is routed to the subsurface.

2.1.6.2. Land use /Land cover (LuLc)

Different land use/land cover has certain influence on groundwater potential and recharge directly through infiltration, runoff and evaporation (Fashae *et al*., 2014). Land cover is the human land use activities which involves built or modifies the natural environment as vegetation or plantation and others.

This influence or minimize evaporation and runoff and increase the rate of water enter to the sub-surface soil (infiltration). Hence, the vegetation cover increases the chance of groundwater recharge and can be an indication for groundwater potential. On other hand, the land cover is the physical materials that cover the land surface by settlement, road/asphalt, grass and water. In settlement and built up area infiltration is low because of land covered by pavement and building, therefore in such area low recharge are expected.

2.1.6.3. Slope

The slope is one of the important factor which highly controlling the infiltration and runoff capacity of precipitation and surface water flow. Where steep slopes are present, groundwater potential is low because there is more surface runoff and decrease the infiltration rate of water into the ground by allowing less residence time for precipitation. In areas characterized by flatlands and/or valleys, groundwater potential and recharge is high because it is easier for the water to enter (infiltrate) to the ground and decrease the runoff on the surface by allowing more concentration to percolate(Venkateswaran *et al*., 2016). This so indicate high slope regions have high runoff and low infiltration rate that are not suitable for groundwater recharge, because of water cannot get enough time to infiltrate to the ground and vice versa. The slope map of the area is extracted from digital elevation model (DEM) using surface-spatial analysis tools in ArcGIS.

2.6.1.4. Geomorphology

Geomorphological studies are one of the most significant aspects in the assessment of surface and groundwater resources or hydrological behavior. It is characterized various landforms and structure feature including hills, plateaus, pediment/Pedi-plan, level plain, flood plain, alluvial plain, valley, etc. of the area which is favorable for groundwater occurrences. Avinash *et al.*, (2011) demonstrated that geomorphology is a good agent for groundwater potential analyses. The hydro-geomorphologic units like alluvial/flood plains, valley fills, level plateau, buried channels and lineaments are very good sources (high significance) for groundwater occurrence. On the other hand, mountain or structural hills, pediment zone and gullied lands are poor (less significance) groundwater potential zones.

2.6.1.5. Lithology

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

2.6.1.6. Lineament Density

Lineaments are naturally occurring curvilinear or linear structurally controlled features in a landscape, which are an expression of an underlying geological structure, including faults (Bashe, 2017; Nair *et al*., 2017). Hence, lineament play a fundamental role in groundwater potential as the structural weakness or underlain by zone of localized weathering increase the infiltration capacity, permeability and secondary porosity. These factors are hydro-geologically very important as they make ways for groundwater movement and storage. Lineament density of an area can indirectly reveal the probability of groundwater potential occur, since the presence of lineaments usually denotes a permeable zone.

The lineament density is generated by extracting the lineament from DEM using the Arc toolbox and drainage network is created using ArcGIS. Lineament density (Ld.), defined by

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

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

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

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

2.6.1.7. Drainage Density

Drainage pattern is a reflection of the rate that precipitation infiltrated compared with surface runoff. It indicates the inverse function of permeability capacity, infiltration capacity and recharge capacity of rocks and soil surface which is an important factor for groundwater evaluation (Mesfin, 2011). The term drainage density of the basin first introduced by Horton(1932) which is defined as the ratio of total (cumulative) line length of stream network to the basin area(the area of consideration) which describe the closeness of the spacing of the stream channel and river. It can be calculated by using the following formula:

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

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

- High drainage is the resultant of weak or impermeable surface (fine texture soil type). Sparse vegetation and mountain relief which have high runoff and low infiltration result. While low drainage density is the result of high permeable subsoil (course texture soil type) and low relief which have less runoff and high infiltration.
- High drainage density indicate high runoff and less infiltration which results in less occurrence of groundwater and reverse are true, low drainage density has less runoff and high infiltration results in high contribution of groundwater potential and recharge (Waikar and Nilawar, 2014).

2.6.1.8. Topographic Roughness

The roughness is mainly a characteristic of weathered rocks. It shows how big is the inter-cell difference of a central pixel from its surrounding cells in DEM. The roughness index expresses the amount of elevation difference between adjacent cells of a digital elevation model (DEM). Higher the roughness, the more undulation and vice versa. It calculates the difference in elevation values from a center cell and the eight immediately surrounding it.

2.6.1.9. Soil Texture

Types and textures of the soil have an important role on the amount of water that can be infiltrated into the subsurface formation (Govind, 2014). Soil store rainwater in their pores before it infiltrates to greater depths and recharges the aquifer system. The water stored at the upper layers was evaporated easily, it negatively affects groundwater potential (Habtamu 2014). The major soil units in the catchment are categorized as chromic Luvisols, Eutric vertisols, humic nitsoils and lithic leptosoils. It comprised the major soil texture of sandy, sandy loam and clay types.

2.6.1.10 Topographic Wetness Index (TWI)

Topographic wetness index reflects the role of topography on hydrological process, showing the ration of the upstream contributing area with orthogonal breadth to the flow direction (Beven and Kirkby, 1979; Sorensen et al., 2006). The topographic wetness index (TWI) has been used as an estimator of relative wetness assuming that fraction of hill slope flow occurs as slope-parallel lateral flow such that flow accumulation should increase with local contributing area and decrease with local slope. It is defined as TWI = Ln (sca/tanβ), where sca is the specific contributing area (upslope contributing area per unit contour length) draining to each grid cell and tanβ is the local slope.

2.2. Multi-Criteria Decision Analysis (MCDA)

In GIS framework, multi-criteria decision analysis is a sub-discipline of operation research and systematic procedure for combine layers of spatial data of criteria to analyzing and selecting the best feasible option from the given alternative. It was designed in the 1960 to help decision-makers to integrate various alternatives. They analyze and support decision through formal analysis of alternative options, their attribute, evaluation criteria, goals or objectives, and constraints. Many studies was suggested that, MCDA techniques is an effective and selective tool to analyze structure decision problem and choose the best option based on designed criteria for delineating groundwater potential zone. Among different MCDA method, this study mainly depends on Analytical Hierarchy Process (AHP) (Malczewski, 2006).

2.2.1AHP and its Application in groundwater Potential Zone Mapping

The Analytic Hierarchy Process (AHP), introduced by Thomas Saaty (1980), is an effective tool and internationally acceptable for dealing with complex decision making, and may aid the decision maker to set priorities and make the best-fit decision. It can be used in many fields of studies which attempted to identify groundwater potential zones that the important factors which affect the occurrences of groundwater are slope, drainage density, lithology, geomorphology, land use/cover , lineament density , soil type and rainfall(Aneesh and Paresh Deka, 2015; Ramu *et al.,* 2014; Sajikumar and Gigo, 2013). So depending upon the suitability and the type of region of study, all the nine parameters or any few relevant parameters have been chosen and weighted by AHP to generate groundwater potential zones (Rajkamal *et.al.,*2014; Guptaa and Srivastava, 2009; Rambabu *et al.,* 2015). In the studies done to identify groundwater potential zones in Bengaluru and Mysuru (Aneesh and Deka, 2015; Ramu *et al.,* 2014), all the above mentioned criteria have been used and thematic maps have been made and given proper weight based on the importance to groundwater occurrences and movements. AHP technique has been followed to find the weights not only just for the main criteria but also for the subclasses within each criterion. Normalized weights have been calculated for the criteria features as well as for sub classes.

2.3. Groundwater Flow Direction

Groundwater levels represent the potentiometric state of water recharge, storage and discharge of the aquifer (Conlon et al., 2005; Yu et al., 2016). Ground water flow implies that ground water is recharged over broad upland areas and discharged at relatively focused lowland areas as surface water (Messene, 2017). Depending on the several hydrogeological factors, such as geology, drainage, soil, slope, elevation and other parameters the groundwater level fluctuate and varying from place to place (Chandra et al., 2015; Tiwari et al., 2016).

The topographic setting gives an idea about the general direction of groundwater flow and its influence on groundwater recharge and discharge (Gintamo, 2015). Topographically, much like the flow of water in a River, the groundwater flow is subjected to gravity and is almost always in motion, flowing from areas of higher elevation to areas of lower elevation (Mulugeta and Tafa, 2010). Thus, the direction of groundwater flow can be considered as a gradient of topographic slope without static water level. Generally, mapping groundwater contour is important to identify groundwater flow direction (Doyo, 2020). Groundwater flows from recharge area to discharge area. Flow lines diverge from recharge area and converge towards the discharge area (Fetter, 2001).

Groundwater does not usually remain stationary, but moves or flow underground according to natural slope (topography), geological formation and external pressure due to pumping well/well drilling. Measuring the elevation of groundwater at different location and map the counter line (connect the point of equal elevation) as equipotential line on the area is the most direct method of determining the direction of groundwater movement. Groundwater moves along a flow path perpendicular to equipotential line, and direction of movement is from higher elevation line to lower elevation and drain into stream, lake, sea, ponds and boreholes (Oborie and Nwankwoala, 2017).

Mulugeta (2007) had conducted groundwater circulation and hydrochemistry of the corridor at upper Gidabo River and Lake Hawassa, Sidama Region, Ethiopia. Groundwater flow systems were evaluated by identifying source of contamination (chemical difference between high and low elevation) by examining hydrochemical parameter data like the distribution of total dissolved state (TDS). The orientations of faults are also one of the possible methods to determine groundwater flow direction, because groundwater always flows along fault oriented or aligned.

2.4. Groundwater potential site selection Tools

The movement of groundwater depends on hydrological, lithological, atmospheric, soil, and topographic nature of a region (Andualem and Demeke, 2019; Das, 2019; Mallick *et al*., 2019) and therefore, the groundwater study needs multidisciplinary data. The use of geospatial techniques of SWAT and GIS with multi criteria decision making (MCDA)-AHP method in GW potential site studies only began very recently. GIS-techniques play a vital role in processing, understanding, Organizing, quantifying a vast number of data with minimal error (Jha *et al*., 2007).

Ethiopian Rift (ER) is an important area in the country in connection with its water resources (Legesse and Aynew, 2006; Pascual-Ferrer *et al.*, 2014; Berhanu *et al*., 2017; Desta and Lemma, 2017). In this basin there are a few machines drilled boreholes, but most of them are controversial due to their low productivity and some of them are drying. As the water supply-demand increases the potential for future development and abundant use of the groundwater resources is an important issue to deal with (Izady *et al.*, 2014; Mechal *et al.*, 2017). Therefore, the procedures and conclusions from this work provide base information for policy makers, future investigation of groundwater resources in the Catchment and other watersheds.

2.5. Conceptual Framework of GW Potential Zone Mapping

Conceptual framework is summarized how all reviewed literatures under this chapter is conceptualized to the current study in order to formulate simplified view (framework) for identifying and mapping potential groundwater zone. In order to prepare groundwater potential zone map some necessarily important data needed to be identified that are relevant to a particular study area. To map groundwater potential zone conventionally existing data, hydrological data and meteorological data are obtained from different sources to develop potential groundwater zone map of the current study. Hence, it is necessary to understand the methods and way to approach towards groundwater potential zone identification and mapping.

From the analysis of related literature review above, this study summarizes groundwater potential zone mapping using SWAT and GIS-based MCDA-AHP techniques by identifying factor influence the occurrence of groundwater potential zones that affect the occurrence and movement of groundwater are recharge, lineament density, geomorphology, lithology, soil type, land use/cover, drainage density, slope, topographic roughness and total wetness index (TWI). So depending up on the suitability and the type of region of study, the main parameters or any relevant parameters had been chosen and weighted by AHP to generate groundwater potential zones.

Establishing relationship between SWAT, GIS processing and hydrologic phenomenon maximizes the efficiency of identification of potential zones for water resources development. For the same, all those are used to develop a composite map showing different classes of groundwater water potentialities, the layers have integrated in the GIS environment by giving different weightages to respective layers in terms of their influence on groundwater, this method is called Weighted Index Overlay Analysis method. However, the weights of different parameters/ themes/ layers can be given arbitrarily by the user on the basis of his personal judgment. Here, the role of decision maker is critical. Hence, by using AHP, multiple criteria can be evaluated, compared with each other, priorities can be set and their weights can be accorded on a rational quantitative basis, thus aiding the decision maker in making rational decisions. The map generated from weighted overlay GIS environment with AHP method helps very well in predicting the groundwater potential surface.

Overall summarized conceptual framework of all reviewed literatures under this chapter is contextualized to the current study (to formulate simplified view (framework) for identifying and mapping groundwater zone) shown on Figure 2.1 below.

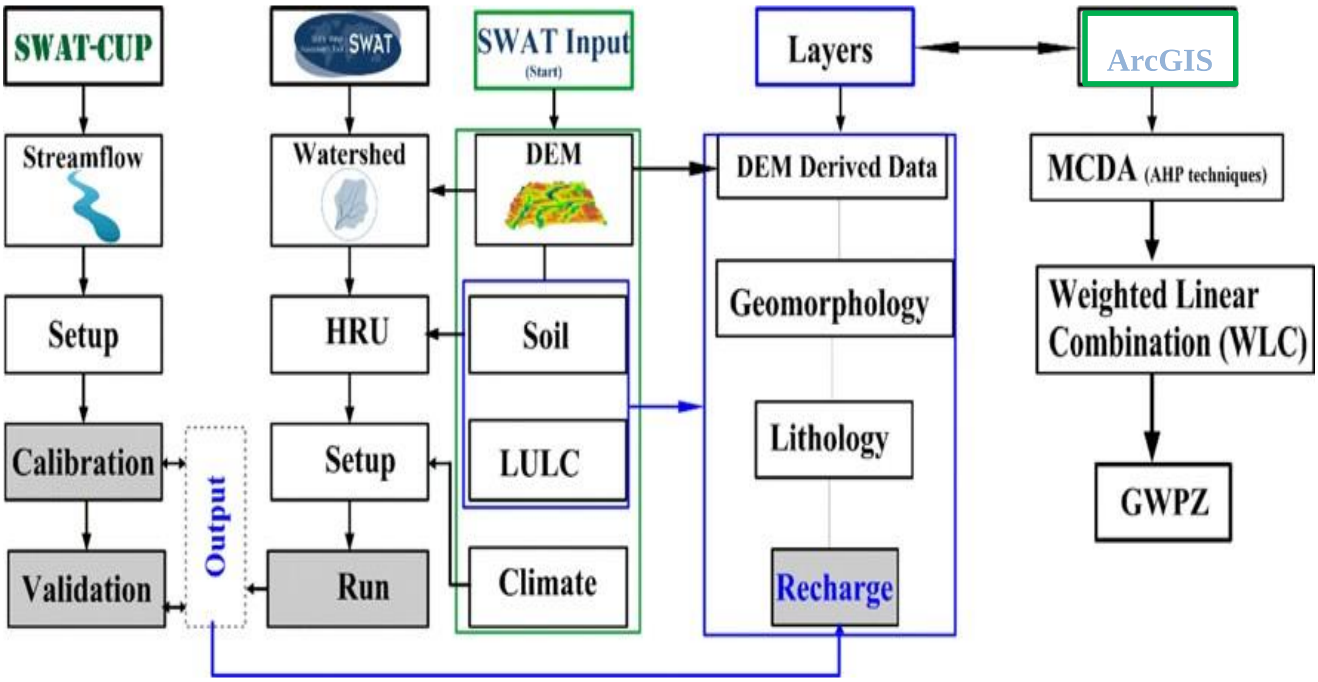


Figure 2.1: The Conceptual Framework of the Methods

3. MATERIAL AND METHODS

3.1. Description of the Study Area

3.1.1. Location and Accessibility

The Gidabo Catchment is one of the largest catchment which is found at south-eastern part of rift valley lakes basin of Ethiopia (Figure 3.1). It is one of the three medium sized rivers discharging in to Lake Abaya. The river is approximately 120km in length with estimated area of 3302km^2 (Michel, 2015) originates on the north-eastern mountain range of Soka Sonicho specific place of Gelala Mountain with 6.8ºN-6º57'N flows west first and then for most of its course south wards along the eastern floor of the Great Rift Valley, then drains in to lake Abaya at 38ºE-38º38'E, the elevation catchment is 1175m above mean sea level (a.m.s.l) in lake Abaya and 3200m a.m.s.l at the Gelala summit in the north east.

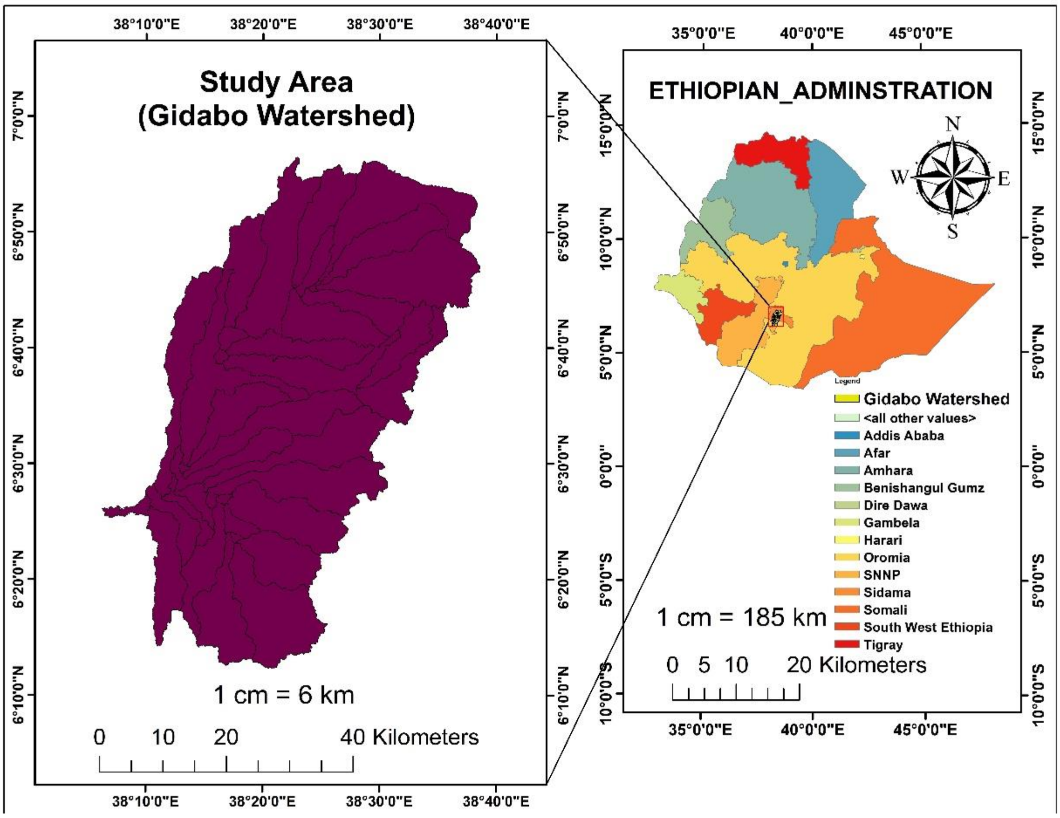


Figure 3.1: The study area map of Gidabo Watershed

3.1.2. Climate

The climate change impact on the hydraulic cycle is one of the major challenges in the context of water resource management (Messene, 2017). Climate in the Gidabo River Catchment ranges from semi-arid in the rift floor to humid in the mountains of the escarpment. In the highlands and escarpment bounding the rift floor precipitation exceeds 1600mm/year, whilst at the lowest altitude in the rift floor precipitation is often below 800mm/year. Precipitation is characterized by a bimodal pattern with maximum peaks during April and May, ("small rainy" season), during October to September, in the ("Main rainy" season). Like as most parts of Ethiopia. The diurnal variation of air temperature in the basin is more visible than its seasonal variation. Average monthly temperature varies from 21ºC to 25ºC in the rift floor to less than 11.5ºC to 13.5ºC in the high altitude plateau /highland (Mechal, 2015).

3.1.3. Soil

Soil is one of the important factors which control the movement and occurrence of groundwater potential (Natural Resource Conservation Service, 2015). The soil is a weathering product of ignimbrite. It is frequently deep and reddish brown, clayey-loamy. In the south the soils are reddish brown, clayey to loamy textured. The thickness according to the morph dynamics stability and mostly it possesses excellent drainage. In the south, the soil become brownish and clayey textured: the thickness ranges from 0.5 to 4m in topographical lower places colluvium materials are found, which result from creeping of the slopes, they are poorly drained and swampy. (Yasin, 2004).

3.1.4. Land use and Land cover

The land use condition in the Gidabo Catchment is controlled by alititude and rainfall. According to Habtamu and Rapprich (2014) the vegetation cover in the study area varies from east to west. It depends on the alititude and soil type across the catchment. In the plateau, up to 3000 m.a.s.l , some cereal juniper trees, bamboo-ticket, exist. The valleys slopes are covered with grassland and some cereal crops like barley and wheat occur on the wide marshy valleys which separate the convex interfluves. The major crops grwon in the catchemnt are coffee, enset, maize, and teff as well as the livestock production is also the main activity of the community. The top most part of the escarpment (2400-2700 m.a.s.l), contains considerable bamboo tickets, which the local people use for different purposes.

In the northeastern part of the Catchment the juniper trees at the top and conifer trees at lower elevation (coffee is extensively cultivated together with Enset (False Banana), the former one limited to the lower escarpment, up to 2300 a.m.s.l). The slopes up to 2000m are widely taken up by crops (maize and sorghum), and cash crops as well as fruits (mango, banana, orange etc.) whereas above 2000m crops like barley, beans etc. grows. The natural vegetation in the eastern part of the catchment has been changed by human activity, and is replaced by voluminous coffee cultivation.

3.1.5. Geology Setting

The geological setting of the Main Ethiopian Rift is complex due to composition of volcanic rocks of different types and age that is lateral discontinuous and intersected by fault

(Agarwal, 2013 as cited Kebede, 2015) in addition to its geological complexity, the rift setting is characterized by great physiographic difference between the rift floor and the highland. One of the serious problems related to groundwater use in Ethiopian rift is poor water quality associated with areas with intensive agriculture have shown thickening of aquifer sediment due to the extensive pumping of boreholes, leading to a decrease in storage capacity of deep aquifers and further reducing surface water resources. In addition to these environmental impacts, overexploitation of aquifers can also contribute to inequity between social groups since access to expensive pumping technology is limited and not evenly distributed (Molla et al., 2017).

The Gidabo River Catchment lies in the Ethiopian rift system, which is enclosed by variety of volcanic rocks (Basalt, Ignimbrites, and Rhyolites, Trachyte’s, Pyroclastic) and to a minor part by lacustrine sediments. These rocks are highly affected by the late tertiary rifting activity and erosion processes which resulted in a wide range of elevations from 1175m a.m.s.l at lake Abaya in the west to about 3200m a.m.s.l at the Gelala summit in the north east. As a result of typical rift morphology the three major physiographic regions are the rift floor, escarpment and highlands (Mechal. 2015). There are two geological futures are considered in this study such as lineament and lithology. Lineament is a linear feature on the earth’s surface such as fault and lithology is the composition of geologic formations within the earth’s subsurface. For example sandstone, limestone etc.

3.1.6. Hydrogeology

Hydrogeology is the branch of applied geology that studies the distribution and movement of ground water in relation to its geologic environment. Hydrogeology combines aspects of both the physical sciences, such as chemistry and physics, with their applications in engineering and biology (Bredehoeft, 1989). Hydro geologists work both in the field to measure data directly from groundwater basins, wells or springs, as well as in the office performing site investigations or managing sensitive water resources within a region. They play a vital role in supplying fresh water globally given increasing demand for limited resources around the world. The level of complexity of the hydrogeological setting was highly variable from region to region in Ethiopian rift (Saraf and Choudhury, 1998) understanding of the regional and local hydrogeological setting was required for adequate development of groundwater resource. The hydrogeology of the Gidabo catchment is complex due to the geometry of the rift, the variability and lateral discontinuity of the volcanic rocks and the disruption of lithology by faults (Srivastava and Bhattacharya, 2006).

3.2. Data Sources and Processing

Both the SWAT model and the GWPZ mapping have extensive data requirements. The SWAT model needs time-series and spatial data including solar radiation, rainfall, wind speed, temperature, and relative humidity. I have collected the data mainly from different offices and freely available websites as described in Table 3.1.

Geomorphology, lithology, stream flow, soil, and springs and wells data were obtained from MoWIE database. A 20m spatial resolution LULC and DEM were downloaded from GlobeLand 30(Jun et al., 2014) and USGS, respectively. The DEM-derived topographic attributes such as lineament density, slope, roughness, and topographic wetness index and drainage density were processed mainly in the ArcGIS interface. All the maps were re-projected to Adindan/UTM zone 37N before incorporating in the modeling and GWPZ mapping process.

Table 3.1: Raw and Processed Data Sources and Descriptions

Data(Raw data)	Source and description
Climate	National Metrological Institute of Ethiopia
Stream flow	Ministry of Water Resources, Irrigation, and Energy, Ethiopia
DEM	USGS “earth explorer” website
Spring and well	Sidama and SNNP regional state water, mine and energy office and water work construction enterprise
LULC	The Global Land Cover-SHARE Website
Soil	Harmonized world soil database (FAO)
Lithology	

	Ethiopian National Cartography and Remote Sensing Institute
Geomorphology	Ethiopian Geological Survey
DEM derived data	These maps are processed using different algorithms in ArcGIS, the maps are lineament density, slope, Roughness, topographic wetness index, and Drainage density.

3.2.1. Observed Meteorological Data

For the simulation of hydrological processes, the National Metrological Service Agency of Ethiopia (NMSAE) supplied the relevant climate data for this investigation. For this study five station was selected, because there are likely to be few meteorological stations within the catchment with a long period of record, data from stations surrounding the basin was also utilized from 1991 to 2020, meteorological variables such as humidity, solar radiation, and wind speed, as well as rainfall, maximum and minimum temperature, were gathered from meteorological stations Aletawondo, Yirgalem, Hagerselam, Dilla, and Kebado.

Table 3.2: Location of selected precipitation gauging stations within the catchment

Staion No.	Station Name	Latitude (^{o})	Longitude (^{o})	Elevation a.m.s.l (m)	Duration of Data	% of missing values
1	AletaWondo	6.604	38.418	1947.00	1991-2020	12%
2	Yirgalem	6.817	38.393	1831.00	1991-2020	13.5%
3	Hagereselam	6.470	38.520	1856.00	1991-2020	11.2%
4	Kebado	6.433	38.333	1807.00	1991-2020	10.2%
5	Dilla	6.367	38.300	2809.00	1991-2020	10.3%

(Data Source: NMAE, 2022)

3.3. Data Analysis

3.3.1. Filling Missing Rainfall and Stream Flow Data

Most of the rainfall and stream flow data in the study area have short breaks in their records, and buck up of systems it is necessary to estimate the missing rainfall to keep the continuous time series of the data. The data series obtained from stations contains numerous missing data inside the records different techniques had been employed to fill the data gap; such as inverse distance square method, stations average method, normal ratio method, and quadrant method and so on. When the total annual rainfall at any of the “n” gauges differ from annual rainfall at the point of interest more than 10% normal ratio method was recommended (Sajikumar and Pulikkotti 2013). In this the Normal Ratio Method was used to estimate missing rainfall and stream flow data. This method relies on the assumption that consecutive days of precipitation are, on average, similar compared to overall long-term averages. By taking the average historical ratio between two successive values, this method can estimate the potential rainfall on days when it was not collected or recorded. This method helps to provide a more accurate picture of overall precipitation patterns and can be used as part of a larger data set.

$$\mathrm{Pm} = \frac{1}{N}\sum_{n=1}^{n}\left(\frac{Nm}{Ni}\right) * Pi$$

Whereas, $\mathrm{Pm} =$ the computed missing data on each section

$Nm =$ average annual rainfall at rain gauge for data were missed

$Ni =$ the total average annual rainfall on the station

$N =$ total number of station

$Pi =$ the precipitation for the same period for the the same storm

3.3.2. Consistency Checking

If the conditions relevant to the recording of a rain gauge stations have undergone a significant change during the period of record, inconsistency would raise on the rainfall data of the stations. Double mass curve analysis was used in this work to find contradiction in a rainfall data. The double mass curve is a well- known, easy to use technique for detecting and correcting anomalies in hydrological data that are induced by changes in observation methods or data processing.

The double mass curve is based on a graph comparing station's cumulative quantities vs. cumulative amounts of a group of nearby stations over the same period. The graph draws a straight line if the processing is homogenous. If there is a major change in the regime, it should be reviewed for consistency and continuity by using: -

$$\mathrm{P_{CX}} = \left(\frac{P_X * M_C}{M}\right)$$

Where, $\mathrm{P_{CX}}$ $is\ corrected\ precipitaion\ at\ staion, X$

$P_X\ is\ uncorrected\ precipitaion\ at\ staion, X$

$M_C\ is\ corrected\ slope\ of\ the\ double\ mass\ curve$

$M\ is\ uncorrected\ slope\ of\ the\ double\ mass\ curve$

3.3.3. Homogeneity Test

The homogeneity of the selected gauging stations daily rainfall records were carried out by non-dimensional equation. The non-dimensional observed precipitation data is said to be homogenous if the periodic data are proportional to an appropriate simultaneous period, method, materials, place, and environment (McKuen, 1998). Homogeneity analysis was used to separate a change in the statistical properties of the time series data which was caused by either natural or man-made like alterations to land use relocation of the observation of gauging stations. Therefore, checking homogeneity of group stations is essential to select the representative meteorological station for the analysis of areal rainfall estimation.

The restrictions of homogeneity assure that the observations are from the same population. The non-dimension of the month's values was calculated as;

$$\mathrm{Pi} = \frac{Pi*}{p1} * 100\%$$

Where, $\mathrm{Pi\ is\ a\ non-dimensional\ value\ of\ rainfall}$

$Pi* = \mathrm{\ is\ over\ year\ averaged\ monthly\ rainfall\ at\ station, i}$

$P1$ = is the over year average yearly rainfall of the station

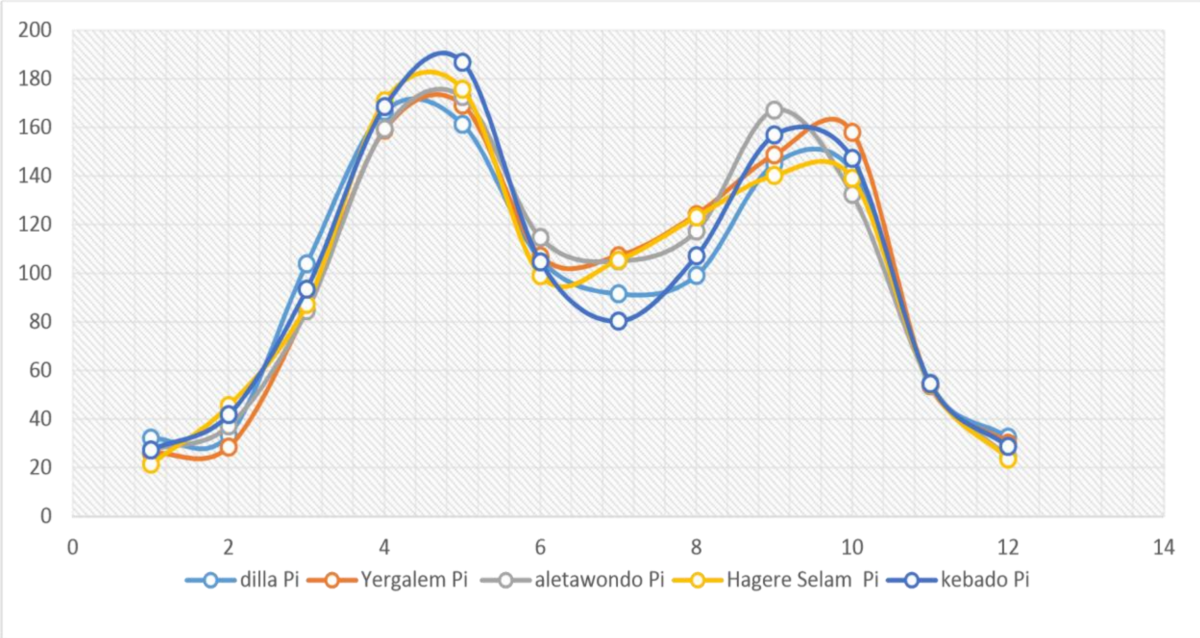


Figure 3.2: Homogeneity test of rainfall

3.3.4. Estimation of Aerial Precipitation

Theisson polygon method was used to calculate daily areal precipitation. Rainfall varies in strength and duration depending on where it falls, hence the rainfall recorded by each rain gauge should be weighted according to the area it supposed to represent. This strategy is beneficial in places that are not particularly uneven surface, but rather plain, and when the number of rain gauging stations is small in comparison to the size of the area.

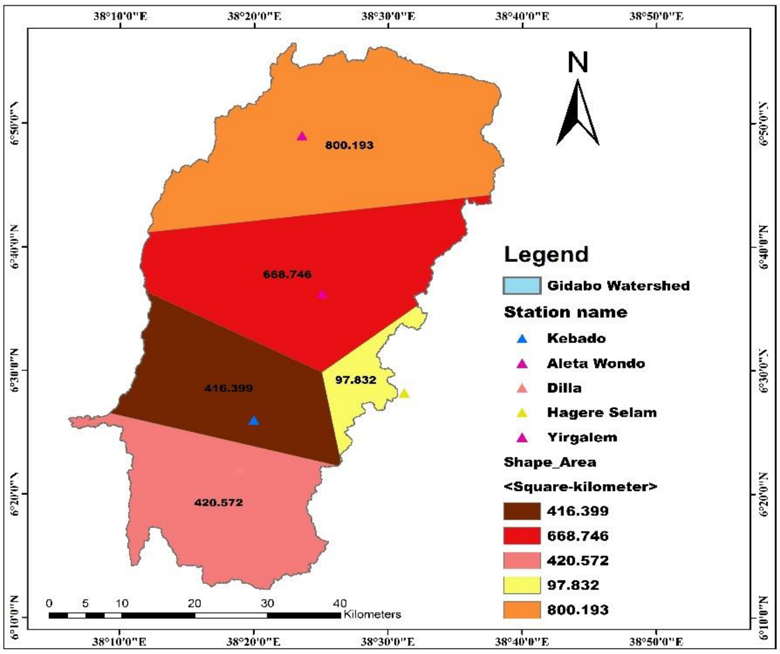


Figure 3.3: Theisson Polygon of Rainfall gauging stations

3.3.5. SWAT Model Description and Data Input

The SWAT model simulation was shown as the best modeling tool for a variety of reasons. First and foremost, it is a public domain model that is freely used. Second, in nations like Ethiopia, long-term observational data series are few, making sophisticated models impractical: nevertheless, SWAT is computationally effective, efficient and uses minimal data.

3.3.5.1. Catchment Delineation

Based on flow directions and accumulations, the ArcGIS tool in Arc SWAT divides watersheds into a number of hydrological related sub basins. The delineation of the catchment and sub basins was done using automatic delineation process that used a Digital Elevation Model (DEM). A high level of spatial variability can be simulated, since SWAT allows the division of the Catchment into large number of sub-watersheds, which are then further subdivided into unique combinations of soil, land use and slope characteristic areas called hydrological response units (HRUs). The smaller the threshold area, the more the intricate the drainage networks are, and the more sub basins and HRUs. This, on the other hand, necessitate greater processing time and space. As a result, an optimal Catchment size was chosen that balances both. Five catchment outlets were manually added to the gauging stations, in addition to those provided by the model, and which were later utilized as a point of calibration and validation of simulated flows. As a result, five gauging stations were defined: - Yirgalem, Aletawondo, Hagerselam, Kebado and Dilla.

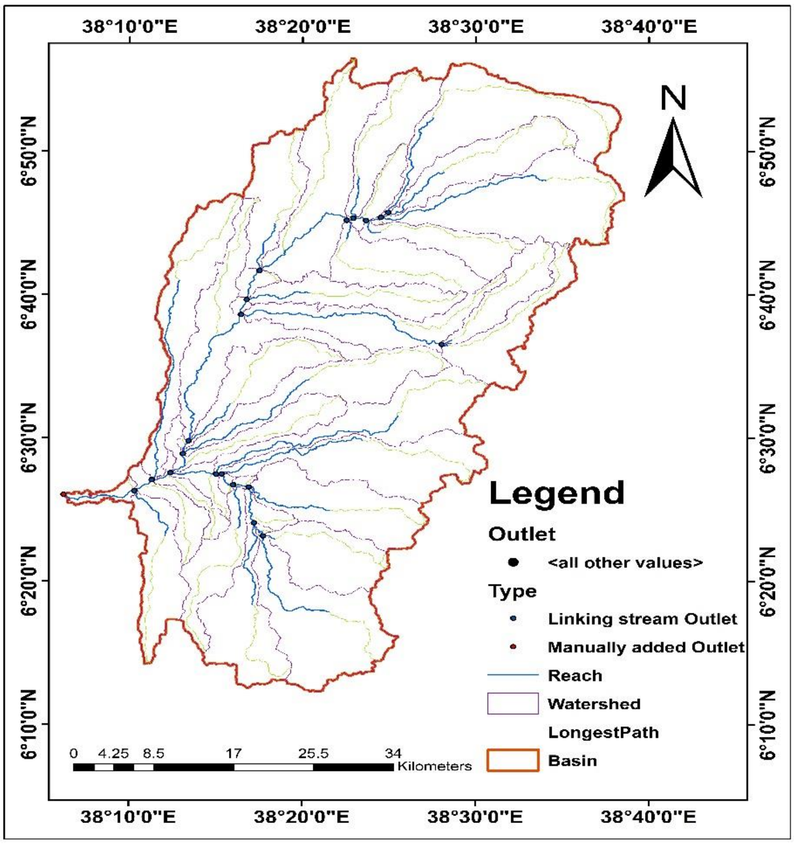


Figure 3.4: Delineation of Gidabo Watershed

3.3.5.2. SWAT Model Data Input

The major SWAT model inputs are the shuttle Radar Topographic Mission (STRM) DEM data with 20m resolution was used to delineate the Gidabo River Watershed. The sub-watersheds are delineated such that they represent the physiographic regions (highland, escarpment and rift floor), Soil, Land-use/Land-cover, and Weather data. The model setup starts with importing grid-based spatial data, delineating the watershed, creating sub basins, and definition of HRU. The SWAT model uses DEM to delineate the Catchment and create stream networks and sub basins.

A. Digital Elevation Model (DEM)

SWAT Catchment delineator methods require Digital Elevation Model (DEM) data to calculate flow accumulation, stream networks, and Catchment delineation. In addition, the drainage patterns of the land surface landscape were studied. The DEM was used to drive sub basin metrics such as slope gradient, terrain slope length, and stream network characteristics such as channel slope, length, and width.

Digital Elevation Model (DEM), land use/land cover, and soil are the three spatial data inputs that SWAT model requires. As a digital file, a DEM describes the elevation of any point in a Particular area at a specific spatial resolution. It’s one of SWAT’s most important inputs for dividing the Catchment into sub-watersheds or sub-basins, as well as analyzing the drainage pattern, slope, stream length, and channel width within the watershed. The inputs are 10*10m DEM from MoWIE office, land use/cover with 10*10m resolution with the scale of 1:250,000. The research area’s soil map was clipped from the soil shape file obtained from MoWIE, which has a resolution of 10*10m and its scale ratio of 1:250,000.

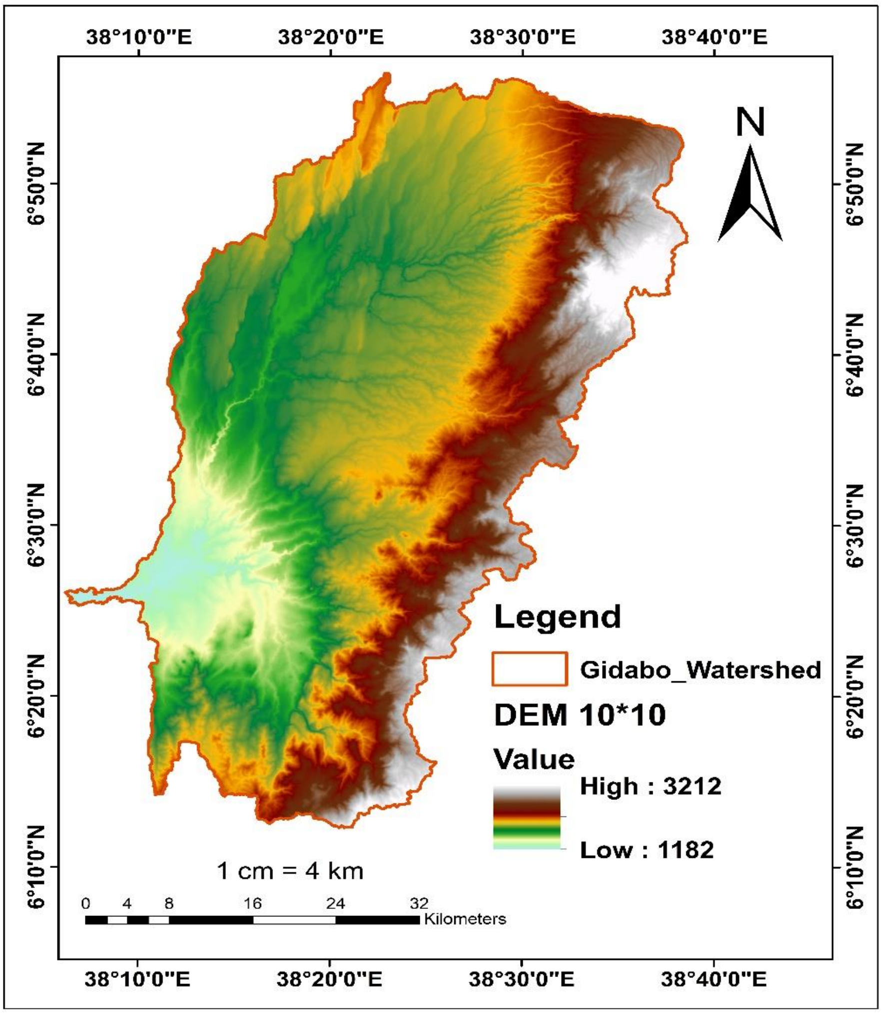


Figure 3.5: Digital Elevation Model (DEM) of Gidabo Watershed

B. Climate Data

SWAT requires daily precipitation, maximum and minimum temperatures, solar radiation, relative humidity, and wind speed. To complete the SWAT model setup the climate data were processed using weather generator model WXGEN, prepared in the required format, and added to the SWAT model database. One weather station data were processed and imported into the model. The weather generator initially generates precipitation for the day separately based on the values of the weather generator parameters. Maximum and minimum temperatures, solar radiation, and relative humidity are all calculated. Finally, the wind speed is generated. Only one synoptic weather station in the Gidabo Catchment was used for this investigation, which was generated using the Ethiopian weather generator.

The stream flow data starting from 1997 to 2006 at Measso river gauging stations were obtained from MoWIE, were used to calibrate and validate the model. Regression method was used to estimate missing data.

C. Land use/cover

Land use/cover is one of the most important factors that affects surface erosion, runoff and evapotranspiration in a watershed. Land use/cover map from MoWIE office with 10*10m resolution with scale 1:250,000 were used to run the model.

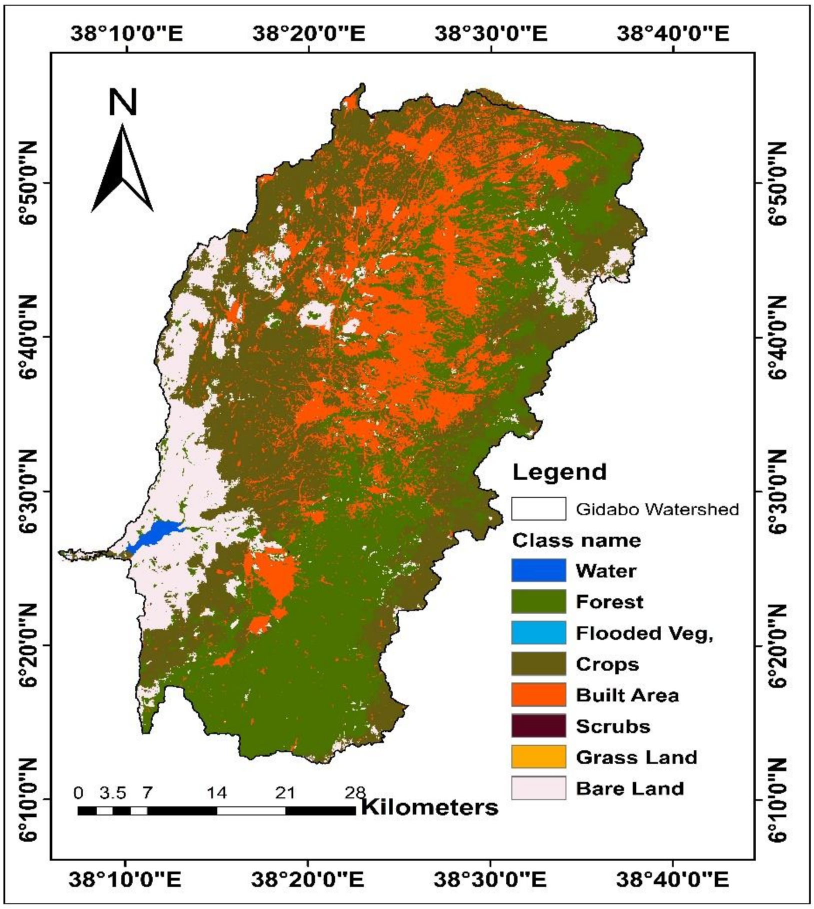


Figure 3.6: Land-Use/Land-Cover Map of Gidabo Watershed

Table 3.3: Land-use/Land-cover

No	Swat Code	Code Name	% of coverage	Area(KM^2)
1	FRST	Forest-Mixed	0.794	19.0564
2	AGRR	Agricultural Land-Row Crops	70.542	1794.805
3	WETN	Wetlands-Non-Forested	0.358	8.592179
4	AGRC	Agricultural Land-Close grown	12.106	338.55105
5	URML	Residential-Med/Low Density	4.10	98.402
6	WATR	Water	2.24	53.761
7	RNGB	Range-Brush	7.86	188.6439
Total			100	2400.05

D. Soil

Soil data, which includes both physical and chemical parameters, is one of the main inputs for the SWAT model. The Ministry of Water Resources and Energy of Ethiopia provided a soil shape file with a resolution of 10m*10m and a scale of 1: 250,000 for the research area.

It was necessary to create a User Soil Database in order to integrate the soil map into the SWAT model. All varieties of soils in the study region were represented in this database, along with their characteristics. Even though the soil map was clipped to the size of the study region from an Ethiopian soil map (MoWIE), the physio-chemical parameters of each soil type were taken from FAO ((Hemme et al., 2019).

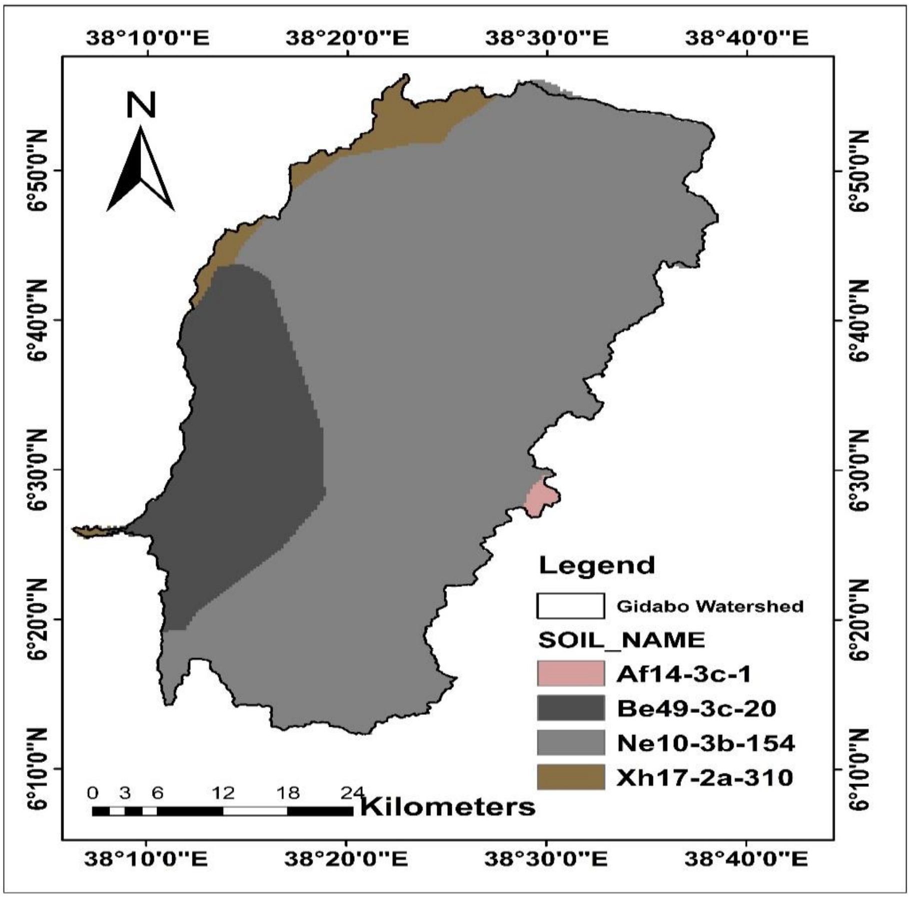


Figure 3.7: Soil Map of Gidabo Watershed

Table 3.4: FAO Soil type Classification

NO	Soil code	Code Texture	% of Coverage	Area(km^2)
1	Ne10-3b154	SANDY CLAY	50.026	1200.649
2	Xh17-2a310	LOAM	43.449	1042.798
3	Be49-3c-20	CLAY	5.216	125.1866
4	Af14-3c-1	CLAY_LOAM	1.309	31.41665
		Total	100	2400.05

The land use, soil and slope data sets were imported, overlaid and linked with the SWAT databases. Threshold values of 5% land use, 20% soil, and 20% slope were used to discretize the 41 sub-watersheds into 148 HRUs.

The weather variables used for droving the water balance are daily precipitation, minimum and maximum daily air temperature. These data were obtained from the Ethiopian National Meteorological Agency (NMA) for weather stations located within and in close proximity to the Catchment (Table 2).

3.4. SWAT Model Performance Evaluation

The parameter sensitivity analysis was done using the Arc SWAT interface and the built-in SWAT sensitivity analysis tool (Van Griensven et al., Van Griensven and Bauwens, 2005). As suggested by Neitsch et al. (2011), the sensitivity of the simulated stream flow to twenty hydrological parameters was tested using the default lower and upper bound parameter values. Based on the sensitivity test, 12 parameters have considerable effect on stream flow simulation, which means that they have a relative sensitivity of more than or equal to 0.01(Table 3.5).

Table 3.5: Flow parameters Definition and Ranges selected for Calibration

Parameter	Definition	Range
r_CN2.mgt	Runoff curve number by soil conservation service (SCS)	-0.5 – 0.5
v_GW_DELAY.gw	Groundwater delay (days)	0 – 500
v_GWQMN.gw	Minimum depth of water required in the shallow aquifer for return flow to be initiated(mm H_2O)	0 – 5000
v_ALPHA_BF.gw	A coefficient that shows how ready the water to moves to the root zone from shallow aquifer	0.02 – 0.4
v_ ESCO.hru	Base flow recession coefficient	0 –1
v_ CH_K2.rte	A coefficient to adjust the soil evaporation demand	0.01–150
r_ SOL_AWC. sol	Hydraulic conductivity of the main channel (mm/hr.)	-0.5 – 0.5
r_SOL_K.sol	Soil available water capacity (mm H_2O)	-0.5 –0.5
v_SURLAG.bsn	Saturated hydraulic conductivity (mm/hr.)	0.05 –24
r_HRU_SLP.hru	Average slope steepness (m/m)	0 –0.6
r_SOL_BD.sol	Moist bulk density (Mg/m^3)	-0.5 –0.6

Note: v_ parameter value is replaced; r_ parameter value is multiplied by (1+ a given value)

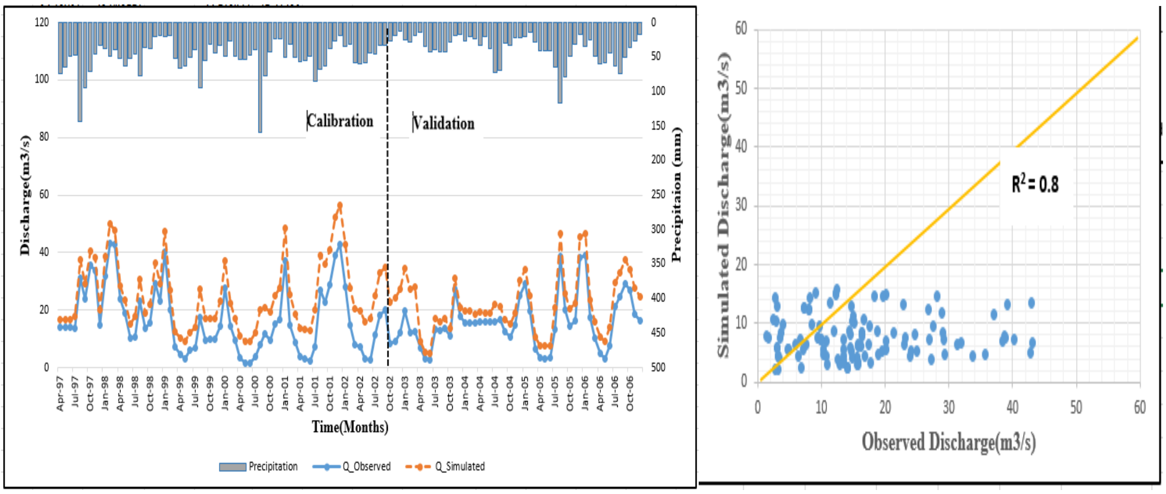
Hydrological models usually contain parameters that need to be estimated through calibration so that observed and simulated output values are in agreement (Tolson and Shoemaker, 2007; Zhnag et al., 2009, 2011).

The first three years of the available data from 1991-1993 were used as a warm-up period to mitigate the unknown initial conditions and were excluded from the analysis. The period from 1997-2002 were used for calibration and the period from 2003-2006 for validation, as Gidabo at measa station has no data for 2006-2020, no model validation was carried out in this case.

The Sequential Uncertainty Fitting Program (SUFI-2) of the SWAT-CUP package were was used for parameter optimization. The parameter ranges are based on the recommendations given in the SWAT documentation of Neitsch et al. (2011).

The overall model performance is found to be satisfactory for measa discharge stations for both calibration and validation periods. Recharge was computed at the HRU scale and the results aggregated to the sub-basin scale. Due to a lack of groundwater monitoring wells in the watershed, it was not possible to compare the simulated discharge with groundwater fluctuations.

Qi and Si are the observed modeled discharge for the i^{th} day of modeling period; $\bar{Q}$ and $\bar{S}$ are mean of n observed and calculated discharge respectively.



(a) Seasonal Variation (b) Scatter Plot

Figure 3.8: Monthly Observed and Simulated Stream flow over a Period of 1997-2006

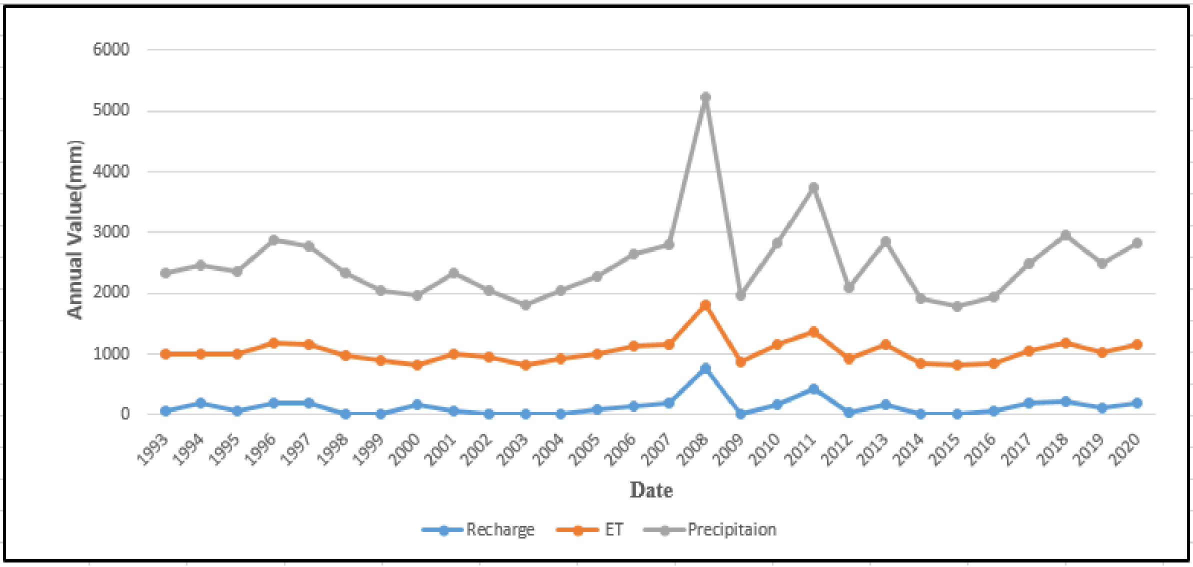


Figure 3.9: Annual Average Recharge, ET, and Precipitation over a period of 1993-2020

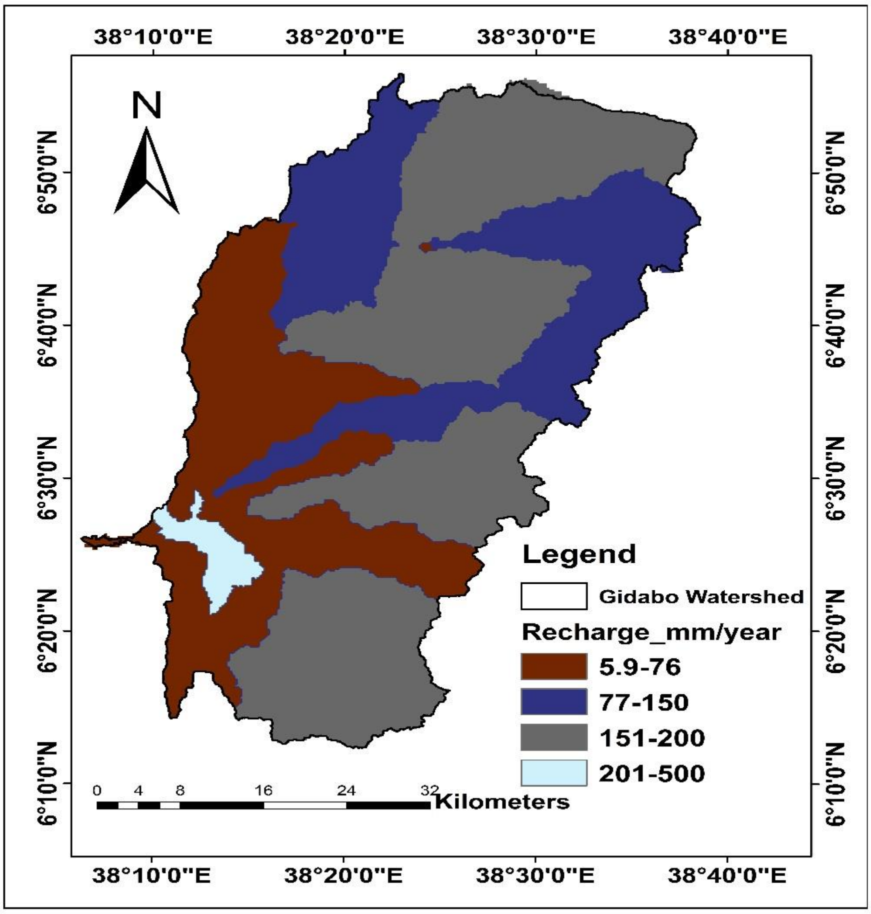


Figure 3.10: Spatial variation of simulated average annual recharge

3.5. Delineation of Groundwater Potential Zones

Multi criteria decision analysis using Analytical Hierarchical Process (AHP) is the most common and well known GIS based method for delineating groundwater potential zones. This method helps integrating all thematic layers. Groundwater potential zones were identified by considering 10 essential parameters. The thematic maps which prepared for each parameters, were converted to raster data set having the same pixel and different weightage as per their groundwater potential controlling capacity.

Pairwise comparison matrix was generated, to weight parameters. The consistency for the generated matrix was checked using AHP techniques. These 10 thematic layers were supposed to control flow and storage of water in the area. The association of these influencing factors are weighted according to their reaction for groundwater occurrence. A parameter with a high weight illustrates a layer with high impact and a parameter with a low weight illustrates a small impact on groundwater potential. The weightages of each parameter were assigned according to Saaty's scale (1–9) of relative importance value. As per the classification, weights are assigned to the thematic layers based on their importance and water holding capacity.

3.5.1. Analytic Hierarchy Process (AHP) Techniques

The Analytic hierarchy process (AHP) is a decision-making technique employed to evaluate complex decisions with multiple criteria. AHP is based on pairwise comparison of the alternatives and the involved criteria, using subjective judgment (Hoppner et al., 2011; Saaty, 2008). AHP uses weighted pairwise comparisons of alternatives and different criteria to obtain a relative ranking amongst them. This could be used in place of traditional number-crunching methods as it allows experts to consider many qualitative aspects which may not be possible when only numerical values are used. A recent survey conducted by (Razavi, Aminifar, Rabiei & Zarei, 2017) showed that using the AHP has resulted in improved decision-making accuracy in comparison to other techniques such as the Analytic Network Process (ANP), Multi-Attribute Utility Theory (MAUT) and others. A total of 10 different thematic layers were considered for this study. These 10 thematic layers are supposed to control factor of flow and storage of water in the area. The association of these influencing factors are weighted according to their reaction for groundwater occurrence.

4. RESULTS AND DISCUSSIONS

4.1. Development of Thematic Maps

As mentioned in the methodology SWAT was used to model spatiotemporal variation of groundwater recharge and various thematic maps have been developed for the selected ten parameters those affect the occurrence of groundwater potential, using GIS techniques. Each parameter has been ranked based on saaty's analytic hierarchical process to generate the groundwater potential map of the area.

4.2. Suitability Level of Factors and Reclassified Thematic Map

Groundwater potential zone mapping in the study area involves ten thematic layers such as geomorphology, lithology, slope, soil, land use/cover, lineament density, drainage density , slope, roughness, and TWI were weighted, normalized, reclassified and ranked, and integrated by weight overlay analysis(WOA) in a GIS environment. SWAT was used to simulate spatiotemporal variation of groundwater recharge and integrate the reclassified thematic layers in WOA to develop groundwater potential map.

All thematic layers were classified. Weighted and ranked according to suitability standardized to groundwater potential occurrence. For this study the reclassified map was ranked into four classes (1-4) described as very low, low, moderate, and high.

4.2.1. Recharge

Groundwater recharge is an important factor which influences the availability of groundwater, making it central to understanding groundwater potential. In recent decades, increasing attention has been given to managing aquifers sustainably (Olsen & Schou, 2018). By temporarily storing and slowly releasing surface water, the recharging of aquifers provides an effective solution for dealing with droughts, floods and dependency on seasonal rainfall (Estony & Talalaiyarasu, 2017). As well as helping to maintain groundwater availability even during climatic extremes, groundwater recharge also increases groundwater potential through both natural means such as percolation of rainwater towards the water table and artificial techniques such as injection boreholes (Oliveira et al., 2015). In summary, the higher the groundwater recharge the higher the groundwater potential.

Table 4.1: Groundwater Recharge suitability classification for GWP Zone identification

Factor	Yearly Average Recharge Range(mm/year)	Rank	Suitability classification
Groundwater Recharge	5.9-76	1	Very Low
	77-150	2	Low
	151-200	3	Moderate
	201-500	4	High

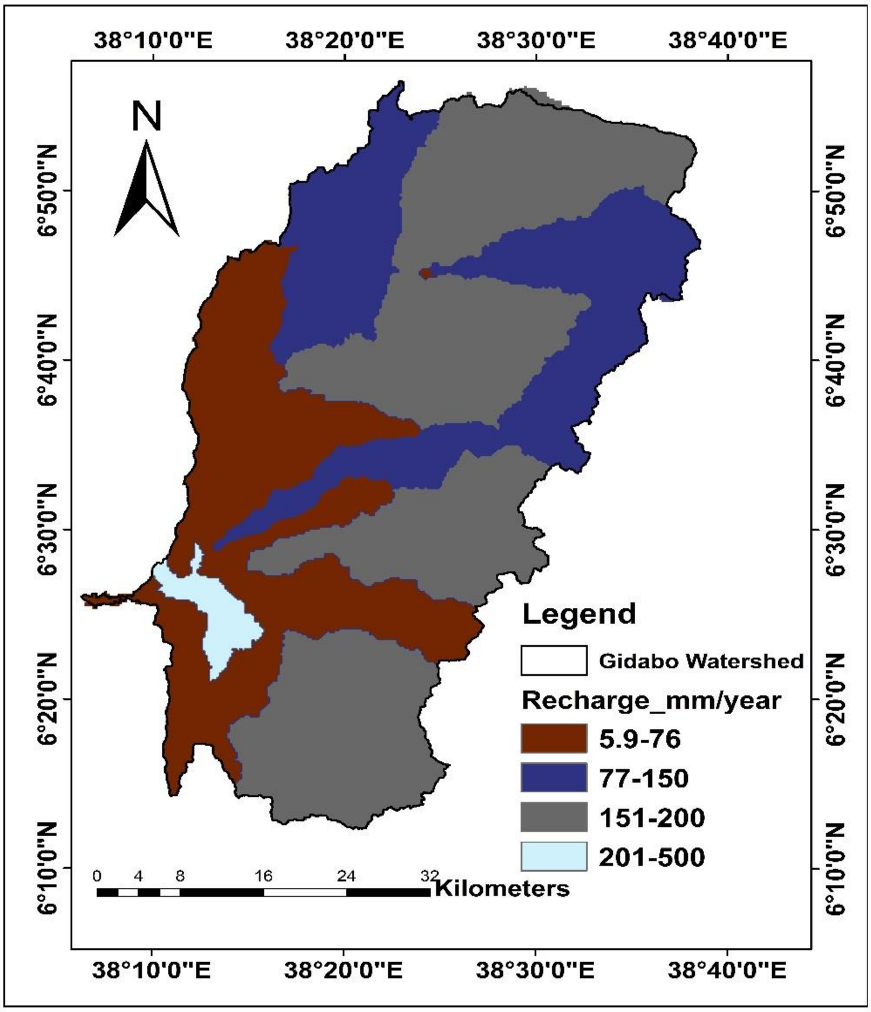


Figure 4.1: Yearly Average Recharge Ranges of Gidabo Watershed (Source: SWAT Output, 2021)

4.2.2 Geomorphology

Geomorphology represents the landform and topography of an area, and is one of the main factors used widely for the delineation of groundwater potential zones. It gives information about the distribution of various landform features as well as processes like temperature changes, geo - chemical reactions, movement of water, freezing and thawing etc. The highland region of the study area consists of hilly terrain and undulating surfaces. However, the lowland region is composed generally of gently undulating surfaces.

The main geomorphic features of the study area are the lower lateritic plateau, denudation hills, valleys and water bodies. Geomorphological map of the study shows various landforms and geomorphic unit that play fundamental role in groundwater occurrence and movement. The volcanic terrain of Ethiopia comes in a variety of landforms that has a significant importance to groundwater occurrence and movement (Seifu Kebede, 2013). The highland region of the study area consists of hilly terrain and undulating surfaces. However, the lowland region is composed generally of gently undulating surfaces.

The dissemination and range of the morphological features are highly adaptable with respect to the lithological variation. The upstream side of the river basin is composed mainly of denudation hills. The dissemination and range of the morphological features are highly adaptable with respect to the lithological variation. Land units, such as valley fills, plains and terrace have been associated with high groundwater potential while peak, mountains and ridge have been associated with poor groundwater potential (Solomon, 2003; Teixeira, 2003). Open high hills, open high mountains, hills and mountains which are obtained in this catchment shows poor potentiality for groundwater occurrence and recharge due to its sloping topography, mostly act as runoff zones. Figure 4.2 depicts the geomorphology of the Gidabo river basin. The high weight is assigned for valley fill, water bodies, younger and older coastal plain of coastal/fluvial origin and low weight for lower lateritic plateau and denudational hills.

Table 4.2: Geomorphological suitability classification for GWP Zone identification

Factor	Geomorphic/landform type	Rank	Suitability classification
Geomorphology	Mountain/hilly/escarpment/high plateau	1	Very Low
	Undulating plateau/rolling	2	Low
	Piedmont plain/foot slope/moderately discrete plateau	3	Moderate
	Level plateau/semi plain/wetlands/waterlogged land	4	High

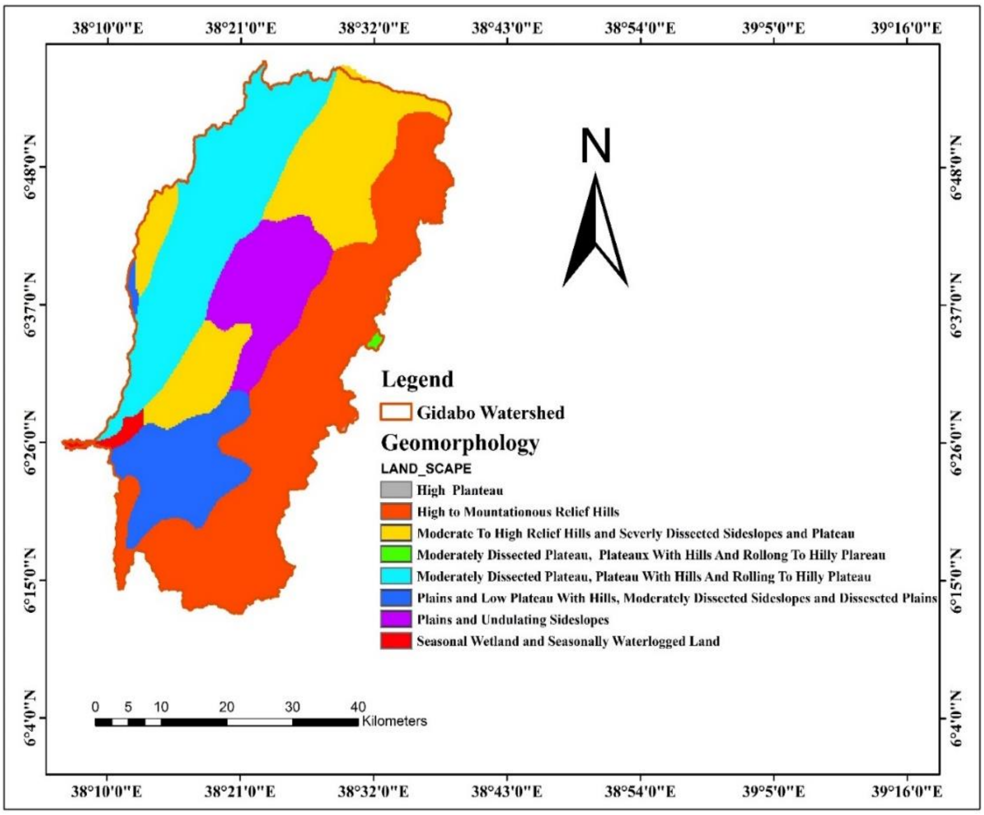


Figure 4.2: Geomorphological map of study area (Data Source: Ethiopian Geological Survey, 2021)

4.2.3. Geology/Lithology

Lithology plays an essential role in controlling both the overall occurrence of groundwater, as well as its more local distribution and hydrodynamic properties. Geologically, the lithology can range from aquifers composed of coarse-grained materials to tight water-tight clays that are predominantly impermeable. Several studies have demonstrated that a direct relationship exists between geo-materials and porosity/permeability parameters used to characterize hydrogeologic aquifers (Marques et al., 2017). In particular, sediments with high gravel or sand content have exceptionally permeable matrixes with large pore sizes leading to readily transferrable groundwater; this is not so for fine grained materials such as clays and mudstones (Banerjee et al., 2019). In addition to controlling overall permeability, lithology also has implications in regards to chemical fluxes relating to groundwater residence time. Generally, unique rock compositions dissolve at different rates with contrasting binding potentials resulting in completely different compositional signatures (Wilson et al., 2020). This fact further highlights how lithology largely dictates water residence time and solute retention providing context for some of the uniqueness associated with regional aquifer composition.

Table 4.3: Lithological classification in the study Catchment

Factor	Lithologic Unit	Description	Rank	Suitability classification
Lithology	Q	Quaternary undivided alluvium and lacustrine sediments	4	High
	Ti	Tertiary extrusive and intrusive rocks	3	Moderate

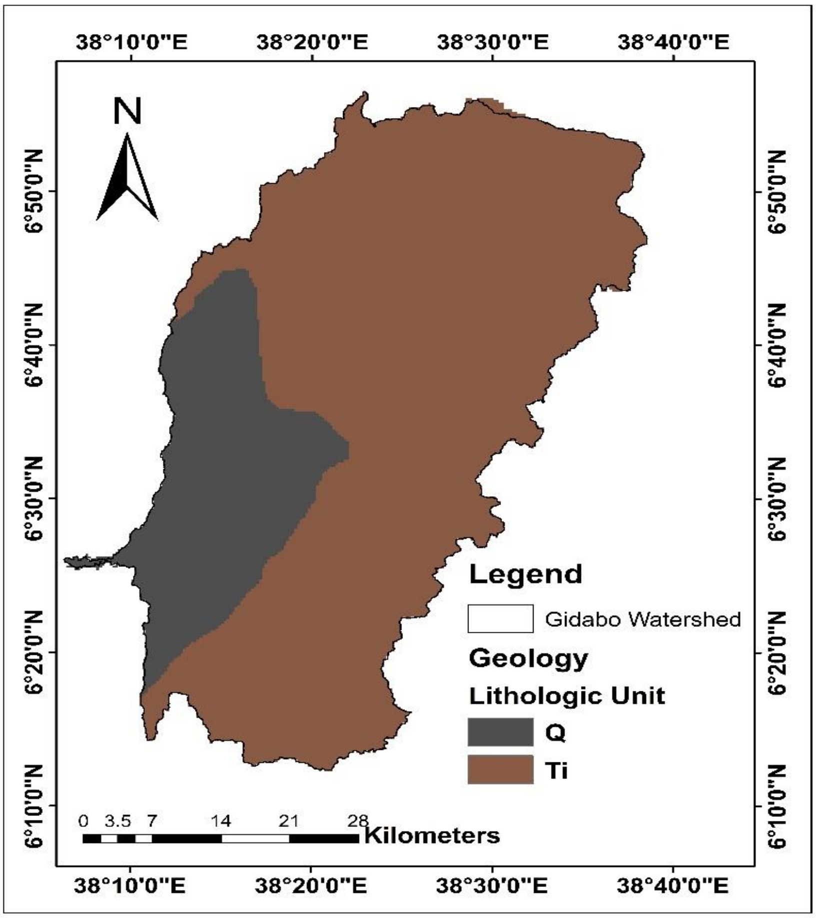


Figure 4.3: Lithological map of the study area (Source: Ethiopian National Cartography and Remote Sensing Institute, 2021)

4.2.4. Slope

Slope of the study highly indicate characteristic of groundwater occurrence and movement in Catchment that govern the capable of holding water by infiltration or it promotes runoff (Argaz *et al*., 2019). The slope is a significant terrain characteristic which express the steepness of the ground surface. Slope gives essential information on the nature of the geologic and geodynamic processes operating at regional scale. Surface runoff and rate of infiltration are influenced essentially by slope of the surface. Larger slopes produce smaller recharge because the water received from precipitation flows rapidly down a steep slope during rainfall.

Therefore, it does not have sufficient residence time to infiltrate and recharge the saturated zone. Figure 4.4 depicts the slope map of the Gidabo river basin. The slope values were reclassified and categorized into four classes such as flat to gently sloping (0 – 5), sloping to strongly sloping (5 - 15), moderately steep (15 - 30), and steep (30- 73).

Here, the slope of the study area was classified and ranked as shown Figure 4.4 on suitability for groundwater occurrence. The highest weight/value is assigned to lowest slope value (i.e. Flat to gently sloping) which give highest contribution for groundwater occurrence and recharge. Whereas the lowest weight is given to highest slope value (i.e. Steep slope).

Table 4.4: FAO Slope classification in the study Catchment

Factor	Slope (Degree)	Description	Rank	Suitability classification
slope	0 – 5	Flat to Gently Sloping	4	High
	5-15	Sloping to Strongly sloping	3	Moderate
	15-30	Moderately Steep	2	Low
	30-73	Steep	1	Very Low

(Source: Nuru, 2018; Tegegn, 2015)

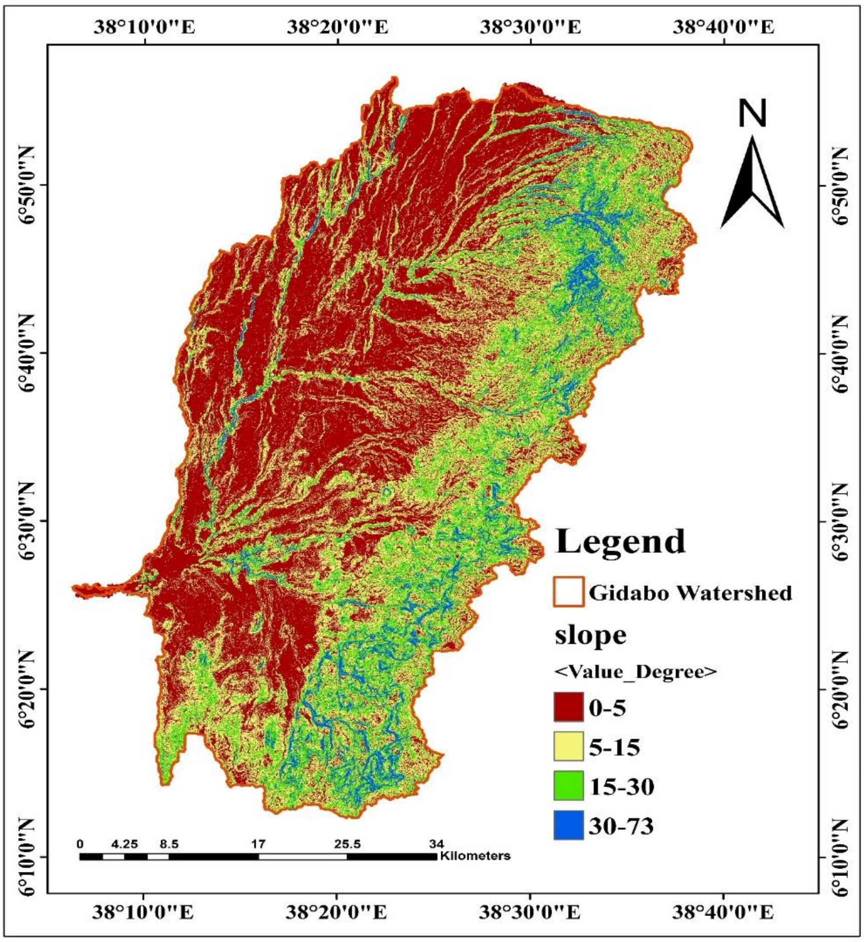


Figure 4.4: Slope map of the study area

4.2.5. Land use/cover

LULC gives the essential information on infiltration, soil moisture, groundwater, surface water etc., in addition to providing indication on groundwater requirements. The Gidabo river basin exhibits a spectrum of land use categories which include agriculture land, evergreen forests, forest plantation, and scrub forests, built up land, barren land and water bodies (Figure 4.5).

The area covered by agricultural and swampy area, which traps and hold water, which give great contribution on increasing groundwater recharge of the catchment and high weight were assigned whereas grass land and bush land have moderate effects on groundwater potential on the catchment. In other part built up area negatively affect the groundwater potential by increasing runoff during rainfall and the least weight were assigned.

The LULC classes like forest and agriculture land hold substantially high proportion of water than the built-up land, barren land and rocky surfaces. The high weight is assigned for the forest, agriculture land and water bodies. The low weight is assigned for the built up land and, barren land and rocky surfaces.

Table 4.5: Land use/cover suitability class for GWP Zone identification

Factor	LuLc Types	Rank	Suitability classification
Land Use/Cover	Urban/ Built/Settlement area	1	Very Low
	Bare Land/ Woody Cover	2	Low
	Agricultural/Cultivation/grass Land	3	Moderate
	Wet land and Water Bodies	4	High

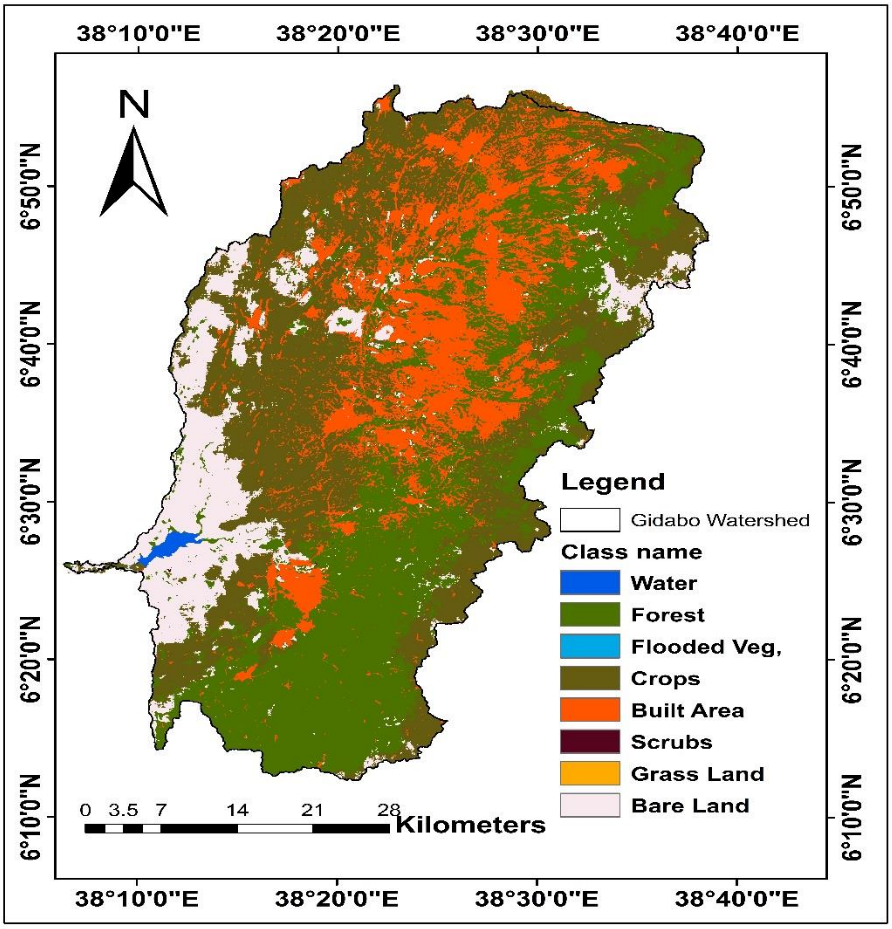


Figure 4.5: Land use/land cover map of the study area (Data Source: GLC-Share, 2021)

4.2.6. Soil

Soil property influences the relationship between runoff and infiltration rates of the soil. It determines the water storage capacity and affects the resistance of water flowing into deeper layers. The development of soils depends primarily on geologic and climatic conditions. Soil plays an important role in the occurrence and movement of groundwater in the study area. For this study both soil types and texture were considered comparatively. Soil types affect the water holding and infiltration capacity of the soil while the texture of the soil particularly plays an important role in determining the infiltration, which control the percolation of surface water into aquifer and run-off on surface and sub-surface of the land in the catchment.

The major identified soil types of the Gidabo catchment are Eutric Nitosols, Eutric Cambisols, Haplic Xerosols and Ferric Acrisols. The textural classes for the identified soil types of the Gidabo Catchment were obtained from soil user manual namely sandy clay, Clay_Loam and loam. Loam soil is moderately well drained and consist of fine loams, the soil moisture content of the soil is very good due to its fine loam texture. Clay soil has higher water storage with low infiltration rate hence assigned low weight and found around the rift floor of the catchment.

Table 4.6: FAO soil classification of the Catchment

Factor	SNAM	Soil Type	Soil Texture	Rank	Suitability classification
Soil	Af14-3c-1	Ferric Acrisols	Clay_Loam	1	Very Low
	Xh17-2a-310	Haplic Xerosols	Loam	2	Low
	Be49-3c-20	Eutric Cambisols	Sandy Clay	3	Moderate
	Ne10-3b-154	Eutric Nitosols	Clay	4	High

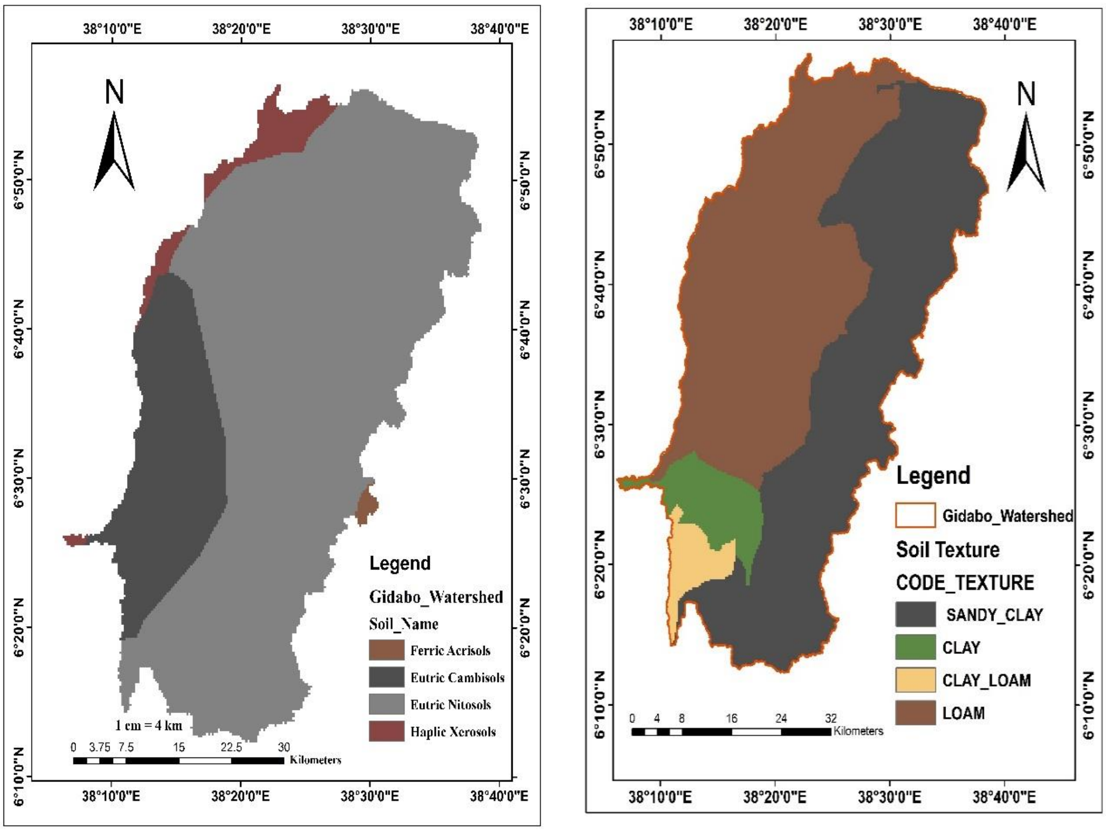


Figure 4.6: Soil classes and soil texture of study area (Data Source: Harmonized world soil database, 2021)

4.2.7. Drainage Density

Drainage density plays a very crucial role in groundwater availability and contamination. The drainage network depends on lithology and it provides an important index of infiltration rate. Drainage density is an inverse function of permeability.. High drainage density represents less infiltration and hence do not favor much on the groundwater potential of the area. Low drainage density represents high infiltration and hence contributes more to the groundwater potential. The drainage density was reclassified and categorized as Very low (0.12 - 0.78km/km^2), Low (0.79 - 1.0km/km^2), Moderate (1.1 - 1.3 km/km^2), and High (1.4 - 1.8km/km^2). Drainage density is inversely proportional to permeability (Testy, 2010). High drainage density represent less infiltration, which contributes less for groundwater potential while low drainage density represents high infiltration which positively affect the groundwater potential. Therefore, it is an important parameter in the delineation of the groundwater potential zone.

For groundwater potential zonation, high weight assigned for low density and low weight assigned for high density. Figure 4.7 depicts the drainage density map of the Gidabo river basin.

Table 4.7: Drainage density suitability class for GWP zone identification

Factor	Drainage Density (Km/Km^2)	Description	Rank	Suitability classification
Drainage D.	0.12- 0.78	Low density	4	High
	0.79- 1.0	Moderate density	3	Moderate
	1.1 - 1.3	High density	2	Low
	1.4 - 1.8	Very high density	1	Very Low

(Source: Waikar and Nilawar, 2014)

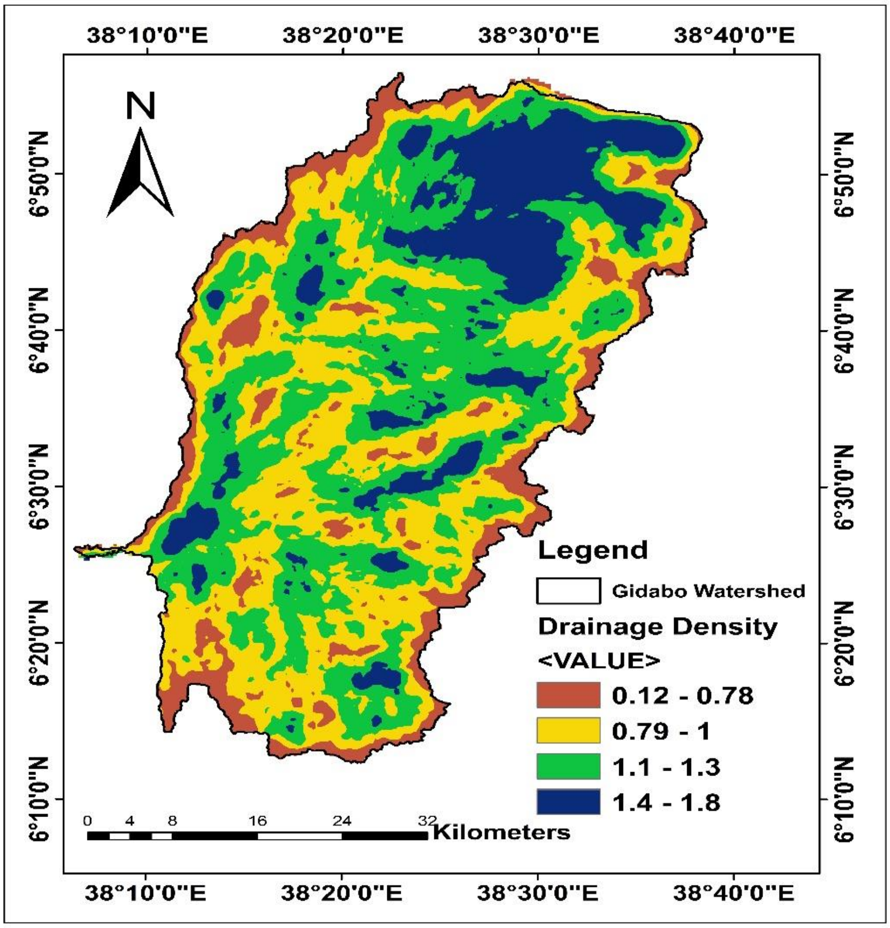


Figure 4.7: Drainage density of study area watershed

4.2.8. Lineament Density

Lineaments are structurally controlled linear or curvilinear features. It can be identified from the satellite imagery by their relatively linear alignments. Lineaments represent the zones of faulting and fracturing resulting in increased secondary porosity and permeability. The lineament density of study area is very important in groundwater potential zone identification. The lineament density map was then prepared using line density in GIS software and is depicted in Figure 4.8. By carefully examining the values obtained, the data were reclassified into four categories - Very low (0 - 0.14km/km^2), Low (0.15 - 0.38km/km^2), Moderate (0.39 - 0.66km/km^2), and High (0.67 – 1.3km/km^2). The ranks are given for lineament density based on proximity of lineaments

The main geological structures of the area were fractured resulting from Main Ethiopian Rift (MER), which is suitable for groundwater infiltration. According to Suganthi *et al.* (2013) high lineament density value indicate high weight or suitability for GWP zone whereas the low weight value for groundwater potential is low lineament density area. It is revealed that the intensity of groundwater potential decreases with increasing distance from the lineaments. High weight is assigned for high density and low weight for low density classes.

Table 4.8: Lineament density suitability class for GWP zone identification

Factor	Lineament Density (Km/Km^2)	Description	Rank	Suitability classification
Lineament D.	0 - 0.14	Very Low density	1	Very Low
	0.15 - 0.38	Low density	2	Low
	0.39 - 0.66	Moderate density	3	Moderate
	0.67 – 1.3	High density	4	High

(Source: Behzad *et.al.* 2017; Waikar and Nilawar, 2014)

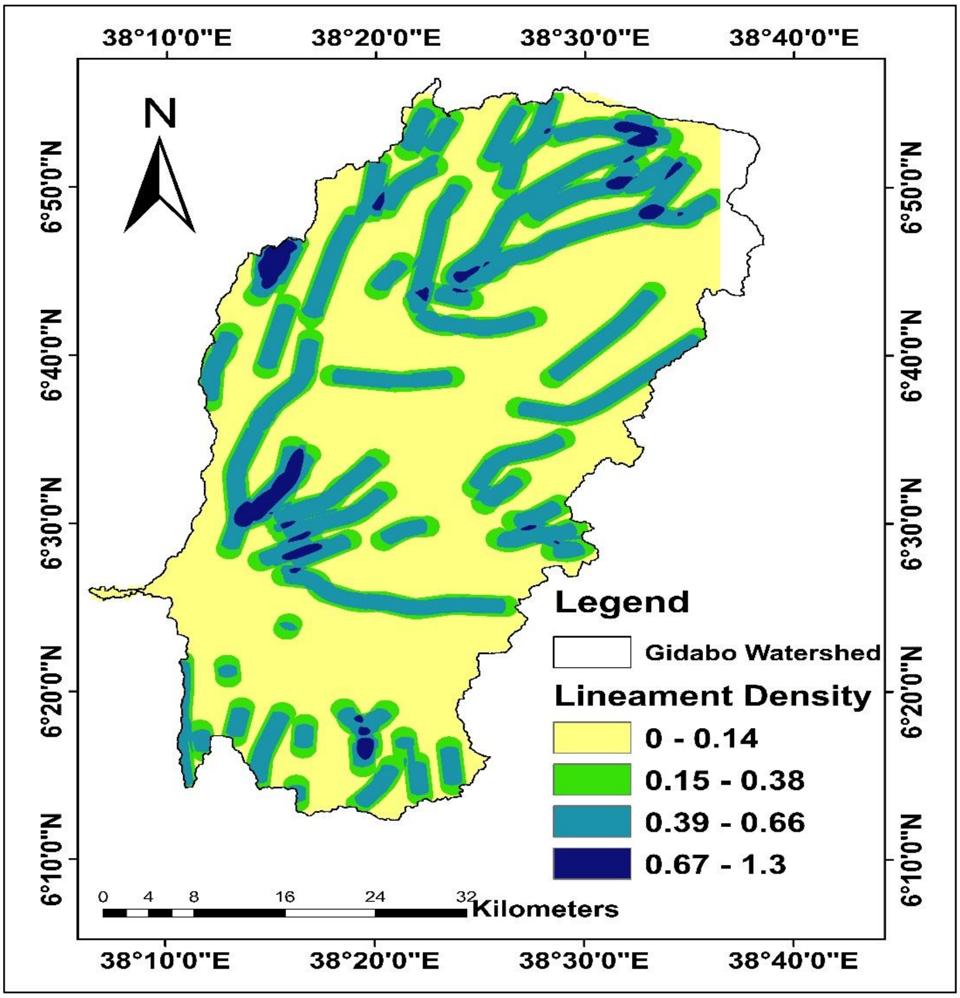


Figure 4.8: Lineament density map of the study area

4.2.9. Topographic Roughness

The roughness is mainly a characteristic of weathered rocks. It shows how big is the inter-cell difference of a central pixel from its surrounding cells in DEM. The roughness index expresses the amount of elevation difference between adjacent cells of a digital elevation model (DEM). Higher the roughness, more the undulation and vice versa. It calculates the difference in elevation values from a center cell and the eight immediately surrounding it. An area reach in with thick weathered rocks has a less GWPZ compared to a highly rough topography where usually a thin layer of weathered area dominates and hence less possibility for ground water availability. Figure 4.9 illustrates the roughness map of Gidabo river basin and the values varied from 0 to 0.98.

The values were reclassified into four categories viz: 0.11- 0.41, 0.42 - 0.5, 0.51 - 0.58, and 0.59 - 0.89. The high weights are assigned for low roughness value and vice versa.

Table 4.9: Topographic roughness suitability class for GWP zone identification

Factor	Topographic roughness value	Rank	Suitability classification
Roughness	0.11 - 0.41	4	High
	0.42 - 0.5	3	Moderate
	0.51 - 0.58	2	Low
	0.59 - 0.89	1	Very Low

(Badhwar A., Sharma N., Shandilya S. (2019)

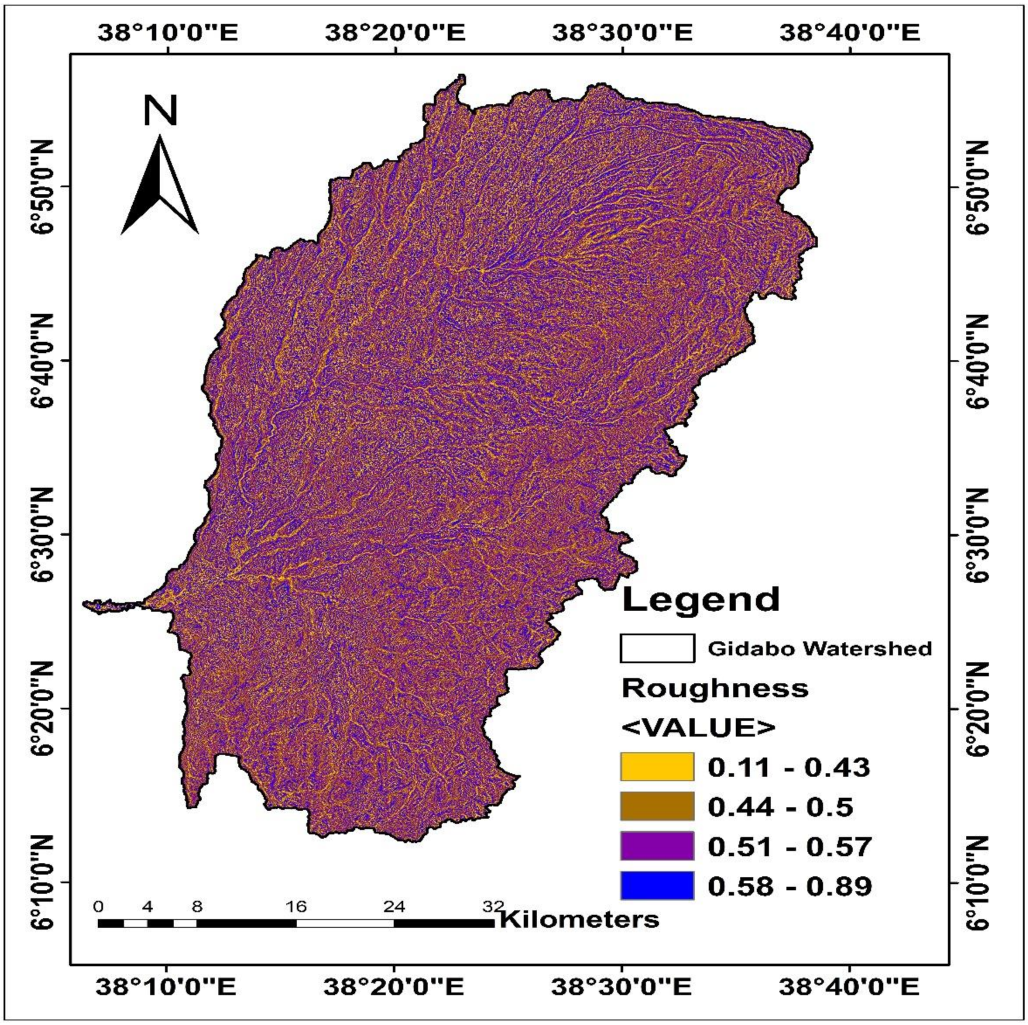


Figure 4.9: Topographic roughness of study area

4.2.10. Topographic Wetness Index (TWI)

Topographic wetness index reflects the role of topography on hydrological process, showing the ration of the upstream contributing area with orthogonal breadth to the flow direction (Beven and Kirkby, 1979; Sorensen et al., 2006). The topographic wetness index (TWI) has been used as an estimator of relative wetness assuming that fraction of hill slope flow occurs as slope-parallel lateral flow such that flow accumulation should increase with local contributing area and decrease with local slope. It is defined as TWI = $Ln\ (sca/tan\beta)$, where *sca* is the specific contributing area (upslope contributing area per unit contour length) draining to each grid cell and $tan\beta$ is the local slope. Areas with higher topographic wetness index values are likely to be wetter relative to areas with lower values. In the Gidabo watershed, the TWI varies from 3.1 -19. The values were reclassified into four categories such as 3.1 – 6.1, 6.2 - 7.6, 7.7 – 9.9, and 10 – 19. The high weights have been assigned for high TWI and vice versa. Figure 4.10 shows the TWI map of the Gidabo river basin.

Table 4.10: Reclassified topographic wetness index of Gidabo watershed

Factor	Topographic Wetness Index	Rank	Suitability classification
Topographic Wetness Index	3.1 – 6.1	1	Very Low
	6.2 – 7.6	2	Low
	7.7 – 9.9	3	Moderate
	10 - 19	4	High

(Source: Yang, H. et al. (2020)

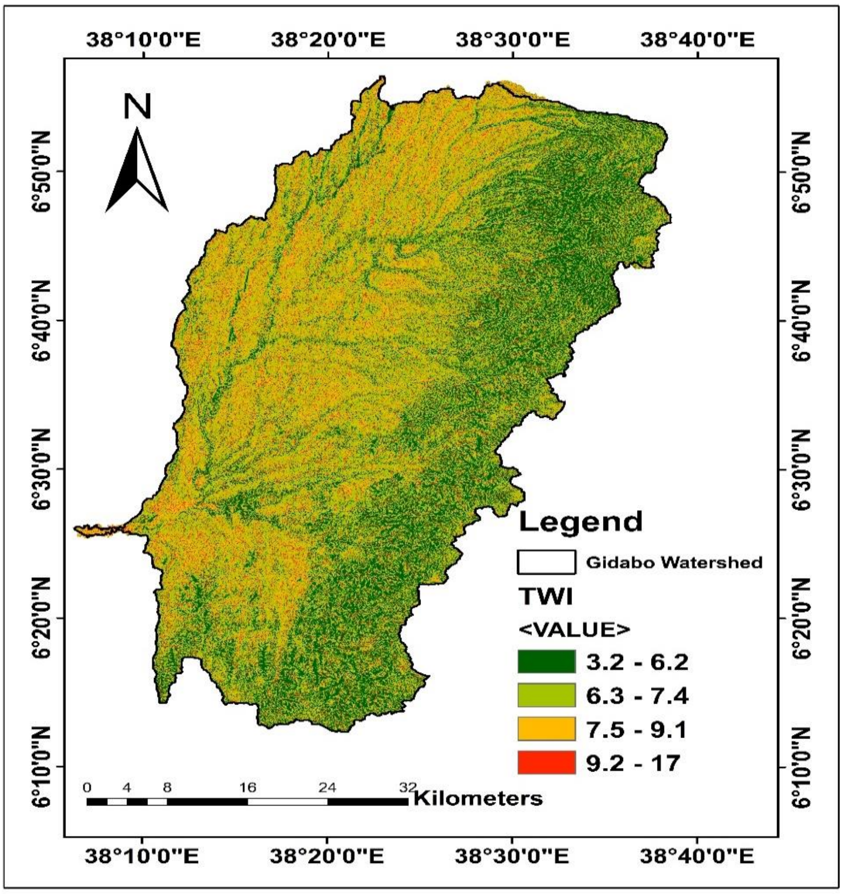


Figure 4.10: Topographic wetness index of Gidabo watershed

4.3. Assignment of Weight to Factors

The weight of physiographic, geology and climatic factor were determined on basis of the factors relative importance. The physiographic and geologic factors are the major factors affecting GWPZ of Gidabo Sub-basin. Recharge is the dominant factor that determine the occurrence of groundwater. Hence, it is a dominant factor influencing the GWPZ of study area. Next to groundwater recharge geomorphological landforms determine runoff, to some extent rainfall conditions. Geomorphology, land use/land cover and geology, distribution are the second, third and fourth factors influencing the GWPZ of Gidabo Sub-basin. The importance of lineament is related to the ability of lineaments to act as conduit sites for groundwater recharge and flow throughout the area. Types of rocks determine peculiarities of cross-section structures hydrological property affecting groundwater movement. Saaty's (1980) pair-wise comparison of themes mentioned in Appendix table 5.

Table 4.11: Pair-wise comparison matrix table of ten thematic layers in the Catchment

Param	Rech	Geom	LuLc	Geo	Soil	Slp	DD	LD	TWI	Roug
Rech	1	9/8	9/7	9/6	9/6	9/5	9/4	9/5	9/4	9/3
Geom	8/9	1	8/7	8/6	8/6	8/5	8/4	8/5	8/4	8/3
Lu/Lc	7/9	7/8	1	7/6	7/6	7/5	7/4	7/5	7/4	7/3
Geo	6/9	6/8	6/7	1	6/6	6/5	6/4	6/5	6/4	6/3
Soil	6/9	6/8	6/7	6/6	1	6/5	6/4	6/5	6/4	6/3
Slp	5/9	5/8	5/7	5/6	5/6	1	5/4	5/5	5/4	5/3
DD	5/9	5/8	5/7	5/6	5/6	5/5	1	5/4	5/4	5/3
LD	4/9	4/8	4/7	4/6	4/6	4/5	4/5	1	4/4	4/3
TWI	4/9	4/8	4/7	4/6	4/6	4/5	4/4	4/5	1	4/3
Roug	3/9	3/8	3/7	3/6	3/6	3/5	3/4	3/5	3/4	1

The abbreviation Rech, Geo, Geom, LD, DD, Slp, LULC, and Roug represent; Recharge, geology, geomorphology, lineament density, drainage density, slope, land use land cover, and Roughness, respectively.

Table 4.12: Upper pair-wise comparison matrix

Param	Rech	Geom	LuLc	Geo	Soil	Slp	DD	LD	TWI	Rough
Rech	1	9/8	9/7	9/6	9/6	9/5	9/4	9/5	9/4	9/3
Geom		1	8/7	8/6	8/6	8/5	8/4	8/5	8/4	8/3
Lu/Lc			1	7/6	7/6	7/5	7/4	7/5	7/4	7/3
Geo				1	6/6	6/5	6/4	6/5	6/4	6/3
Soil					1	6/5	6/4	6/5	6/4	6/3
Slope						1	5/4	5/5	5/4	5/3
DD							1	5/4	5/4	5/3
LD								1	4/4	4/3
TWI									1	4/3
Roug										1

The abbreviation Rech, Geo, Geom, LD, DD, Slp, LULC, and Roug represent; Recharge, geology, geomorphology, lineament density, drainage density, slope, land use land cover, and Roughness, respectively.

Table 4.13: Lower pair-wise comparison matrix

Param	Rech	Geom	LuLc	Geo	Soil	Slp	DD	LD	TWI	Rough
Rech	1									
Geom	8/9	1								
Lu/Lc	7/9	7/8	1							
Geo	6/9	6/8	6/7	1						
Soil	6/9	6/8	6/7	6/6	1					
Slope	5/9	5/8	5/7	5/6	5/6	1				
DD	5/9	5/8	5/7	5/6	5/6	5/5	1			
LD	4/9	4/8	4/7	4/6	4/6	4/5	4/5	1		
TWI	4/9	4/8	4/7	4/6	4/6	4/5	4/4	4/5	1	
Roug	3/9	3/8	3/7	3/6	3/6	3/5	3/4	3/5	3/4	1

In order to interpret and give relative weights to each criterion, it is necessary to normalize the comparison matrix. To change the above pairwise comparison matrix to normalization form, I followed the following step wise techniques.

Step-1

Table 4.14: Pairwise comparison matrix changed to Decimal form

Param	Rech	Geom	LuLc	Geo	Soil	Slp	DD	LD	TWI	Roug
Rech	1	1.13	1.29	1.5	1.5	1.8	2.25	1.8	2.25	3
Geom	0.89	1	1.14	1.33	1.33	1.6	2	1.6	2	2.67
Lu/Lc	0.78	0.88	1	1.17	1.17	1.4	1.75	1.4	1.75	2.33
Geo	0.67	0.75	0.86	1	1	1.2	1.5	1.2	1.5	2
Soil	0.67	0.75	0.86	1	1	1.2	1.5	1.2	1.5	2
Slp	0.56	0.63	0.71	0.83	0.83	1	1.25	1	1.25	1.67
DD	0.56	0.63	0.71	0.83	0.83	1	1	1.25	1.25	1.67
LD	0.44	0.5	0.57	0.67	0.67	0.8	0.8	1	1	1.33
TWI	0.44	0.5	0.57	0.67	0.67	0.8	1	0.8	1	1.33
Roug	0.33	0.38	0.43	0.5	0.5	0.6	0.75	0.6	0.75	1
Sum	**6.34**	**7.15**	**8.14**	**9.5**	**9.5**	**11.4**	**13.8**	**11.85**	**14.25**	**19**

Step 2

The above pairwise comparison decimal matrix divide by each columnar sum value gives normalization of pairwise comparison matrix. Example from the above table 1÷6.34 = 0.16 is shown below and Criteria weights is Average Raw values of each parameters.

Table 4.15: Compute the weights of each parameter/Criteria weights

Param	Rech	Geom	LuLc	Geo	Soil	Slp	DD	LD	TWI	Roug	Criteria Weights
Rech	0.16	0.16	0.16	0.16	0.16	0.16	0.16	0.15	0.16	0.16	**0.16**
Geom	0.14	0.14	0.14	0.14	0.14	0.14	0.14	0.14	0.14	0.14	**0.14**
Lu/Lc	0.12	0.12	0.12	0.12	0.12	0.12	0.13	0.12	0.12	0.12	**0.12**
Geo	0.11	0.1	0.11	0.11	0.11	0.11	0.11	0.1	0.11	0.11	**0.1**
Soil	0.11	0.1	0.11	0.11	0.11	0.11	0.11	0.1	0.11	0.11	**0.1**
Slope	0.09	0.09	0.09	0.09	0.09	0.09	0.09	0.08	0.09	0.09	**0.08**
DD	0.09	0.09	0.09	0.09	0.09	0.09	0.07	0.11	0.09	0.09	**0.09**
LD	0.07	0.07	0.07	0.07	0.07	0.07	0.06	0.08	0.07	0.07	**0.07**
TWI	0.07	0.07	0.07	0.07	0.07	0.07	0.07	0.07	0.07	0.07	**0.07**
Roug	0.05	0.05	0.05	0.05	0.05	0.05	0.05	0.05	0.05	0.05	**0.05**

Evaluations of Consistency Ratio (CR)

The Consistency Ratio (CR) is done based on criteria weights and pairwise comparison matrix which is help as preference ratings checked.

Criteria Weight	**0.159**	**0.14**	**0.121**	**0.108**	**0.108**	**0.089**	**0.09**	**0.07**	**0.07**	**0.05**
Param	Rech	Geom	Lu/Lc	Geo	Soil	Slp	DD	LD	TWI	Roug
Rech	1*0.159	1.13*0.14	1.29*0.121	1.5*0.108	1.5*0.108	1.8*0.089	2.25*0.09	1.8*0.07	2.25*0.07	3*0.05
Geom	0.89*0.159	1*0.14	1.14*0.121	1.33*0.108	1.33*0.108	1.6*0.089	2*0.09	1.6*0.07	2*0.07	2.67*0.05
Lu/Lc	0.78*0.159	0.88*0.14	1*0.121	1.17*0.108	1.17*0.108	1.4*0.089	1.75*0.09	1.4*0.07	1.75*0.07	2.33*0.05
Geo	0.67*0.159	0.75*0.14	0.86*0.121	1*0.108	1*0.108	1.2*0.089	1.5*0.09	1.2*0.07	1.5*0.07	2*0.05
Soil	0.67*0.159	0.75*0.14	0.86*0.121	1*0.108	1*0.108	1.2*0.089	1.5*0.09	1.2*0.07	1.5*0.07	2*0.05
Slp	0.56*0.159	0.63*0.14	0.71*0.121	0.83*0.108	0.83*0.108	1*0.089	1.25*0.09	1*0.07	1.25*0.07	1.67*0.05
DD	0.56*0.159	0.63*0.14	0.71*0.121	0.83*0.108	0.83*0.108	1*0.089	1*0.09	1.25*0.07	1.25*0.07	1.67*0.05
LD	0.44*0.159	0.5*0.14	0.57*0.121	0.67*0.108	0.67*0.108	0.8*0.089	0.8*0.09	1*0.07	1*0.07	1.33*0.05
TWI	0.44*0.159	0.5*0.14	0.57*0.121	0.67*0.108	0.67*0.108	0.8*0.089	1*0.09	0.8*0.07	1*0.07	1.33*0.05
Roug	0.33*0.159	0.38*0.14	0.43*0.121	0.5*0.108	0.5*0.108	0.6*0.089	0.75*0.09	0.6*0.07	0.75*0.07	1*0.05

Table 4.16: Evaluations of Consistency Ratio (CR)

The abbreviation Rech, Geo, Geom, LD, DD, Slp, LULC, and Roug represent; Recharge, geology, geomorphology, lineament density, drainage density, slope, land use land cover, and Roughness, respectively.

Param	Rech	Geom	LuLc	Geo	Soil	Slp	DD	LD	TWI	Roug	**Weighted Sum**
Rech	0.16	0.16	0.15	0.16	0.16	0.16	0.2	0.13	0.16	0.15	**1.6**
Geom	0.14	0.14	0.14	0.14	0.14	0.14	0.2	0.11	0.14	0.13	**1.4**
Lu/Lc	0.12	0.12	0.12	0.13	0.13	0.12	0.16	0.09	0.12	0.12	**1.2**
Geo	0.11	0.11	0.1	0.11	0.11	0.1	0.14	0.08	0.1	0.1	**1.1**
Soil	0.11	0.11	0.1	0.11	0.11	0.1	0.14	0.08	0.1	0.1	**1.1**
Slp	0.09	0.09	0.08	0.09	0.09	0.09	0.11	0.07	0.08	0.08	**0.9**
DD	0.09	0.08	0.08	0.09	0.09	0.08	0.1	0.08	0.08	0.08	**0.8**
LD	0.07	0.07	0.07	0.07	0.07	0.07	0.07	0.07	0.07	0.07	**0.7**
TWI	0.07	0.07	0.06	0.07	0.07	0.07	0.09	0.05	0.07	0.06	**0.7**
Roug	0.05	0.05	0.05	0.05	0.05	0.05	0.07	0.04	0.05	0.05	**0.5**

Table 4.17: Evaluations of Consistency Ratio (CR) of Weighted Sum Value

The abbreviation Rech, Geo, Geom, LD, DD, Slp, LULC, and Roug represent; Recharge, geology, geomorphology, lineament density, drainage density, slope, land use land cover, and Roughness, respectively.

Table 4.18: Evaluation of Lamda max (λmax) value

Parameters	Weighted Sum	Criteria Weights	$\frac{\boldsymbol{Weighted\ sum\ value}}{\boldsymbol{Criteria\ Weights}}$
Recharge	1.6	0.16	10
Geomorphology	1.4	0.14	10
Lu/Lc	1.2	0.12	10
Geology	1.1	0.1	11
Soil	1.1	0.1	11
Slope	0.9	0.08	11.25
Drainage Density	0.8	0.09	8.89
Lineament Density	0.7	0.07	10
TWI	0.7	0.07	10
Roughness	0.5	0.05	10

After this calculate the value of Lamda max (λmax)

$$\lambda\text{max} = \frac{10 + 10 + 10 + 11 + 11 + 11.25 + 8.89 + 10 + 10 + 10}{10}$$

$$= \frac{102.14}{10} = 10.214$$

❖ Then calculating the value of consistency index (CI)

$$\text{Consistency Index(CI)} = \frac{(\lambda\text{max} - \text{n})}{(n-1)}, where\ n = 10$$

$$\text{Consistency Index(CI)} = \frac{(10.214 - 10)}{(10-1)}, where\ n = 10$$

$$\text{CI} = \frac{0.214}{9}$$

$$= \mathbf{0.024}$$

❖ After calculating the Consistency Index (CI) of the given matrix from Saaty (1980) we determine the Random Index (RI) depending on the computed parameters.

Table 4.19: Saaty's (1980)

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

For this study the number of parameters ($n = 10$) which affect the Groundwater potential zone are ten, then the respective Random Index (RI) value for ten parameters is 1.49.

$$\text{Consistency Ratio(CR)} = 1.49\ , where\ n = 10$$

Finally we calculate the consistency ration (CR)

$$\text{Consistency Ratio(CR)} = \frac{Consistency\ Index(CI)}{Random\ Index(RI)}$$

$$\text{Consistency Ratio(CR)} = \frac{0.024}{1.49}$$

$$= \mathbf{0.016}$$

CR is less than 0.05 for a 3x3 matrix, 0.09 for a 4x4 matrix and 0.1 for larger matrices, then the pairwise comparison matrix is said to be consistent. Depending on consistency ratio (CR) rule, If the value of CR>0.10, then the criteria weight values of the matrix indicates inconsistencies and the method (AHP) may not give a meaningful result (Saaty1980). But when the value of CR comes to this study was 0.016 that means it is under acceptable limits which indicate the computed weight values are valid. Therefore it can be computed for weighted overlay analysis in GIS software, which used to delineate the Groundwater potential zone, is shown from the following tables.

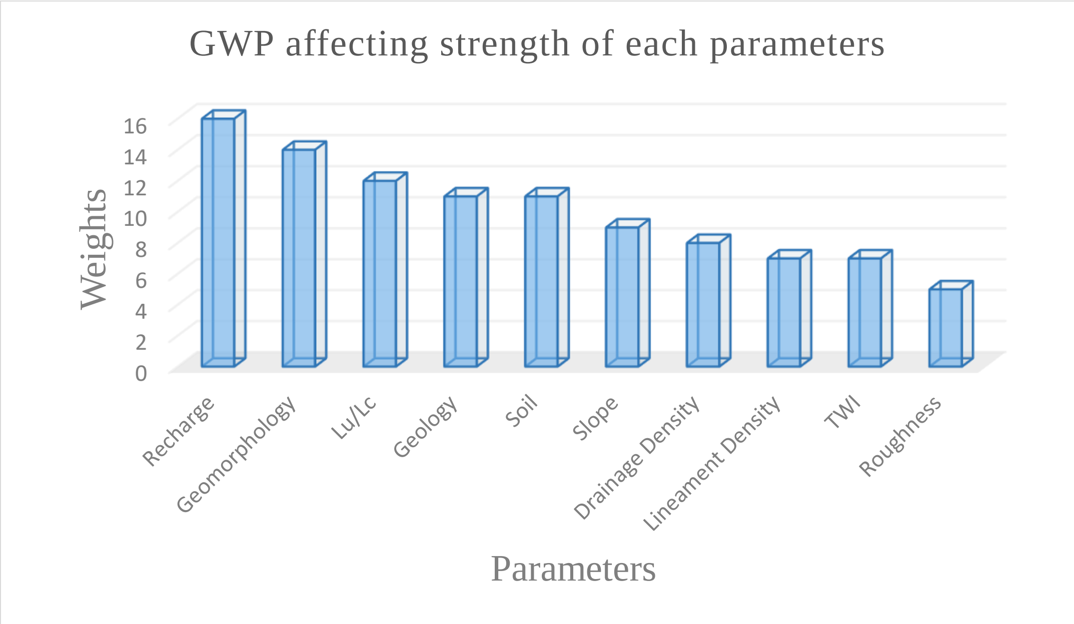


Figure 4.11: Weights of groundwater affecting parameters

4.4 Delineation of Groundwater Potential Zones

The groundwater potential zone were delineated by weighted, normalized and finally overlaid the reclassified thematic layers. The factors used to generate groundwater potential zone map were groundwater recharge, lithology/Geology, geomorphology, slope, Lineament density, land use/cover, drainage density, soil, TWI and Roughness.

The thematic maps which prepared for each parameters, were converted to raster data set having the same pixel and different weightage as per their groundwater potential controlling capacity. Pairwise comparison matrix was generated, to weight parameters, the consistency for the generated matrix was checked by the AHP techniques.

The delineated groundwater potential zone map (GWPZ) is developed by weighted overlay by linear combination of all thematic layers (map) affect groundwater potential of the study.

$$\mathrm{GWPZ} = 16\% * Recahrge + 14\% * Geomorphology + 12\% * \mathrm{LuLc} + 11\% * \mathrm{Geology} + 11\% * \mathrm{Soil} + 9\% * \mathrm{Slope} + +8\%\mathrm{DD} + 7\%\mathrm{LD} + 7\%\mathrm{TWI} + 5\% * \mathrm{Roughness}$$

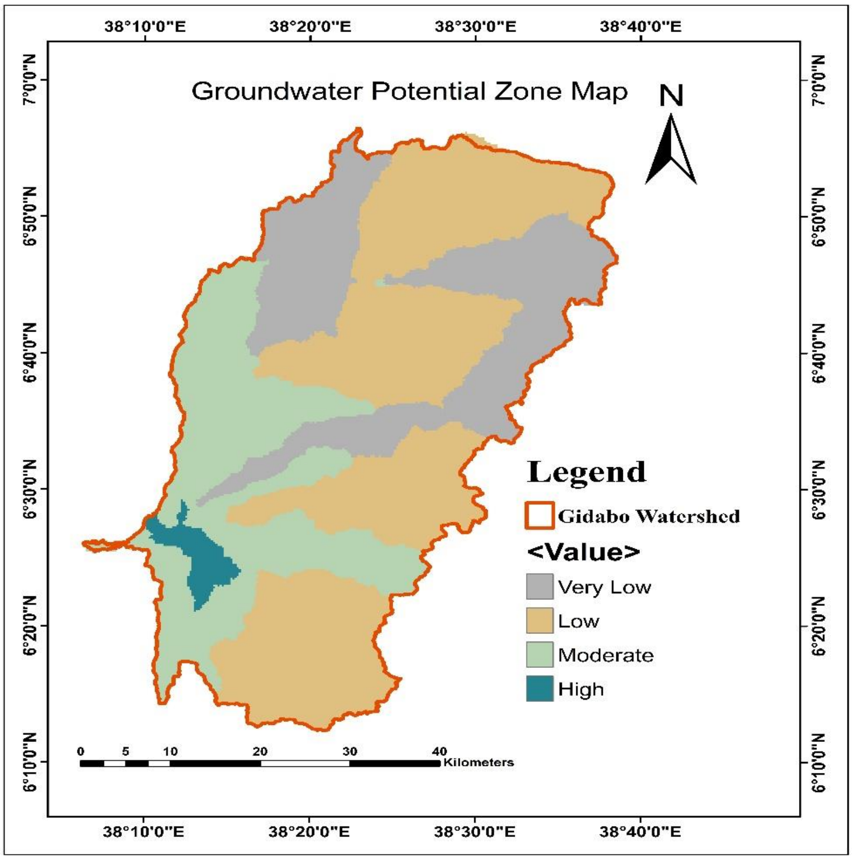


Figure 4.12: Reclassified Groundwater potential Zone

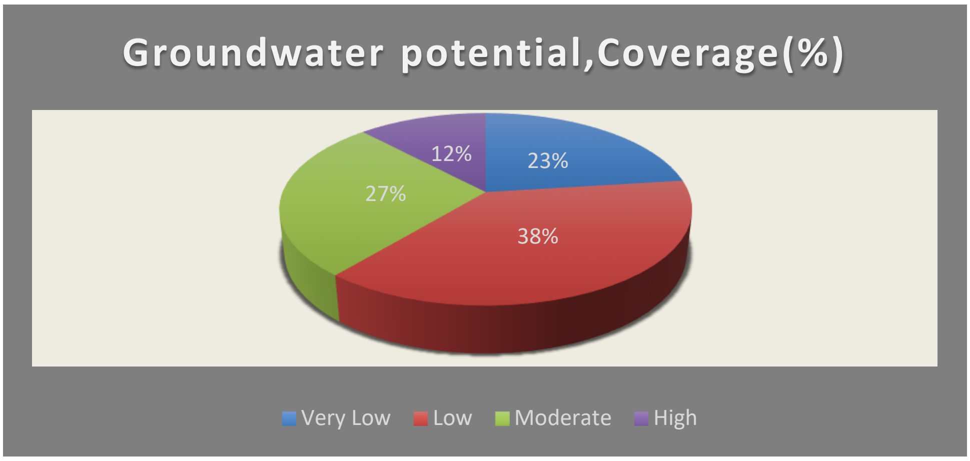


Figure 4.13: Groundwater potential coverage pie chart

4.5. Result Validation

Mapping of groundwater potential zone by using SWAT and GIS based MCDA techniques with existing conventional data was validated when existing water inventory point was a close agreement with groundwater potential zone delineated. Many boreholes information were considered from field observation data obtained from MoWIE groundwater and borehole development office, Sidama and SNNP regional state water, mine and energy office and water work construction enterprise.

The aquifer classification in the hydrological map of Ethiopia, which estimated optimum yield (Liter/Second) classified as high potential (10.8 – 68.4L/S), moderate potential (0.45-9.9L/S), and low potential (0.045-4.5L/S) (Tesfay,2010). Based on these classification and observed borehole yield of the catchment, borehole yield can be categorized as high potential zone (5-15L/S), moderate potential zone (3-5L/S), low potential zone (1-1.5L/S) and very low potential zone (< 1L/S).

From around 71 boreholes 57 agreed groundwater potential zone categories the rest of 14 boreholes are not matched due to various reason. However, same exception occurs, where the generated potential map does not agree with the validation data. The boreholes which are found at the high potential categories are perfectly agree with the generated potential map, all of the boreholes are with yield 3-15L/S, as presented Figure 4.11 below.

From which the boreholes are located at "very low" categories with yield (2.6-3.25L/S) disagree. They were above the expected yield, due to the depth at which borehole were dug, the developed depth of the two boreholes were below the suitable aquifer, and it was consuming the yield from surrounding boreholes. From the boreholes which were located at low and moderate potential zones, boreholes with low yield (2.7-6L/S) and moderate (6.7-10L/S) potential zones were matched with generated groundwater potential zone map. Their yield were above the expected yield, which was due to their location where they were located at foot of the mountain having stream recharging area, high lineament density and minimum slope with weathered rock formation. Borehole yield with 2.5L/S at moderated zone was somehow below the expected yield. This was due to its location which was located approximately at the border of low potential zone. Verification result showed that the accuracy of the result was above 80%. From this validation result, it was observed that, SWAT and GIS Based MCDA techniques were better than other techniques, for groundwater potential mapping. If the techniques implemented it reduces borehole failures, consuming time, money and energy. The result of verification study was presented in figure below.

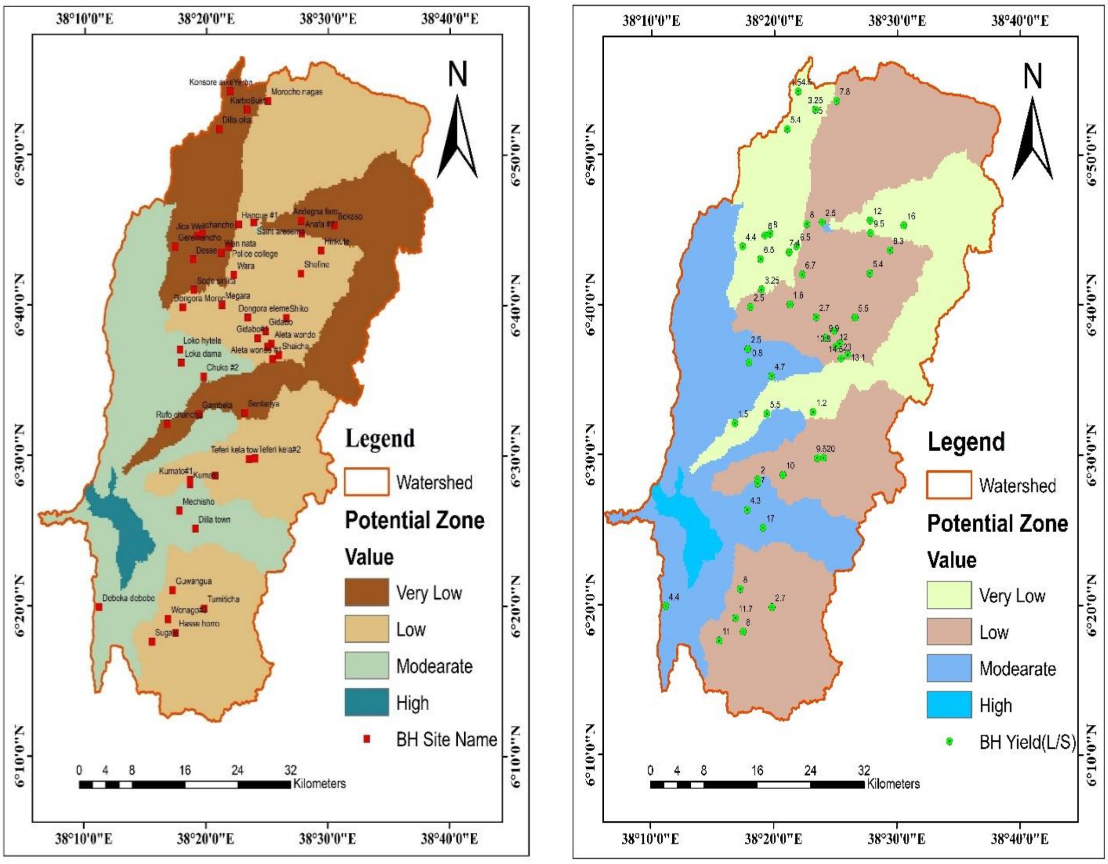


Figure 4.14: Validity map for developed groundwater potential zones

4.5 Groundwater Flow Direction Analysis of the Study Area

The course of flow of groundwater is shown from groundwater contour map. Hence, groundwater contour map for the shallow and deep aquifer system of the study location is generated from well point of static water level (SWL) in order to understand the flow direction. In most components of the area groundwater level distribution is comparable to the topography (slope), which follows the elevation variation. Accordingly, the inclination of the topography (slope) factor, geomorphology and aquifer (lithological) characteristic and lineament density and alignment are the most important factor control groundwater flow direction because this thing are greater susceptible for groundwater flow system occurring .

The groundwater flow route in Gidabo watershed area indicate that groundwater generally flows from the upland areas in the east towards Lake Abaya to the west, which corresponds to be closer to the rift floor undeniable and surrounding areas, and main Gidabo River. Generally, it is feasible to say the topographically highlands (some ridges) are considered as recharge areas whereas lowlands (flat to gentle) are groundwater storage potential and/or discharge areas and for the given catchment, the results further indicate a substantial groundwater flow into Lake Abaya..

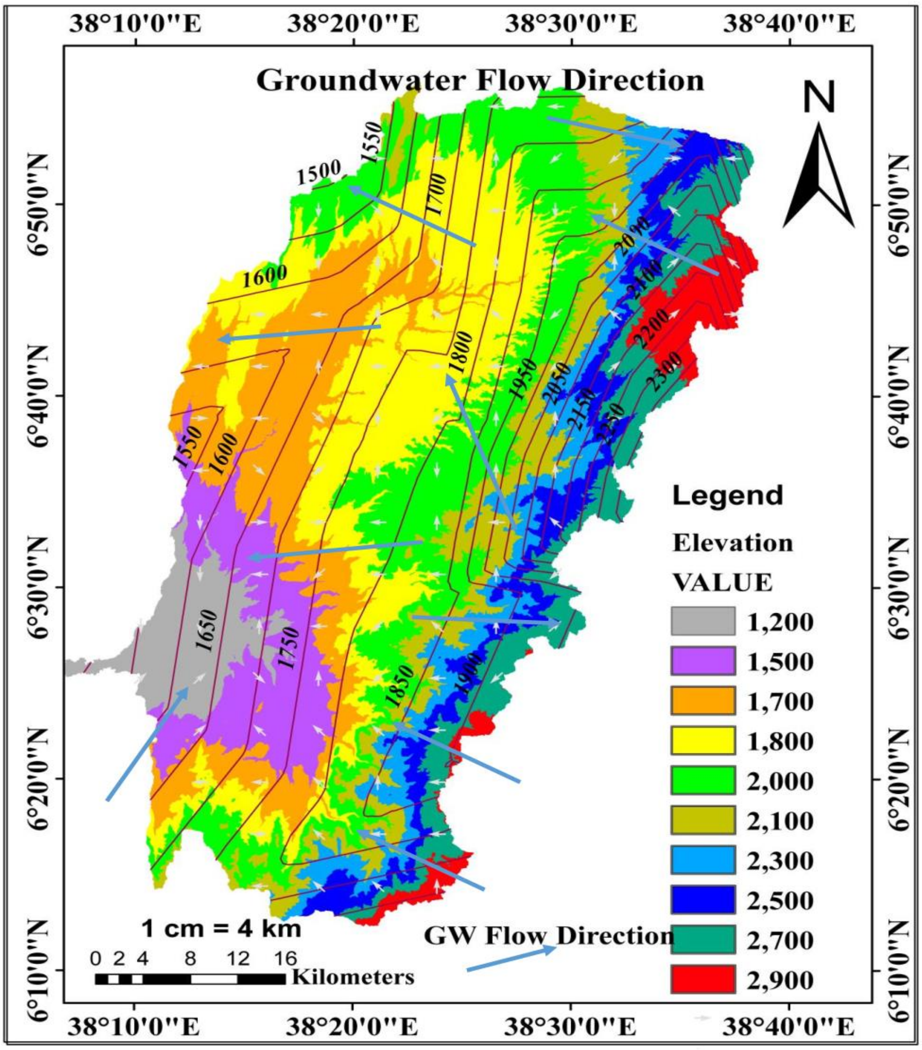


Figure 4.15: Groundwater flow direction analysis of the study area (Gidabo Watershed)

5. SUMMARY AND CONCLUSION

5.1. Summary

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

The Gidabo River Catchment is one of the largest catchments which is found at south-eastern part of rift valley lake basin of Ethiopia. The river is approximately 120km in length with estimated area of 3302km2 (Michel, 2015). The elevation catchment is 1175m above mean sea level in Lake Abaya and 3200m a.m.s.l at the Gelala summit. Soil is one of the important factors which control the movement and occurrence of groundwater potential (Natural Resource Conservation Service, 2015).

Integration of geospatial tools (soil and water assessment tool (SWAT) and geographical information system (GIS) has established to be more convenient, time-saving and cost effective techniques to assess and manage groundwater resource. Multi-criteria decision analysis (MCDA) approach of Analytic Hierarchy Process (AHP) used to evaluate the level of influence (importance) of each factor governing groundwater governing groundwater and prioritize accordingly. MCDA techniques is an effective and selective tool to analyze structure decision problem and choose the best option. Some of major factors influence or responsible for groundwater resource identification and locate potential site are discussed.

To prepare the thematic maps of each factor and verify the delineated GWPZ, several data were collected from various sources. The historic time series of meteorological data, spatial data of soil, geology, DEM, satellite images and the existing water point's inventory data were used. Various software and computer programs employed for processing, identification and preparation of groundwater potential map include; Arc SWAT, SWAT-CUP and ArcGIS 10.4. A weighting overlay approach of ArcGIS 10.4 was selected as the basic tool for the development of GWPZ. The groundwater prospect zones were evaluated based on the groundwater potential index computed from the integration of all groundwater influencing thematic layers. Groundwater potential zone map (GWPZ) is developed by weighted overlay by linear combination of all thematic layers (map) affect groundwater potential of the study. Factors used were groundwater recharge, lithology/Geology, geomorphology, slope, Lineament density, land use/cover, drainage density, soil, TWI and Roughness.

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

On the other hand, high slope regions have high runoff and low infiltration rate that are not suitable for groundwater recharge.. Sedimentary rocks were considered as having a high potential for groundwater due to their high porosity and permeability relative to igneous and metamorphic rocks. The presence of lineaments in an area usually denotes a permeable zone. Drainage pattern is a reflection of the rate that precipitation infiltrated compared with surface runoff. It indicates the inverse function of permeability capacity, infiltration capacity and recharge capacity of rocks and soil surface. High drainage is the resultant of weak or impermeable surface (fine texture soil type). Sparse vegetation and mountain relief which have high runoff and low infiltration result. The soil is a weathering product of ignimbrite.

In the south the soils are reddish brown, clayey to loamy textured. The land use condition in the Gidabo River catchment is controlled by altitude and rainfall. The roughness index expresses the amount of elevation difference between adjacent cells of a digital elevation model (DEM). Figure 18 illustrates the roughness map of Gidabo river basin and the values varied from 0 to 0.98. It shows how big is the inter-cell difference of a central pixel from its surrounding cells in DEM. Topographic wetness index reflects the role of topography on hydrological process. It is defined as TWI = Ln (sca/tanβ), where sca is the specific contributing area and tanβ is the local slope. Areas with higher TWI are likely to be wetter relative to areas with lower values.

Mapping of groundwater potential zone by using SWAT and GIS based MCDA techniques with existing conventional data. Many boreholes information was considered from field observation data obtained from MoWIE, Sidama and SNNP regional state water, mine and energy office and water work construction enterprise. Boreholes with low and moderate potential zones were matched with generated groundwater potential zone map. The groundwater flow route in Gidabo Catchment area tends to be closer to the rift floor and surrounding areas. The inclination of the topography (slope) factor, aquifer characteristic and lineament density and alignment are the most important factor control groundwater flow direction.

The spatial distribution of rainfall of the study area which was significantly influenced by topographic variability of the sub-basin result in the spatial variability of GWPZ. Due to the percolation of the higher precipitation, the major natural recharge of the Gidabo Sub-basin is believed to occur at elevated regions. The drainage density of an area depends on the topography, slope and sub-surface characteristics. Thus, the higher weight was assigned for drainage density than the factors contributing for high drainage density, except the sub-surface geological formation. The slope gradient directly influences the rainfall infiltration. The high residence time of rainwater permits extensive retention of rainwater to form pools and infiltrate to the water table and the deeper geologic formation. The process will be held if the soil provides the permeability necessary for deeper flow than surface runoff.

For those interdependent factors, the relative weight was assigned depending on the contribution of factors and their ability to determine the spatial variability of groundwater potential. The influence of physiographic, geologic and climatic factors is high, moderate, and low, respectively. The value reveals that the GWPZ of the Gidabo Sub-basin is influenced almost equally by physiographic and geologic factors. The groundwater recharge, geomorphologic landform, land use/land cover, and geology shares the highest weightage 53%.

The resulting groundwater potential index of the study area indicates four zones representing very low, low, moderate and high GWPZ's. The groundwater potential map was validated using the existing well yield and spring discharge. It indicated a good prediction accuracy of 84%.

The groundwater recharge and discharge zone of groundwater zones were determined from the SWAT and groundwater direction vectors respectively. The groundwater flow direction of the study area is particularly towards the Northeast and Southeast. The Gelala mountains highland which is characterized by high rainfall, dense forest and bush lands are the major recharge zone of the study area. Recharge from areas discharges at the valley floor, mountains foothill and low lands. Especially the foothills of lower plateau volcanic terrains formed by volcanic shields characterized by high lineament density are favorable for the emergence of groundwater as springs.

5.2. Conclusion

The result of this study indicates the efficiency of SWAT and GIS based MCDA techniques for mapping the groundwater potential zone of Gidabo Sub-basin. SWAT used to simulate water flow and provides information about groundwater recharge and while GIS helps to store, interpret and retrieve spatial data. The use of ArcGIS weighted overlay analysis shows a good capability to achieve the spatial classification of GWPZ. The powerful and flexible decision-making technique, AHP, helps to set priorities and make the best decision. Identification and evaluation of climatic, physiographic, and geologic factors are essential for mapping the GWPZ's of study area. The study reveals that the integration of recharge, geomorphological landforms, lineament density, geology, drainage density, slope, soil and LU/LC, roughness and TWI thematic layers identify the suitable GWPZ of Gidabo Sub-basin.

The recharge, geomorphologic landform, land-use/land-cover, soil and geology shares the highest weightage. The groundwater recharge is a dominant factor influencing the GWPZ of the study area. The Gelala Mountain's highland which is characterized by high rainfall, dense forest and bush lands are the major recharge zone of the study area. The spatial distribution of rainfall is significantly influenced by the topographic variability of the sub-basin. Recharge from runoff and precipitation provides a source of groundwater infiltration to the area of interest. The resulting GWPZ of study area was classified into four zones representing very low, low, moderate and high. GWPZ's covering an area of 552 km^2, 912 km^2, 648 km^2 and 288 km^2, respectively. The GWPZ was validated by using the existing water point's inventory data.

The overall prediction accuracy of identified groundwater potential zone with actual water point inventory data shows 84% agreement. This, indicates the accuracy and of GWPZ's identification by using SWAT and GIS based MCDA through AHP is reliable. A considerable extent of very high groundwater potential is found in the Southwestern part of the study area. The high productive fractured, jointed and porous basalt (aphyritic basalt) forming flat slope plain and valley landforms between the mountains suit very high groundwater potential. The extensively fractured valley of Gidabo River channels that compose a thick succession of alluvial deposits was classified under high groundwater potential zone. The subsequent edge next to the high groundwater potential zone is characterized by moderate GWPZ’s. Small area of very high groundwater potential zone followed by high groundwater potential was discretely distributed over the Northeastern side between Dilla and Aleta Wondo Woreda.

The barren top of steep slope weather-resistant rocky mountain and drainages are classified under low and very low GWPZ. In this area, most parts of the volcanic terrain are covered by impenetrable forest, whereas the cliffs themselves and peaks remain barren. The low productivity sedimentary aquifer and scarce rainfall distribution of the Southeastern edge enforce the GWPZ’s of an area for categorizing under low and moderate GWPZ.

Recharge from area discharges at the valley floor, mountains foothill, and low land areas. Especially the foothills of lower plateau volcanic terrains formed by volcanic shields characterized by high lineament density are favorable for the emergence of groundwater as springs. The extensively fractured Eastern valley of Gidabo River channels that compose thick succession of alluvial deposits was identified as the discharge areas. Generally, the better agreement of the comparison between the water point’s inventory data and GWPZ approve the efficiency of SWAT and GIS based MCDA technique for mapping groundwater potential of Gidabo Sub-basin.

The remaining groundwater infiltrates into the deeper aquifers and joins the regional flow system towards the rift floor following the topographic gradient. Therefore, the rift floor aquifers receive inflow from two different sources: direct recharge from the local rainfall and indirect recharge from the escarpment and the highland. The latter usually is called mountain block recharge (Wilson and Guan, 2004). This will contribute to fill the gaps by replacing uneconomical and time-consuming conventional approaches of groundwater investigation. Moreover, it is recommended to apply the same method in other places with appropriate modifications, especially for large and inaccessible areas. Hence, it is fair to conclude that the result of this study can be used for planning new groundwater-based projects and expansion of the existing water supply and irrigation project. Further, the delineated GWPZ and the identified groundwater recharge zone can be used as a primary source of information in making decisions related to groundwater management and river basin planning which have a significant contribution to the Catchment management effort of the country.

5.3. Recommendation

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

- ❖ Gelala Mountain highland is the major recharge zone of the study area. It is the major source of surface and groundwater resources. To assure the groundwater quality and increase the available groundwater reserve, the area shall be protected.
- ❖ The suitability of identified GWPZ was not assessed for various purposes. Further study is recommended to evaluate the suitability of groundwater potential zone for irrigation, water supply and other water resources development projects.
- ❖ Human activities have been exerted small to large scale changes on the hydrological cycle (Tadesse, 2017). Evidences suggest that, with extreme urbanization, more than one-half of rainwater runs off and only a fraction of it goes for deep infiltration (Arnold and Gibbons, 1996). The current scenario regarding groundwater resources suggests as the amount of water available is decreasing with time. Moreover, the problem is resulting in the global water crisis in terms of quantity (availability) and quality (Sudhir et al., 2010). Therefore, it is recommended to assess the effect/impact of LU/LC change and over pumping on the groundwater recharge and potential zone of study area.
- ❖ Since the time and resources are limited the study does not include analysis of groundwater water quality and the structural design of groundwater conveyance structures (borehole/dug well depth, cross-section etc.), rather than mapping every zone in the sub-basin with their respective potential and proposing zones of suitable groundwater potential. Hence, it is recommended to assess the quality of identified suitable groundwater potential zone and conduct a detailed hydrogeological study to identify the specific location of water points in very high and high GWPZ.
- ❖ This study specifically focuses on mapping the groundwater potential zone of Gidabo Sub-basin. As it was a qualitative study the groundwater storage was not quantified. Hence, it is recommended to conduct a detail quantitative study using hydrological models.

- To reduce the shortage of potable drinking water, sanitation and hygiene problems of the community Groundwater developing at high potential zones were recommended. Especial at rift floor, Dilla downstream part of Gidabo embankment dam and some parts of Aleta wondo.
- To delineate the GWPZ of Gidabo sub-basin various secondary data were collected from varying sources. Even though the data quality was checked by using various methods, the collected data was not cross-checked with the field investigation (except for those factors which does not require much effort). Having well organized and updated database system in different governmental organization and conducting a detailed field investigation will reduce the inconsistency and missing of data that has been widely shown (may result in inaccuracy of results). Hence it is recommended to have well organized and updated database system in different governmental organization and conduct a detailed field investigation, so as to provide accurate data about the hydrogeological and hydrological systems of the sub-basin
- Delineation of groundwater potential zones using SWAT and GIS Based MCDA techniques are recommended, using updated information from time to time by adding new parameters.

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7. APPENDICES

Tables in the Appendix

Appendix Table 1: Location of meteorological stations used in study area

No	Stations	X(Longitude)	Y (Latitude)	Elevation (m)
1	Aleta wondo	435669.93	729998.10	1947
2	Dilla	424426.20	703790.64	1579
3	Yirgalem	432892.40	753542.35	1786
4	Kebado	426275.41	711154.26	1807
5	Hagere Selam	446925.33	715184.90	2841

Appendix Table 2: Water Source Inventory Point (Validation Data)

No	Local name of site	Source	Easting	Northing	Elevation (m)	Water depth(m)	Yield (L/S)
1	Shiko	BH-1	438425	735391	1852	122	5.5
2	Aleta wondo	BH-2	436140	732217	1892	146	23
3	Bule town	BH-3	434611	695966	2808	70	2.5
4	Bokaso	BH-4	445715	746711	1980	58	16
5	Andegna fero	BH-5	440672	747304	1754	145	12
6	Hinkute	BH-6	443669	743645	1913	141	8.3
7	Shefine	BH-7	440632	740814	1968	175	5.4
8	Wara	BH-8	430485	740669	1767	152	6.7
9	Jica Well	BH-9	424918	745467	1643	244	6
10	Wen nata	BH-10	428556	743397	1760	137	7.4
11	Police college	BH-11	429701	744125	1762	132	6.5
12	Anafa #1	BH-12	440754	745760	1849	153	9.5
13	Hangue #1	BH-13	431203	746856	1686	65	8
14	Saint aresema	BH-14	433506	747092	1732	120	2.5
15	Sodo simita	BH-15	424424	738819	1748	153	3.25

16	Desse	BH-16	424282	742557	1610	141	6.5
17	Geremancho	BH-17	421586	744115	1640	165	4.4
18	Karbo	BH-18	432474	760891	1840	126	5
19	Alewo ceso	BH-19	425832	763042	1872	160	3.8
20	Yerba	BH-20	429952	763117	1955	201	1.5
21	Konsore arke	BH-21	429902	763156	1967	204	4.5
22	Yubo	BH-22	447561	768984	1787	107	9.5
23	Alamura	BH-23	441452	770951	1757	175	6
24	Abela wondo	BH-24	445692	770852	1720	90	1.5
25	Alabo ano	BH-25	432480	760913	1814	192	5
26	Morocho nagas	BH-26	435643	761971	1846	280	7.8
27	Dulecha tebera	BH-27	4371124	767698	1864	208	5.4
28	Wojigira	BH-28	451697	766656	2170	110	5.8
29	Dilla town	BH-29	424641	709583	1552	74	17
30	Tumiticha	BH-30	425996	699819	1974	126	2.7
31	Gidabo	BH-31	435276	733774	1894	152	10.8
32	Gidabo#1	BH-32	434060	732905	1875	126	9.9
33	Shaicha	BH-33	437311	730815	1836	145	13.1
34	Dongora eleme	BH-34	432590	735427	1849	208	2.7
35	Aleta wondo #2	BH-35	435581	731867	1905	162	12
36	Aleta wondo #1	BH-36	436315	730358	1918	154	14.5
37	Hagere selam	BH-37	446568	716727	2741	150	11.3
38	Loko hytela	BH-39	422352	731507	1743	84	2.5
39	Chuko #2	BH-40	425898	728195	1840	114	4.7
40	Megara	BH-41	428678	736999	1786	153	1.6
41	Gambela	BH-42	425209	723579	1781	162	5.5
42	Sentariya	BH-43	432142	723778	1968	151	1.2

43	Rufo chancho	BH-44	420400	722424	1640	93	1.5
44	Loka dama	BH-45	422541	729892	1708	181	0.8
45	Dongora Moroc	BH-46	422777	736675	1682	122	2.5
46	Debeka debobe	BH-47	410088	699963	1599	102	4.4
47	Guwangua	BH-48	421215	702046	1555	160	8
48	Dibicha#1	BH-49	403688	705404	1217	143	5
49	Dibicha#2	BH-50	400770	705453	1242	138	12
50	Mechisho	BH-51	422264	711775	1490	173	4.3
51	Sugale	BH-52	418094	695728	1789	84	11
52	Teferi kela tow	BH-53	432752	718123	1853	132	9.5
53	Dibicha	BH-54	403688	705404	1217	72	5
54	Felke	BH-55	43136	741073	1661	124	16
55	Buko	BH-56	432480	760913	1814	92	3.2
56	Dilla oka	BH-57	428272	758525	1973	158	5.4
57	chancho	BH-58	425718	745678	1680	145	8
58	Kumato	BH-59	423837	715012	1603	55	7
59	Teferi kela#2	BH-60	433707	718161	1854	80	20
60	Kebado#1	BH-61	427627	716075	1785	72	10
61	Kumato#1	BH-62	423835	715524	1935	91	2
62	Abera deko	BH-63	444084	711913	2806	166	7
63	Hasse horro	BH-64	421654	696834	1957	125	8
64	Wonago#3	BH-65	420512	698500	1640	135	11.7
65	Wonago#2	BH-66	459448	697897	1660	135	13.4
66	Logoda	SP	415048	688980	1892		0.81

Appendix Table 3: Description of the Lithological Unit of the Catchment

Sr.No.	Code	Lithological Unit Characteristics
1	Ntr3(PNa2)	**Alkali trachyte flows;** Aphantic, aphyritic alkali trachytes and scattered trachytic plugs, minor proclastic rock and basalt flows. Extensive and Low productive Fractured volcanc aquifer (Kiflu et al., 2009; Zewdie, 2011)
2	PNb1(PNb)	**Alaji formation/ lower flood basalt:** Aphyric and prophytic basalt flows with lesser visicular basalt, minor alkali trachyte flows and tuffs. Extensive and Moderately productive fractured volcanic aquifer (Kebede and Mulugeta, 2011; Zewdie, 2011).
3	Qv (Qg)	**Ginnir Basalt**: Often Scoraceous with minor cinder cones of Scoria and Scoraceous olivine-phyric basalt vitric tuff. Extensive fracture volcanic aquifer (Kebede and Mulugeta, 2011; Kiflu et al., 2009; Mulugeta and Tafa, 2010; Zewdie, 2011)
4	PNtbB	**Tarmaber basalt (PNtbB) -** This rock types are the lower basaltic aquifer with a large amount of scoraceous lava flows and cover dominantly northern part of the study areas. The permeability of this aquifer is highly dependent on the degree and intensity of fracturing, the enhancement of jointing and interconnection of primary porosity. The scoraceous nature of this aquifer is favorable for groundwater storage and movement. It is high productive fissured/or porous aquifer.
5	Q	**Basalt (Q) -** basalt rock unit is upper basaltic aquifer that distributed in Western and Northern part of the study area and found overlain by Ignimbrites and tuffs. It is a quaternary volcanic rocks and encompasses of confined and unconfined aquifer formed from porphyritic basalt, breccia and tuff.

Appendix Table 4: Major Soil Types and their Characteristics in the Catchment

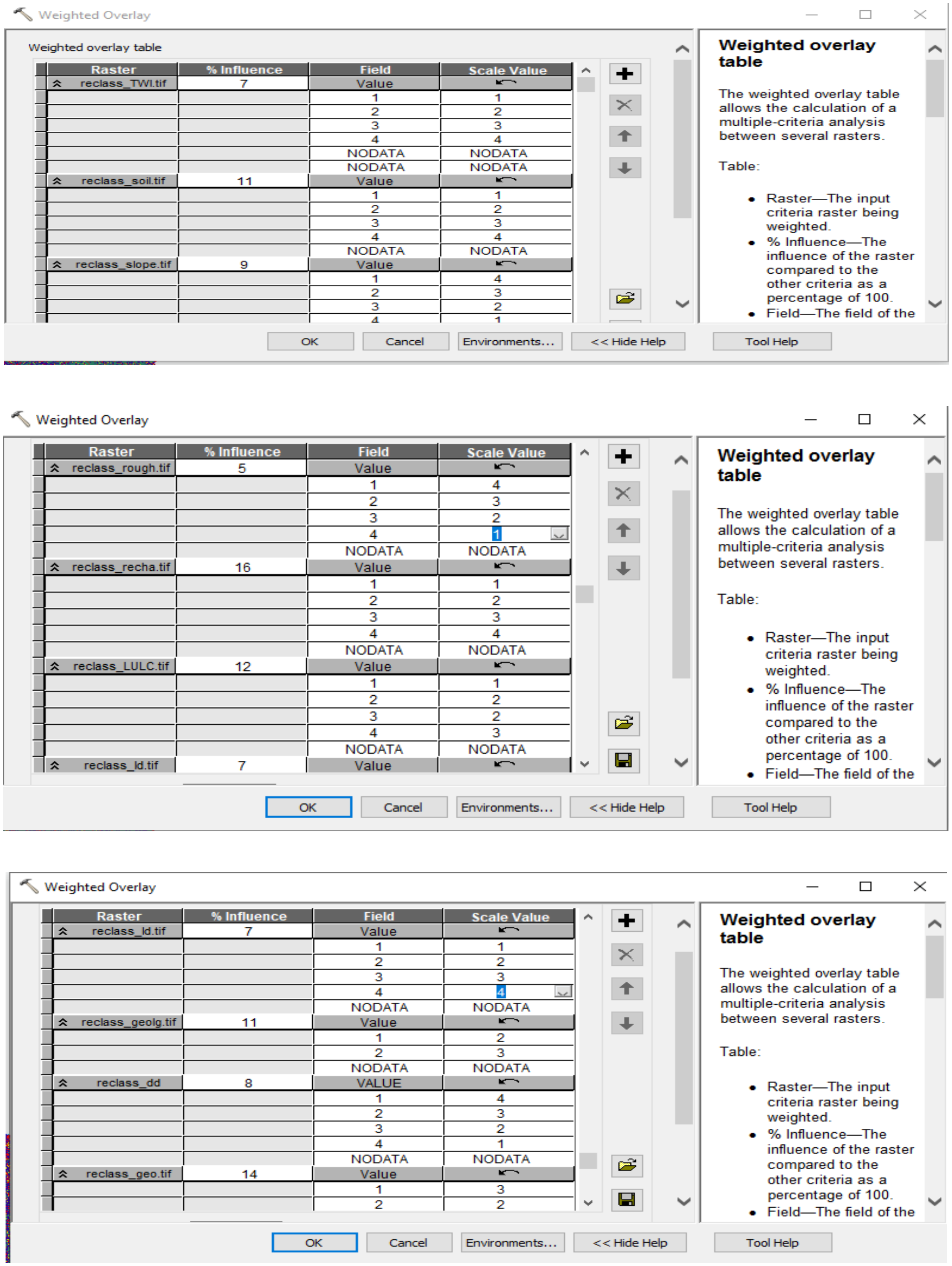
Sr.No.	Soil Units and Characteristics
1	**Acrisols: -** these soils have a distinct argillic B horizon and a low base saturation (less than 50 percent). Acrisols occur in high rainfall area. Normal Acrisols are Orthic Acrisols, those with an Umbric horizon are Humic Acrisols. Chemical these soils are poor, the content of weatherable minerals is rather low, PH is less than 5.5 and available P contents are very low. The moisture storage capacity is good. Only when topsoil is very sandy, tillage operations can create problems like compaction and erosion.
2	**Cambisols: -** Cambisols have a cambric B horizon or a deep Umbric A horizon. Those with only an umberic A horizon are called Humic Cambisols. These are similar to phaeozems, only they have an umberic A horizon. Cambisols with a base saturation of less than 50 percent are Dystric Cambisols. Chromic Cambisols have a strong brown or red colour and Eutric Cambisols have a base saturation of 50 percent or more. Cambisols showing vertic properties are vertic Cambisols.
3	**Leptosols: -** Leptosols comprise very thin (shallow) soils over continuous rock and soils that are extremely rich in coarse fragments or in unconsolidated very gravelly material. Leptosols are particularly common in mountainous regions. **Parent material**: Various kinds of continuous rock or of unconsolidated materials with less than 20 percent (by volume) fine earth.
4	**Luvisols: -**Soils with sub-surface accumulation of high activity clays and high base saturation. Porous and well aerated topsoil. Luvisols have a higher clay content in the sub-soil than in the topsoil. **Parent material**: A wide variety of unconsolidated materials including glacial till, and Aeolian, alluvial and colluvial deposits.
5	**Nitosols: -** Nitosols are clayey red soils with an argillic B horizon. They occur on undulating to rolling land. Dystric Nitosols have a base saturation of less than 50 percent, Eutric Nitosols have a PH of 5.5 or greater.

6	**Vertisols: -** Vertisols (known as black cotton soil) are heavy clay soils with a high proportion of swelling clays. Vertisols are characterized by their sticky nature and high water holding capacity and low infiltration capacity. These soils become very hard and form deep wide cracks from the surface downward when they dry out, which happens in most years. **Parent material**: Sediments that contain a high proportion of swelling clays, or swelling clays produced by re-formation from rock weathering

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

Appendix Table 5: Saaty's scale of intensity relative importance and descriptions

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



Appendix Figure 1: Reclassified Thematic Layers Weighted Overlay Analysis (WOA)