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Spatial Modelling of Groundwater Recharge Zones for Artificial Recharge: Integrating GIS and Remote Sensing in the Akaki River Catchment, Ethiopia

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This is to certify that the thesis prepared by Feven Tamrat Abdi entitled: "***Spatial Modelling of Groundwater Recharge Zones for Artificial Recharge: Integrating GIS and Remote Sensing in the Akaki River Catchment, Ethiopia***" submitted in partial fulfilment of the requirements for the Degree of Master of Science in **Civil Engineering Under Hydraulic Engineering** complies with the regulations of University and meets the accepted standards with respect to originality and quality.

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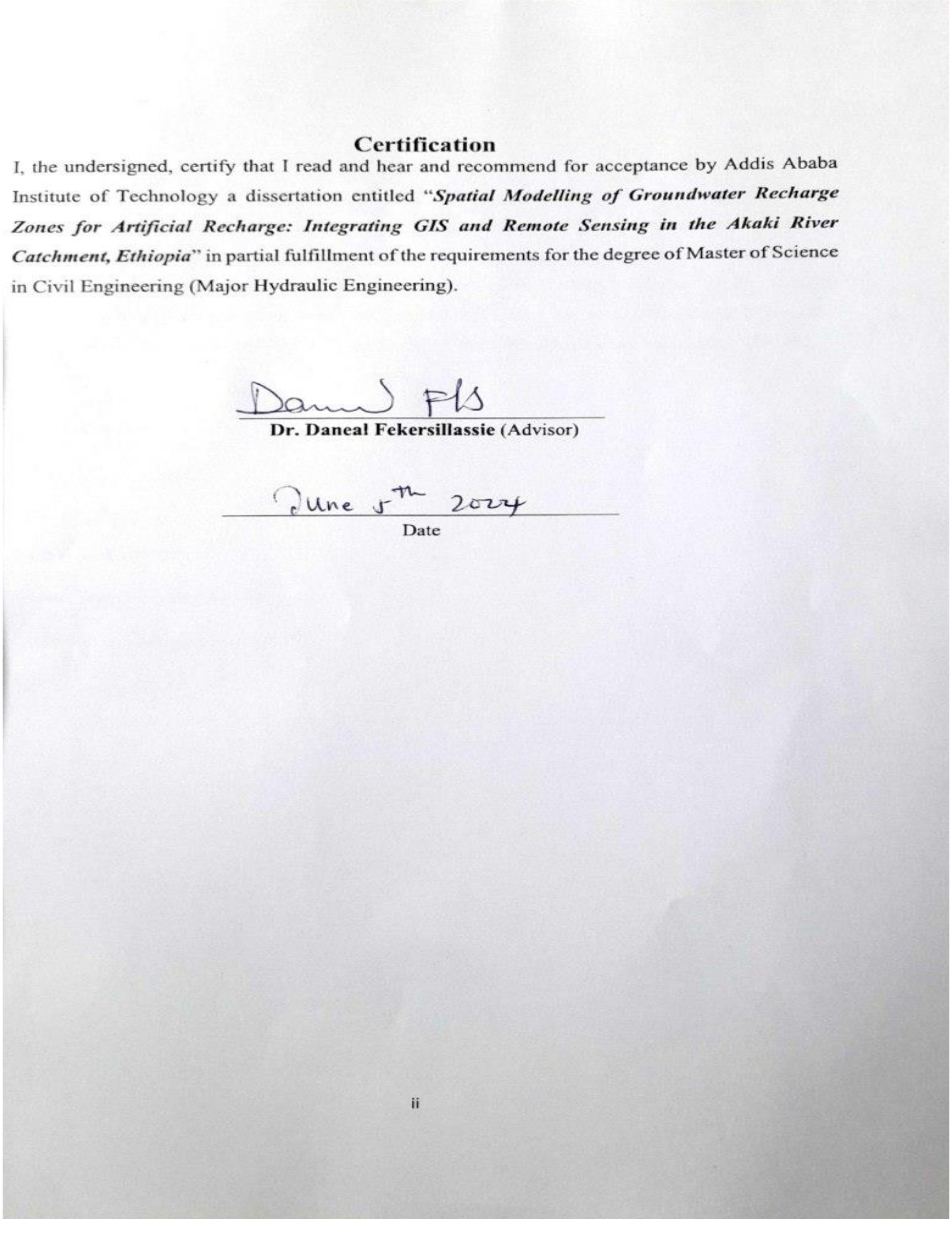

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June 5th 2024

Date

DECLARATION

I, the undersigned, declare that this thesis entitled "***Spatial Modelling of Groundwater Recharge Zones for Artificial Recharge: Integrating GIS and Remote Sensing in the Akaki River Catchment, Ethiopia***" is my original work, prepared under the guidance of Dr. Daneal Fekersillassie. It has not been submitted before anywhere either at the master's level or undergraduate for any award. Any information used from other works has been acknowledged.

Feven Tamrat

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Date May, 2024

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ABSTRACT

Excessive extraction, uncontrolled groundwater withdrawal, and unregulated practices are leading to the depletion of groundwater resources in the Akaki Catchment, Ethiopia. The alarming rise in groundwater extraction is driven by urbanization and population growth, which aim to meet the high water demand in the area. Additionally, urbanization has reduced natural groundwater recharge due to deforestation and increased impervious surfaces. A study using a water balance model showed that the mean annual groundwater recharge decreased from 268.6 mm in 1986 to 260 mm in 2015, attributed to changes in land use and land cover in the catchment. To address this issue, implementing suitable artificial recharge structures can effectively increase groundwater levels. This study aims to identify potential zones for artificial groundwater recharge in the Akaki Catchment, Ethiopia, using integrated approach of Geographical Information System (**GIS**) and Remote Sensing (**RS**) Technologies with Analytic Hierarchy Process **(AHP)** to facilitate the implementation of recharge techniques. Nine groundwater recharge affecting factors were used to map the recharge indexes. The thematic layers were prepared from various remote sensing /satellite data, conventional and secondary data and used for groundwater recharge zone map development by assigning weights using AHP method to each thematic layer and features .The weighted sum overlay analysis (WOA) result showed that the study area can be categorized into three different groundwater recharge potential zones: areas of high groundwater recharge are estimated to cover 1.38 km^2 (0.10% of the study area), moderate recharge 1,192.69 km^2 (82.75%), and low recharge 247.25 km^2 (17.15%). The result was also validated through ROC method and had a prediction of AUC=0.756 and considered as a good prediction. Finally, in this study an effort has been made to recommend the possible types and locations for the selected artificial recharge structures.

Keywords*: GIS, Remote Sensing (RS) AHP, Groundwater Recharge Potential, Akaki Catchment*

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ABBREVIATIONS AND ACRONYMS

AAWSA	Addis Ababa water supply and sewerage Authority
AGR	Artificial groundwater recharge
AGRZ	Artificial groundwater recharge zone
AHP	Analytical hierarchy process
ARS	Artificial Recharge Structure
AUC	Area under the curve
CHIRPS	Climate Hazards Group Infrared Precipitation with Station
CI	Consistency Index
CR	Consistency Ratio
DEM	Digital elevation Model
ENMA	Ethiopian National Metrological Agency
EEC - WEDSWS	Ethiopian Engineering Corporation's Water and Energy Design and Supervision Works Sector
FAO	Food and Agriculture Organization of the United Nations
GIS	Geographic information system
GRPM.	Groundwater recharge potential map
GW	Groundwater
GWRPZ	Ground Water Recharge Potential Zone
GSE	Geological Survey of Ethiopia
ISRIC	International Soil Reference and Information Centre
INOWAS	Innovative Groundwater Solutions
IDW	Inverse Distance Weighting
MAR	Managed Aquifer Recharge
MIF	Multi-influencing factor
MCA	Multi-Criteria Analysis
MCM	Million Cubic Meter
MCDA	Multi-Criteria Decision Analysis
MCDM	Multiple-Criteria Decision Making
MoWE	Ministry of Water and Energy
PARZ	Potential Artificial Recharge Zone
PCMs	Pair-Wise Comparison Matrix’s
RS	Remote sensing
ROC	Receiver operating characteristic curve
UTM	Universal Transverse Mercator
WOA	Weighted Overlay Analysis
WaPOR	Water Productivity Open-access Portal
WLC	Weighted Linear Combination

INTRODUCTION AND BACKGROUND

1.1 Introduction

Groundwater is the sub-surface water that occurs beneath the water table in soils and geologic formations that are fully saturated. Groundwater (GW) is valued as a dependable reservoir of freshwater owing to its purity, diminished susceptibility to pollution, consistent chemical makeup, and cheapness. The increasing demand of water for the domestic, irrigation and industrial sectors has intensified pressure on this vital natural asset, a concern particularly pronounced in densely populated and industrialized nations globally. According to the latest edition of the United Nations World Water Development Report (UNWWD, 2022), groundwater presently provides half of the volume of water withdrawn for domestic use by the global population, including the drinking water for the vast majority of the rural population who do not get their water delivered to them via public or private supply systems, and around 25% of all water is used for irrigation. “In Ethiopia, it is approximated that there exists an annual potential of 122 billion cubic meters (BCM) of water resources, including around 40 BCM of groundwater potential and an annual groundwater replenishment estimated between 28 to 36 BCM” (Puertas, 2015).

“In Ethiopia, groundwater serves as the primary water source for fulfilling domestic, industrial, irrigation, and various developmental needs due to its prolonged residence underground, minimal contamination levels, widespread availability, and accessibility” (Sewnet et al., 2016). Nonetheless, in recent times, reliance on this resource has surged significantly due to rapid population growth, ongoing urban expansion, agricultural and industrial development, and the impacts of climate change. Consequently, overexploitation of groundwater has become common, leading to a substantial decline in groundwater levels. Globally, there is considerable pressure on groundwater resources, and this unsustainable usage is a growing concern, particularly in developing nations like Ethiopia (Todd and Mays, 2005).

Managed Aquifer Recharge (MAR) or Artificial Recharge of Groundwater is one of effective technique, to counter such depletion and is most credible method of maintaining the sustainability of groundwater. Methods for artificial replenishment are commonly utilized to redirect surplus surface water into underground storage and aquifers when such water is abundant. Implementing artificial recharge structures aids in preserving and storing excess surface water for later utilization, thereby potentially enhancing the sustainable water output in areas where aquifers have been depleted.

Therefore, it is crucial to identify potential areas for groundwater replenishment to effectively deploy Artificial Recharge Structures (ARS). Identifying these potential zones for artificial groundwater recharge (AGRZs) offers a pivotal solution to safeguard groundwater through adept resource management and the application of appropriate recharge techniques. Identifying these potential groundwater zones is essential for the efficient utilization and management of existing groundwater resources, as well as for the adoption of tailored recharge methodologies.

The intensity and occurrence of groundwater recharge zone vary from place to place due to various determinant factors. Conventional field survey techniques for identifying potential groundwater recharge zones, involving methods like drilling and various hydrogeological, geological, and geophysical approaches, are consistently time-consuming, expensive, and particularly challenging when applied on a large scale (Arabameri et al., 2019; Murmu et al., 2019; Singh et al., 2018). Furthermore, these survey methods often fail to comprehensively consider the multitude of factors influencing the occurrence and movement of groundwater (Oh et al., 2011).

Nevertheless, in recent times, multi-criteria methodologies utilizing Geographic Information System (GIS) and remote sensing (RS) tools have gained scientific acknowledgment as effective means for delineating groundwater recharge potential zones (Murmu et al., 2019; Singh et al., 2019). A review of literature highlights that an integrated approach combining remote sensing and GIS-based multi-criteria analysis is predominantly favored by researchers and scientists.

In recent years, Multi-Criteria Decision Analysis (MCDA) Methods like the analytical hierarchy process (AHP), fuzzy logic, and multi-influencing factor (MIF) approaches have been widely utilized to establish a comprehensive decision-making framework for managing groundwater resources. Nevertheless, despite the availability of numerous MCDA based researches for Identification of Groundwater Recharge and Potential Zones in Ethiopia, no research explored the potentiality for implementation of artificial groundwater recharge in the Akaki catchment using nine critical recharge affecting factors, determined the appropriate locations and methods/type of artificial recharge structures based on evaluation of determinant factors and validated the map through proper scientific methodology .Hence, more studies are needed in the catchment by extending the utilization of additional critical factors affecting groundwater recharge and scientific model validation.

Therefore, this study seeks to create a spatial model to delineate the groundwater recharge potential zones within the Akaki catchment area, utilizing GIS and Remote Sensing data. The objective is to provide recommendations regarding suitable locations and methods for implementing artificial groundwater recharge in the Akaki catchment.

1.2 Background

The viability of groundwater to sustain both livelihood and ecological systems heavily relies on the natural and artificial replenishment to offset the withdrawal or usage of water (Taylor et al., 2013). However, recent years have seen groundwater conditions deteriorate due to a disparity between replenishment and extraction rates, leading to overexploitation. The ability of groundwater resources to support human livelihoods has been compromised in numerous regions, attributed to factors such as population growth and climate change (Kolusu et al., 2019; Seddon, 2018). Moreover, many countries have witnessed a decline in both the quality and quantity of groundwater due to overexploitation spurred by rapid population growth, particularly in urban areas (Venkatramanan et al., 2015).

Hence, one of the most credible alternatives to tackle over exploitation of ground water is through artificial groundwater recharge. (Todd, 1959) describes artificial recharge in his work as a method to augment the volume of water in aquifers. This approach has been in practice for around 200 years and has been adopted by various countries globally. Some of the advantages of artificial recharge include the restoration of depleted aquifers, storage of excess floodwaters for utilization during dry periods, mitigation of land subsidence, provision of consistent municipal water supply, reduction of groundwater salinity near agricultural lands, and prevention of seawater intrusion in coastal regions.

The ground water resources potential of the Addis Ababa city are found within Akaki catchment located in the Upper Awash River Basin, namely Akaki Phase-4(Koye), Akaki Phase 2, Akaki Phase 3A, Akaki Phase 3B, Legedadi Phase-1 Works, Legedadi Phase- 2 South Ayat North Fanta (SANF) and Addis Ababa Pocket.

Despite the existence of a developed regional groundwater model for the Akaki catchment, studies reveal a lack of effective groundwater management in the well fields. A prevalent issue in the area is the excessive extraction of groundwater to meet the high demand for drinking water in the city. Specifically, in the Akaki well field, significant groundwater table drawdown due to overexploitation has been observed, highlighting this as the primary groundwater management challenge. Research indicates that an escalation in pumping rates from the well fields to meet Addis Ababa's ever-increasing water demand has led to considerable regional groundwater level decline, resulting in the depletion of springs, shallow hand-dug wells, and frequent pump failures.

Therefore, artificial recharge represents a potential solution to combat the issue of declining water tables and to augment groundwater levels, which are adversely affected by overexploitation resulting from rapid population growth and potential climate change and variability (Seddon, 2018). However, the insufficient availability of information regarding the locations and accessibility of groundwater recharge potential zones presents a significant challenge for prioritizing and implementing conservation measures. Thus far, the identification of groundwater recharge potential zones has received minimal attention in the study area.

Therefore, this study focuses on identifying and mapping potential groundwater recharge zones within the Akaki catchment area in Ethiopia. It employs an integrated approach combining Geographic Information System (GIS) and Remote Sensing (RS) techniques with the Analytical Hierarchy Process (AHP) method with the aim of promotion of implementation of Artificial Groundwater Recharge methods.

1.3. Statement of the Problem

The groundwater production from various well fields within the Akaki Catchment, which also serves the city of Addis Ababa with a substantial demand for domestic, commercial, industrial, and institutional purposes, has not been sustained at its designed capacity. Over time, there has been a decline in discharge. Much of this groundwater development is overseen by the Addis Ababa Water Supply and Sewerage Authority (AAWSA) and neighboring towns in the Oromia region. However, there is a lack of formalized procedures and methods for managing the well fields to mitigate groundwater depletion. Furthermore, the trend of groundwater levels in these developed well fields has not been adequately assessed during successive planning phases. Priority has consistently been given to addressing immediate water supply shortages through groundwater development in the catchment, rather than ensuring the long-term sustainability of this resource.

According to a study by (Debebe Muleta, 2020), the current estimated gap between groundwater withdrawal and recharge within the Akaki catchment is about 50MCM/year (for an estimated groundwater withdrawals of 153MCM/year Vs. recharge of 103MCM/year including inflow from the portion of Abay plateau in the catchment). According to the study, the gap may increase to 134 MCM/year when ongoing projects of AAWSA are completed. Further, the study found that 84.50% of the current pumping water levels in the Akaki well-field were below the dynamic water level. Specifically, the old Akaki well-field has experienced severe depletion, whereby 13 out of 24 drilled wells were abandoned due to significant declines in water levels. The imbalance between recharge and discharge components (with a larger volume of water being pumped out of the aquifer than being replenished) will further be aggravated in the future due to factors such as urbanization and expansion of settlements, climate change, population growth, increasing rates of deforestation, and alterations in land use and cover resulting from construction activities, which led to a decline in groundwater recharge. As a result, the estimated exploitable groundwater potential of approximately 382 MCM may not be sustainable over the long term. To solve such identified problems, the current research is designed to fill gap of lack of comprehensive groundwater recharge zone mapping incorporating nine critical factors, largely utilizing remote sensing data and model validation and determines the appropriate locations and methods/type of artificial recharge structures based on evaluation of determinant factors.

1.4. Objectives

1.4.1 General Objective

The main objective of this study is to delineate groundwater recharge zones for artificial groundwater recharge implementation within the Akaki catchment area, using Geographic Information System (GIS) and Remote Sensing (RS) techniques with the Analytical Hierarchy Process (AHP) method.

1.4.2 Specific Objective

Listed below are the specific objectives of this research thesis:

- ➢ Identifying factors that influence groundwater recharge.
- ➢ Utilizing Remote Sensing (RS) and Geographic Information System (GIS) integrated Analytical Hierarchy Process (AHP) methodology to delineate groundwater recharge zone map (GRZM).
- ➢ Validate groundwater recharge potential zone map.
- ➢ Recommendation on the appropriate artificial recharge structures and their locations.

1.5. Research Question

The research questions devised to achieve the research objectives of this study are:

(I) What are the primary factors influencing groundwater recharge in the study area

(II) What is the spatial distribution and potential for groundwater recharge in the study area taking into account the integration of various thematic layers and how can GIS be utilized for this purpose?

(III) How to validate the result of the groundwater recharge zone map of the study area?

(IV) What are the possible alternative methods and locations of artificial groundwater recharge?

1.6. Scope and Limitation

The study focuses on mapping potential groundwater recharge zone index of the Akaki catchment, and the data will be limited to this area. This study mostly depends on factors derived from conventional data ‘a and relies heavily on Remote sensing data such as DEM, meteorological data, geological, soil texture, land use land cover, etc., however *available aquifer storage and source water availability* were not considered. On the other hand, the identification of groundwater water recharge potential zones in this thesis work is made by using only MCDA_AHP decision framework. In the future, this study could be expanded by employing other MCDA and soft computational methods (such as Multi Influencing factor, Frequency Ratio, Fuzzy Logic, and Boolean Logical Operators) to give weights to the map layers and can be cross validated.

Areas that have been identified as suitable for MAR should be investigated with subsequent detailed in-situ measurements to characterize in detail the subsurface hydrogeology of the site as the map is based on surface parameters extracted from Remote Sensing data and Conventional data. Additionally, the recommended recharge structures and sites for the selected artificial recharge structures are of a preliminary nature and therefore detailed in situ investigations shall be made before implementing the structures, through detailed hydro meteorological, hydrological, geophysical, hydrogeological and hydro chemical investigations to ascertain the scope and feasibility of artificial recharge. It is also worth mentioning that implementing Artificial Groundwater Recharge may lead to alterations in hydrological patterns, water quality concerns, ecological disruptions, habitat loss, soil erosion and sedimentation, social and cultural impacts, and regulatory challenges.

1.7. Significance of the Study

The implementation of AGR techniques enhances water storage in aquifers, ensuring long-term security of groundwater for sustainable water supply. In the study area, it is crucial to delineate potential AGR Zones (AGRZs) for the effective implementation of these techniques. Consequently, the findings of this study can aid in provision of valuable information for selecting optimal sites for constructing artificial recharge. The maps generated by this study/approach could be used as a basic guide by government and water policy decision-makers when choosing appropriate locations for groundwater management practices and outcomes of this study can assist engineers, planners, and water managers in strategizing the implementation of different proposed sites for groundwater conservation measures, including artificial recharge structures. The study reduces the time and cost for selecting potential sites and provides a dataset and can be a guidance tool to focus on the sites for further investigation.

1.8 Thesis Organization

This thesis has five main chapters. The Introductory part (chapter one), sets the background of the study and has a brief overview of the study conducted providing the rationale behind the research, including the statement of the problem, objectives, the research questions, significance and limitations of the study. This is then followed by the Literature Review, by providing the fundamentals of the concept of groundwater depletion, presents case studies and methodologies for its determination, introduces Managed Aquifer Recharge (MAR) with case studies, and provides a brief explanation of factors influencing groundwater recharge. It also reviews theoretical and empirical studies related to the current research, such as the application of the GIS software and advanced Remote Sensing techniques for groundwater recharge potential site selection, and Multi-Criteria Decision Analysis (MCDA) methods. The third chapter i.e. Methods and Materials, gives the general attributes of the study area, data types/sources, materials used, , and how the study data’s are prepared and analyzed etc. The fourth chapter presents incorporates the results & discussion corresponding to analysis. At last, in chapter five conclusions and recommendations are provided.

LITERATURE REVIEW

2.1 Groundwater

Groundwater typically refers to the water present in fully saturated geological formations beneath the water table (Freeze and Cherry, 1979). It resides within and slowly traverses through geological formations like aquifers, comprised of soils, sand, and rocks. Groundwater recharge occurs as moisture descends from the land surface towards the water table in the unsaturated zone, a process known as infiltration (Harter, 2003). Infiltration plays a vital role in the hydrological cycle, as it replenishes groundwater resources from precipitation (Mohammad, 2018).The infiltration of water into the ground and its subsequent percolation into deeper layers is termed "recharge". Recharge can transpire through various mechanisms, including direct infiltration of rain and snow, seepage through stream beds, inflow from adjacent formations into subsurface layers, and infiltration from irrigation (Asano, 1985). These forms of recharge are specifically termed "natural recharge". The intricate interplay between groundwater and surface water can significantly influence recharge and discharge processes (Sophocleous, 2002). Surface waters have the potential to recharge groundwater while also impacting its quality. Similarly, groundwater often contributes to streams and lakes by augmenting their water and solute content (Winter, 1998).

2.2. The Concept of Groundwater Depletion

According to (Mohammad, 2018), the term "safe yield" of a groundwater basin was first introduced as early as 1915, defining it as "the net annual supply which may be developed by pumping and Artesian flow without persistent lowering of the ground-water plane." Subsequent definitions by (Todd, 1959) provided a more general perspective, defining it as "the amount of water which can be withdrawn from it annually without producing an undesired result." (Meinzer,1923) further elaborated on safe yield, describing it as "the rate at which water can be withdrawn from an aquifer for human use without depleting the supply to such an extent that withdrawal at this rate is no longer economically feasible."

(Mohammad, 2018) explained that “before pumping, the groundwater system typically maintains a dynamic equilibrium, with storage remaining constant and the sum of all inputs equaling the sum of all outputs”. “However, if a new stress is introduced to the system, either recharge must increase, discharge must decrease, or water must be removed from storage” (Mohammad,2018). “As water is extracted from storage, the groundwater surface, the water table in unconfined aquifers, or the potentiometric surface in confined aquifers declines, potentially increasing the cost and difficulty of pumping water" (Mohammad, 2018). This process of water removal from storage is termed "mining" or "overdraft," and some level of mining typically occurs before a new equilibrium is established following the introduction of a stress such as human extraction through wells (Theis, 1940). In extreme cases, if all water is extracted from storage, a groundwater basin may be practically depleted (Mohammad, 2018).

Groundwater depletion occurs when the rate of extraction of groundwater from an aquifer exceeds the rate of natural recharge, leading to a decline in groundwater levels over time. An aquifer can be considered depleted when its groundwater levels drop to a point where they are no longer sustainable for long-term use. Several indicators may suggest that an aquifer is depleted such as:

Persistent Decline in Water Levels: If groundwater levels consistently decline over time, even during periods of low or no pumping, it indicates that the rate of extraction exceeds the natural replenishment rate.

Increased Pumping Costs: As groundwater levels drop, it becomes more difficult and expensive to pump water from wells, as pumps must work against greater hydraulic head pressures.

Land Subsidence: Over-extraction of groundwater can lead to land subsidence, where the land surface sinks as the aquifer is depleted. This is particularly evident in areas with compressible aquifer materials such as clay.

Saltwater Intrusion: In coastal areas, excessive pumping can lead to saltwater intrusion into the aquifer, contaminating freshwater resources and rendering them unsuitable for use.

Drying up of Wells or springs: When groundwater levels drop below the depth of wells or springs, they may cease to flow or become completely dry.

Once an aquifer is depleted, it may take a long time, if ever, to fully recover, depending on factors such as the rate of natural recharge and the geologic characteristics of the aquifer. (Konikow and Kendy, 2005) "Considering factors such as water quality, aquifer salinization, subsidence concerns, and the risk of seawater intrusion, characterized depletion as a physical process leading to a decrease in the total or usable volume of the resource". In the context of the Akaki Catchment, groundwater depletion is associated with the actual decline in groundwater levels, deterioration in yield, and the drying up of wells.

2.3. Methods of Determination of Groundwater Depletion

Groundwater level monitoring, achieved through the assimilation of water level fluctuations, stands as the most direct and straightforward method for estimating the volume of water depleted from an aquifer. This technique involves integrating changes in hydraulic head across the aquifer area and multiplying this area by a representative aquifer storage factor to derive an estimate of storage depletion. However, significant challenges arise with this method, including the establishment of extensive monitoring networks and the collection of water level data across large areas at regular intervals (Muhammad, 2015).The water balance approach utilizes various scientific methodologies to estimate and account for different types of recharge and discharge processes, thereby determining groundwater storage variations and depletion over specific timeframes. Numerical simulation models, grounded in water balance calculations, have proven useful for estimating the net groundwater removed from an aquifer. Nevertheless, the accuracy of these models in predicting depletion hinges on the quality of hydrogeological data provided as input. Recent advancements in three-dimensional hydrogeological modelling have enabled a more precise representation of aquifers, underlying geological formations, and the interconnected processes linking the groundwater system to both surface water in general and ecological processes specifically (Muhammad, 2015).

2.4 Over View of Impact of Groundwater Depletion Globally and Cases

Over the past half century, groundwater depletion has emerged as a widespread issue globally, primarily attributed to the widespread availability of pumped wells, which has led to a surge in groundwater development for municipal, industrial, and agricultural purposes (Kendy, 2005). Worldwide, groundwater withdrawals collectively amount to approximately 750–800 km3/year (Shah T, 2000). In numerous regions, groundwater reserves have been depleted to the extent that well yields have diminished, pumping costs have escalated, water quality has deteriorated, aquatic ecosystems have suffered damage, and land has experienced irreversible subsidence (Debebe M, 2020).

According to (Muhammad, 2015), “one of the most prevalent causes of land subsidence is the excessive extraction of groundwater, resulting in a decline in water levels and subsequent reduction in water pressure within the aquifer”. This, in turn, leads to the compaction of aquifers and sinking of the ground surface. Instances of land subsidence resulting from excessive groundwater extraction have been reported in various regions, including Italy, Japan, the USA, and (Poland, 1984). For example, in the San Joaquin Valley, California, over-extraction of groundwater has led to land subsidence, resulting in differential changes in elevation across the landscape. This has heightened the costs associated with the construction and maintenance of water transport infrastructure, such as canals, irrigation, and drainage systems.

Regions experiencing significant groundwater depletion, as assessed by the most reliable scientific data available, include the southern and central parts of Asia, North China, the Middle East and North Africa (MENA) region, North America, certain areas of Australia, and numerous localized regions in southern Europe (Muhammad, 2015). In the United States alone, approximately 700–800 km3 of groundwater has been extracted from aquifers over the past century (Konikow and Kendy, 2005). For instance, in the Fuyang River Basin located within the North China Plain, the water surface has experienced a substantial decline, plummeting from 8 meters to 50 meters between 1967 and 2000 (Shah et al., 2000).

Likewise, between 2003 and 2009, approximately 143.6 km3 of groundwater was depleted in the north-central Middle East, encompassing sections of the Tigris and Euphrates River Basins as well as western Iran (Voss et al., 2013). In various regions of Australia, the excessive withdrawal of groundwater from aquifers is leading to declining water levels in shallow unconfined systems and reduced groundwater pressures in deep confined and semi-confined systems.

2.5 Artificial Recharge of Groundwater and Case Studies

To address the escalating issue of declining water levels, it is imperative to prioritize initiatives focused on water conservation and artificial groundwater recharge. Managed Aquifer Recharge (MAR) entails deliberately recharging water into aquifers for later retrieval or environmental enhancement (Dillon et al., 2009b). In the literature, terms such as MAR, groundwater banking, and artificial recharge of groundwater are used interchangeably. (Dillon, 2005) characterized MAR as a comprehensive term encompassing various approaches for intentionally storing and treating water within aquifers.

The term "artificial recharge" holds different interpretations among various practitioners. The (American Society of Civil Engineers (ASCE), 2001) defines artificial recharge “as the intentional modification of the natural recharge pattern to enhance recharge”. Artificial recharge can also be defined as "any method that introduces water into a permeable stratum." It can also be described as “the process of increasing groundwater levels at a rate surpassing that of natural replenishment conditions. Thus, any human-made facility that supplements water to an aquifer may be classified as artificial recharge “(CGWB, 1994).

Artificial recharge serves as a method to modify the hydrological cycle, aiming to increase groundwater recharge beyond natural levels (Raghunath, 2007). Although the primary objective, and often the sole desired outcome of an artificial recharge initiative, is to enhance groundwater resources for future extraction, there are several additional benefits linked to artificial recharge. It can be utilized to mitigate land subsidence, enhance the quality of injected water through aquifer geo-purification, manage seawater intrusion, and utilize the aquifer as a conduit (Bouwer, 2002).

The artificial recharge of groundwater stands out as a longstanding water resources management strategy with a history spanning centuries. Historical evidence indicates that as early as the 5th century AD, farmers in regions such as the Middle East, China, and India engaged in the practice of artificial groundwater recharge by harnessing floodwaters (International Water Resources Association, 1983).

Recharge projects have been implemented globally for several centuries. The earliest artificial recharge projects in Scotland and France date back to 1820 (Jansa, 1952). Countries such as the United States, Australia, Israel, Germany, Canada, and South Africa have utilized artificial groundwater recharge as a key water management strategy for their groundwater resources. For instance, (Taheri and Zare, 2011) conducted a study on the applicability and impacts of artificial groundwater recharge in the semi-arid Kangavar Basin in western Iran. The findings revealed positive impacts of artificial recharge, including increased aquifer storage and rising groundwater levels. In response to groundwater level declines due to overexploitation in many parts of India, the government initiated artificial recharge projects nationwide.

France, Greece, Denmark, Netherlands, and Poland, among other European countries, have embraced artificial recharge as a sustainable water management strategy (Lallana et al., 2001). In Africa, there are 52 documented cases of Managed Aquifer Recharge (MAR) concentrated in nine countries. The predominant MAR method is surface spreading/infiltration, followed by open well, shaft, and borehole injection, and then in-channel modification. Notably, in Kenya, the most practiced MAR method is in-channel modification using sand dams, while in Tunisia, it is the spreading/infiltration method, and in South Africa, it is the open well, shaft, and borehole injection method. The Sidfa Riverbank Filtration case in Egypt stands as the sole reported induced river bank filtration case in Africa. River water (both ephemeral and perennial) and treated wastewater serve as the primary water sources for MAR schemes. Additionally, the combined use of storm water runoff/river water and treated wastewater is common.

In Ethiopia, the sole documented instance of Managed Aquifer Recharge (MAR) is represented by a subsurface dam built near the village of Koraro Hawzen in Tigray. This subsurface dam, known as Koraro-01, primarily serves as a domestic water supply for rural communities, relying on groundwater as its water source. The recharge volume for the Koraro-01 subsurface dam was recorded at its lowest (0.001 Mm3/year). This project falls under the category of in-channel modification MAR type. However, the infrastructural design led to the crest of the above-ground subsurface dam being breached due to flooding.

2.6 Methods of Artificial Recharge

The selection of an artificial recharge method is contingent upon various factors, including the water source, water quality, geological and topographical characteristics, aquifer type, soil type, economic considerations, among others (Bear, 2007). In general, groundwater recharge methods can be categorized into two main groups: (a) direct methods and (b) indirect methods.

Direct methods are further categorized into surface spreading techniques and sub-surface techniques. These methods primarily aim to enhance the contact area and duration of surface water in the soil, facilitating maximum infiltration and augmentation of groundwater storage. Surface spreading techniques encompass a range of methods such as flooding, ditch and furrow surface irrigation, stream modification, and the widely accepted approach suitable for small community water supplies, run-off conservation structures, or rainwater harvesting. Meanwhile, subsurface techniques commonly involve injection wells and gravity head recharge wells.

Indirect methods of artificial recharge involve inducing recharge through techniques such as pumping wells, collector wells, infiltration galleries, aquifer modifications, and the implementation of groundwater conservation structures.

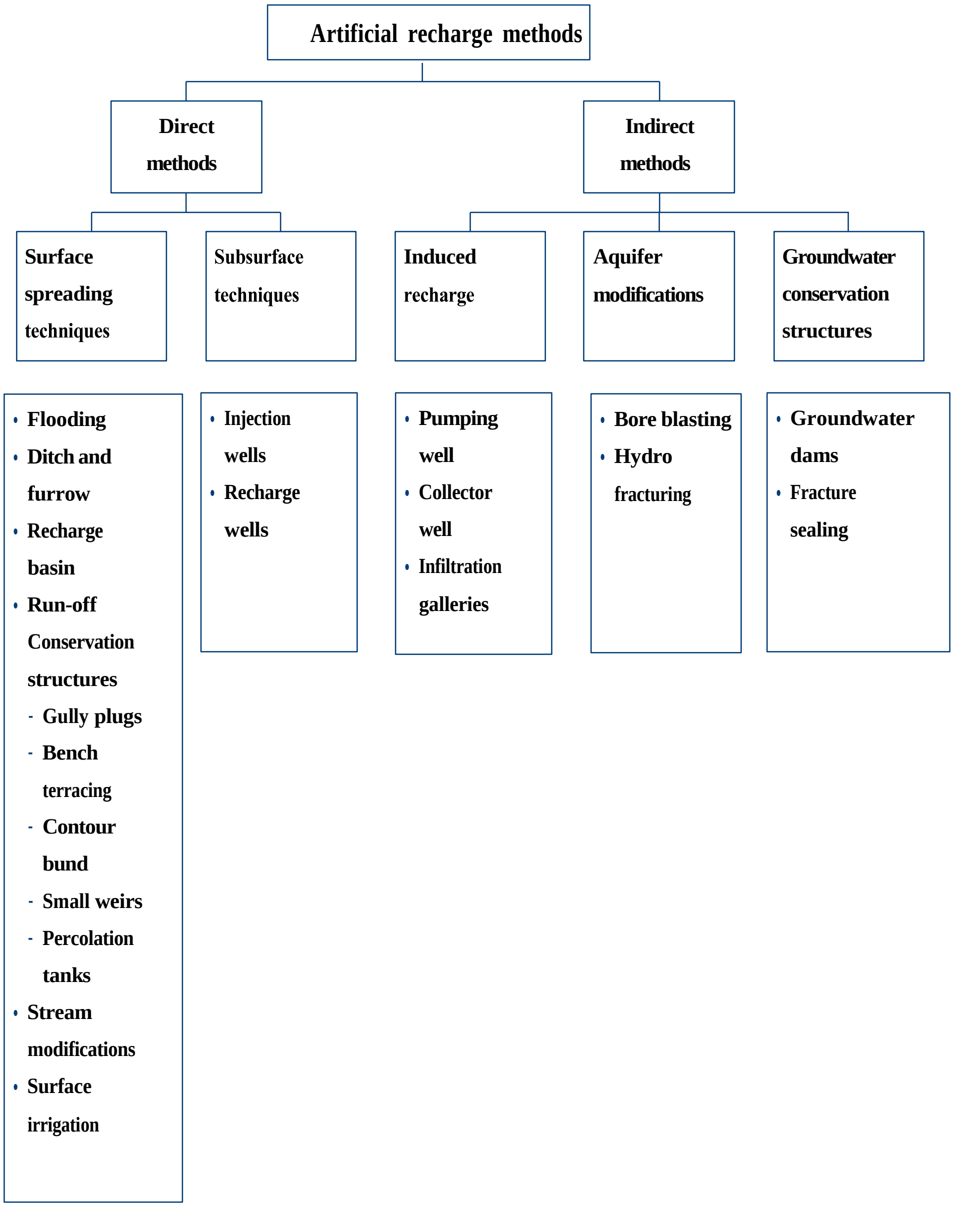

Figure 1: Methods of Artificial Groundwater Recharge

2.7 Source of Water and Identifying the Suitable Site for Artificial Groundwater Recharge

According to the Central Ground Water Board (CGWB of India (2007), potential sources for managed aquifer recharge/artificial recharge include "in situ precipitation within the watershed/area, nearby streams/springs/aquifer systems, surface water supplies from canals connected to large reservoirs within the watershed/basin, surface water supplies via trans-basin water transfer, and treated municipal/industrial wastewaters" (CGWB of India, 2007). A suitable site ensures both economical and effective outcomes for the recharge project. Factors such as the method of recharge and the intended use of extracted water play significant roles in site selection.

The American Society of Civil Engineers (ASCE) outlines the following characteristics as crucial elements for selecting a site for a recharge project.

- Geology
- Hydrology
- Topography
- Meteorology
- Vegetation cover
- Land use
- Distance to the source of water for recharge
- Distance to the area of use, etc.

Methods in Geographic Information System (GIS) applications can be employed to conduct a suitability analysis of the factors mentioned above, aiding in determining the most appropriate location for a recharge project.

2.8. Groundwater Recharge and MAR Suitability Mapping

As per MPO (1987), net groundwater recharge is described as “the volume of water that infiltrates from the subsoil to the water table, primarily contributing to the net increase in the annual groundwater level” (MPO, 1987). ***Potential recharge***, on the other hand, refers to the “maximum amount of recharge capable of reaching the water table” (MPO, 1987).

Groundwater recharge is influenced by various hydrological and environmental factors, including climatic, topographic, soil, land-use, hydrologic, and hydrogeological factors. These factors collectively determine the suitability of an area for artificial recharge. Climatic conditions play a significant role in determining the availability of water for recharge, both spatially and temporally, while topography influences runoff and water retention. Soil type and land use patterns affect the extent of infiltration, and hydrogeological conditions dictate the presence of potential aquifer systems and their suitability for artificial recharge. The spatial and temporal distribution of rainfall primarily governs natural groundwater recharge.

Mapping the suitability of groundwater recharge potential zones is crucial for identifying specific sites suitable for groundwater recharge structures, these studies typically concentrate on identifying suitable/ potential sites for artificial groundwater recharge using the Geographic Information System (GIS) software and employing weighted overlay techniques. This approach integrates thematic maps from various layers using GIS and remote sensing (RS), and applies a Weighted Linear Combination (WLC) method to generate qualitative maps based on suitability factors. Suitability mapping serves as an initial step in feasibility assessments, aiding in the identification of potential locations for artificial recharge.

2.9 Geographical Information System (GIS) and Remote Sensing (RS) Application in Groundwater Recharge Zone Mapping

Geographic Information System (GIS) and Remote Sensing (RS) are cutting-edge technologies for assessing groundwater potential and recharge. Over the past three decades, the integration and utilization of GIS and RS technology has been instrumental in identifying groundwater potential and recharge zones. While other methods such as hydrological investigation, geophysical techniques like geo electrical or seismic refraction methods are available for assessing groundwater and recharge potential, they tend to be costly and time-consuming. In contrast, GIS and remote sensing offer a more modern, efficient, and cost-effective approach to groundwater exploration. These technologies enable comprehensive data acquisition and facilitate the analysis of various factors influencing groundwater potential and recharge zones through user-friendly software interfaces.

GIS is particularly well-suited for handling a diverse array of parameter data influencing groundwater, which is sourced from various outlets, to facilitate the key processes involved in mapping groundwater recharge potential. These processes typically encompass data acquisition, digitization of map data, data processing, and data analysis. Different datasets are organized into thematic maps using GIS software tools. These parametric maps are subsequently overlaid using the "Spatial Analyst" tool.

“Remote sensing, with its benefits of spatial, spectral, and temporal data availability, has emerged as a valuable tool for evaluating, observing, and safeguarding groundwater resources” (CGWB of India, 2007). Its capability to cover large areas, including those that are difficult to access, is a distinct advantage. “Satellite data offers rapid and valuable baseline data on numerous factors influencing the presence and flow of groundwater, including geology, structural characteristics, geomorphology, soil composition, land use, land cover, and lineaments “(CGWB of India, 2007).

Numerous researches have been conducted globally and locally using integrated GIS and RS techniques for Identification of Groundwater Recharge and Potential Zones which will be covered in the empirical literature review section of this literature review.

2.10 Multi Criteria Decision Analysis (MCDA) ,Analytical Hierarchy Process (AHP) and GIS as Recharge Site Selection Tools

The most widely used approaches for delineating groundwater recharge potential zones are commonly categorized into two main groups: "Multi-criteria analysis (MCA) / Multi-criteria decision analysis (MCDA) and Soft computational analysis."

MCDA, also known as Multiple Criteria Decision Analysis or Multiple Criteria Decision Making (MCDM), is a subset of operational research dedicated to addressing decision problems involving multiple criteria for identifying the most favorable solution. Operational research, a branch of mathematics, is recognized for applying sophisticated analytical techniques to achieve optimal or nearly optimal solutions in intricate decision-making scenarios.

Multi-criteria analysis (MCA) is an umbrella term for a number of different techniques and tools by which multiple objectives and decision criteria can be formally incorporated into the analysis of a problem.

Given the deep variety of MCDA methods developed over the years, mapping all the existing techniques is impossible, however some of the well-known and common methods are listed as follows:

- Analytical Hierarchy Process (AHP)
- Analytic Network Process(ANP)
- Aggregated Indices Randomization method (AIRM)
- Case-Based Reasoning (CBR)
- Data Envelopment Analysis (DEA)
- Elimination and Choice Translating Reality (ELECTRE)
- Fuzzy set Theory
- Goal Programming (GP)
- Multi-Influencing Factor (MIF)
- Multi-Attribute Utility Theory (MAUT)
- Preference Ranking Organization Method for Enrichment Evaluations (PROMETHEE)

- Simple Multi-Attribute Rating Technique (SMART)
- Technique for Order Preferences by Similarity to Ideal Solutions (TOPSIS)
- Weighted Sum Model (WSM)…etc.

In MCDA based Groundwater Recharge Potential Mapping AHP, MIF and Fuzzy Logic are the most widely used methods. According to the multi influencing factor (MIF) methodology, the more influence a criterion has on the other criteria and the objective, the higher is its score and higher the weight obtained. The determination of weights among criteria is based on their mutual impact and relevance to the objective. Each criterion's weighting is contingent upon its interactions with others, signifying either a significant or minor influence. (Shaban et al., 2006) assign 1 point for a major effect and 1/2 of a point for a minor effect. By summing the scores for both major and minor effects for each criterion, the relative rate is computed, which is then utilized to calculate the weight of each influencing criterion. Another approach for delineating groundwater potential zones is Soft Computation Analysis (SCA). (Md. Rashed, 2017) notes that there has been a growing adoption of machine learning techniques for groundwater mapping. Methods like Fuzzy logic and Frequency ratio are examples of single-module machine learning models that have been utilized. Additionally, SCA models are capable of conducting intricate analyses with extensive datasets and indicators, as highlighted by Md. Rashed (2017).

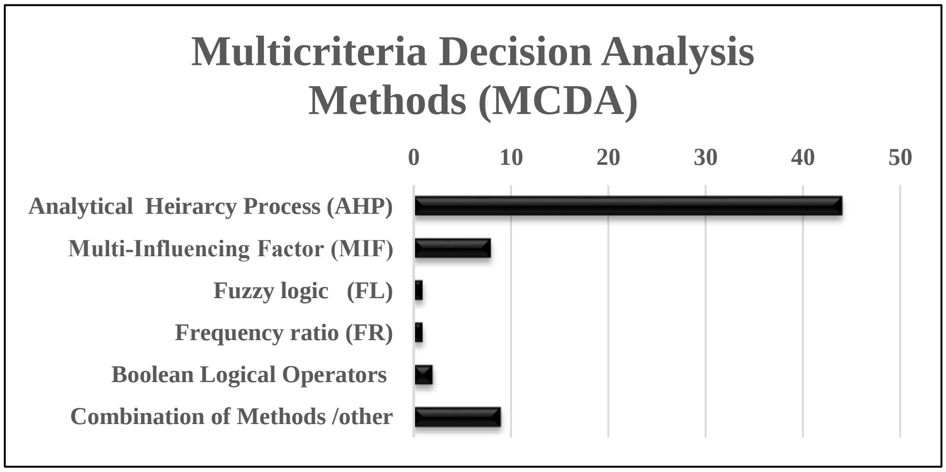

Figure 2: Multicriteria Decision Analysis techniques from the reviewed literatures

As it is shown on figure 2 for this research study among the 64 reviewed literatures 68% have used the Analytical Hierarchy Process (AHP) method for potential groundwater recharge zone mapping, 13% have used Multi-Influencing Factor (MIF) and 14% adopted combined use of AHP, MIF, FL/FR, Boolean Logical Operators etc. Using the Analytic Hierarchy Process (AHP) instead of Multi-Influencing Factor (MIF) mapping allowed to regularly check the consistency of the judgments throughout the decision-making process. This feature ensured that the priorities and assessments of criteria and alternatives remained reliable and free from inconsistencies, enhancing the robustness and credibility of the decision outcomes and hence used in this study.

2.10.1 Analytical Hierarchy Process (AHP)

The Analytic Hierarchy Process (AHP), introduced by Thomas Saaty (1980), is one of the most effective multi-criteria decision making (MCDM) techniques. It is a well-recognized method by decision-makers in establishing priorities and arriving at the most suitable decisions and helps to navigate complicated decision making systems.

Analytic Hierarchy Process (AHP) is a logical and coordinated technique for structuring information alternatives on a hierarchical framework aided by mathematical pairwise comparisons. AHP can be applied to groundwater recharge studies particularly for the selection of potential recharge zones from competing sets of parameters. In order to delineate potential recharge zones within the Akaki catchment AHP technique was implemented in four phases: (1) Selection of factors influencing groundwater recharge zones (2) pairwise comparison matrix, (3) estimating relative weights and (4) assessing matrix consistency.

Saaty developed the AHP method which first constructs a Piece wise matrix followed by calculation of weights for each thematic map. During the weight calculation the consistency of the pair wise matric is checked by Consistency Ratios (CR), and if it of values < or equal to 0.1 the consistency is acceptable.

2.10.2 Groundwater Recharge Zone Mapping and Weighted Overlay Analysis (WOA)

To assess various groundwater recharge zones, crucial factors affecting groundwater recharge shall be taken into account, and a map depicting the potential zones for groundwater recharge will be created by analyzing diverse thematic layers. Following reclassification, the normalized weights derived from the pairwise comparison matrix will be applied to generate the Groundwater Recharge Potential Zone (GWRPZ) using the weighted linear combination (WLC) technique.

The weighted linear combination (WLC) technique is based on the principle of weighted averaging, where the criteria are standardized to a common numerical scale. The GIS tool "weighted overlay analysis" will be employed to calculate groundwater recharge potential index values using the equation recommended by:

$$GWRPI = \sum_{w=1}^{m} \sum_{j=1}^{n} (Wj * Xi) \ldots\ldots \quad (1)$$

W_j represents the normalized weight of the j-th thematic layer, X_i denotes the normalized weight of the i-th feature within the thematic layer, m stands for the total number of thematic layers, and n signifies the total number of features within a particular theme. These GWRPI values will guide the classification of areas into categories such as excellent, very good, moderate, poor, or very poor in terms of groundwater recharge potential.

2.11 Groundwater Recharge Influencing Factors

From an examination of past studies and a review of relevant literature, a comprehensive set of nine influential factors encompassing environmental, hydrological, and hydrogeological aspects has been identified. These factors include Rainfall, Lineament Density, Lithology, Slope, Drainage Density, Soil Texture, Land Use Land Cover (LULC), Topographic Position Index (TPI), and Topographic Wetness Index (TWI). These factors will play a crucial role in delineating the potential groundwater recharge map for the study area and are discussed below.

Rainfall

Precipitation, a fundamental component of the hydrological cycle, significantly influences groundwater potential. Areas experiencing higher rainfall tend to exhibit greater potential for groundwater recharge, while regions with lower rainfall typically have lower recharge rates (Zomlot et al., 2015; Kotchoni et al., 2019). Long-term rainfall patterns are more indicative of groundwater recharge potential compared to short-term precipitation events. Rainfall data can be aggregated over various time scales—daily, monthly, or annually—and interpolated using diverse methods to provide averaged values.

Lineament Density

A lineament refers to a linear characteristic seen in the terrain, revealing the underlying geological framework like folds, faults, joints, or fractures, contributing to secondary permeability. O'Leary et al. described lineaments as straightforward or slightly curved linear aspects of geological formations, encompassing faults, cleavages, fractures, and other discontinuous surfaces, discernible through remote sensing. These lineaments denote zones of vulnerability that disrupt the flow of groundwater, promoting infiltration into the subsurface.

The Lineament Density (LD) is defined as the total length of lineaments per unit area (km/km2) and calculated through the following formula (Yeh et al., 2009):

$$LD=\frac{\sum_{i=1}^{n} Li}{A}\,(\mathrm{km/km2}) \ldots\ldots\ldots\ldots\ldots\ldots\ldots\ldots\ldots\ldots (2)$$

Li represents the total length of lineaments measured in kilometers, while A denotes the area expressed in square kilometers. An area with high LD indicates high secondary porosity, consequently, a high potential for groundwater recharge (Yeh et al., 2009).

Lithology

The composition of rocks, known as lithology, plays a crucial role in determining both the quantity and quality of groundwater as well as the permeability of aquifer formations. It serves as a key determinant in the processes of recharge and infiltration. Consequently, assessing geological and lithological attributes is essential for accurately defining Potential Aquifer Recharge Zones (PARZ). Greater porosity within lithological materials results in increased groundwater storage capacity and enhanced permeability, leading to higher yields of groundwater.

Slope

Slope plays a crucial role in groundwater recharge potential mapping. It determines surface runoff and vertical percolation of water; hence, it affects groundwater recharge processes. Infiltration is inversely related to slope (Yeh et al., 2014; Rahmati et al., 2015). Flat plains generally retain a larger amount of rainwater, thereby aiding the recharge process. Conversely, mountainous regions characterized by steep slopes often experience significant runoff potential and limited infiltration capacity (Singh et al. in 2013).

Drainage-length Density (DD)

The Drainage Density (DD) is defined as the total length of all channels per unit area of the drainage basin (expressed in km/km^2), providing insight into the proximity of channel distribution, as noted by (Singh et al., 2013). (Chowdhury et al., 2009) observed an inverse correlation between permeability and drainage density, indicating that higher drainage density leads to lower infiltration of rainwater and vice versa. DD serves as a metric for assessing channel system development, surface runoff, rock permeability, and infiltration rate, thereby indirectly reflecting the suitability of an area for artificial aquifer recharge. The computation of DD value is based on the following equation, as outlined by (Yeh et al., 2009):

$DD=\frac{\sum_{i=1}^{n} Si}{A}(\mathrm{km}/\mathrm{km2})$ .... (3)

Where Si denotes the total length of drainage in km, and A is the area in km2.

Soil

Soil texture plays a significant role in groundwater recharge, in addition to its impact on various other hydrological processes. Primarily, soil influences infiltration and percolation, which in turn affect groundwater replenishment.

Land Use Land Cover

The classification of land use and land cover serves as a key determinant in the identification of suitable sites for artificial groundwater recharge, as highlighted by (Singh et al., 2013). Land use/cover maps are essential tools for identifying regions with potential for groundwater replenishment. The conditions of land use and cover play a significant role in altering the hydrological cycle, primarily by influencing surface runoff behavior and, consequently, groundwater recharge. Certain land uses promote groundwater recharge, while others have adverse effects. For instance, urban and settlement areas typically accelerate the runoff process, resulting in diminished recharge. Agricultural areas may either positively contribute to groundwater recharge or detract from it, depending on the implementation of soil and water conservation practices.

Terrain Position Index (TPI)

The Topographic Position Index (TPI) stands out as a significant indicator in the groundwater recharge process. It notably impacts the duration water remains within a specific watershed, thereby altering the connection between water sources, as noted by Singh et al. in 2009. Initially, a mean Digital Elevation Model (DEM) is produced using a 3 by 3 window. Subsequently, TPI is computed based on the equation (Yishak and Mikias, 2022):

TPI = DEM − Mean DEM3by3,... (4)

Terrain Wetness Index (TWI)

The Topographic Wetness Index (TWI) is frequently employed to measure the degree of topographic influence on hydrological phenomena, as indicated by (Michielsen,2016). It serves as an indicator highlighting how topographical characteristics impact the location and extent of saturated areas involved in runoff generation. This index mimics the behavior of water as it accumulates at various points and reflects the gravitational tendency for water movement downstream, as described by (Pourghasemi et al., 2012).

2.12 Literature Review of Empirical Studies

Various studies concerning the mapping of groundwater recharge zones through the utilization of Geographic Information Systems (GIS) and Remote Sensing (RS) were reviewed. These studies were sourced from both published and unpublished thesis and researches.

2.12.1 Studies Worldwide

Globally, there are ample number of studies (published and unpublished) worldwide with regards to groundwater potential and recharge zone mapping The method of suitability mapping has been employed globally, which involves the integration of thematic maps from various layers through the Weighted Linear Combination (WLC) technique. of suitability factors to generate qualitative maps (e.g. (Hsin-Fu Yeh *et.al*, (2016), M. Rajasekhar *et.al*,(2021),Tanveer Dar *et.al*.,(2020) ,Omeed H. Al-Kakey *et.al* (2023) etc)).Among the 64 literatures reviewed for this study, Table 1 Summarizes few of the selected global studies.

Table 1: Selected studies worldwide (Groundwater Recharge Zone Mapping studies using GIS and RS)

S. No	Author/Authors	Methodology	Title	Thematic Layers/Factors	Location
1	(Hsin-Fu Yeh *et.al*, 2016)	GIS & RS, WLC (Influencing Factor) ,	Mapping groundwater recharge potential zone using a GIS approach in Hualian River, Taiwan	Lithology, land cover/land use, lineaments, drainage, and slope	Taiwan
2	(A. Mahdavi, *et.al* N.A)	GIS and Fuzzy Logic	Identification of groundwater artificial recharge sites using Fuzzy logic: A case study of Shahrekord plain, Iran	Slope, infiltration rate, thickness of unsaturated zone, surface water Electrical Conductivity, land use and stream network.	Iran
3	(Gaolatlhe Bhutto Lentswe & Loago Molwalefhe, 2020)	GIS,RS,AHP and WOA	Delineation of potential groundwater recharge zones using analytic hierarchy process-guided GIS in the semi-arid Motloutse watershed, eastern Botswana	Lithology, lineament density, ground slope, soil type, soil thickness, and drainage density	Botswana
4	(M. Rajasekhar *et.al*,2021)	GIS & RS, Fuzzy Logic (FL), Frequency Ratio (FR), Analytical Hierarchy Process (AHP),combined methods	"Identification of artificial groundwater recharge zones in semi-arid region of southern India using geospatial and integrated decision-making approaches"	Lithology, soil types, lineament density (LD), drainage density (DD), vadose zone (VZ), rainfall, land use/ land cover (LULC), and slope	India
5	(Monica Chakraborty *et.al* 2021)	GIS, RS,WOA	"Site Suitability analysis for artificial groundwater recharge potential zone using a GIS approach in	Slope Type and percentages, Soil, Geomorphology, Land Use Land Cover, Drainage, Geology, Water Table Fluctuation	India

			Basaltic terrain, Buldhana District, Maharashtra, India”		
6	(Rami Al-Ruzouq *et.a*l 2021)	GIS& RS, AHP, WOA	Multi criteria Spatial Analysis to Map Artificial Groundwater Recharge Zones: Northern UAE	Precipitation, Drainage Stream Density, Geomorphology, Geology, Groundwater Level, Total Dissolved Solids, Elevation, Lineament Density, Residential Euclidean Distance	UAE
7	(S. Selvam *et.al* 2014)	GIS & RS, IF(Major Minor effect), WOA	“A GIS based identification of groundwater recharge potential zones using RS and IF technique: a case study in Ottapidaram taluk, Tuticorin district, Tamil Nadu”	Lithology, slope, land use, lineament, drainage, soil, and rainfall.	India
8	(Adama Gassama Jallow *et.al*,2020)	GIS, RS and Multi-Criteria Evaluation (MCE),AHP, themes normalized using a Fuzzy membership algorithm, Weighted Linear Combination (WLC)	“Groundwater Recharge Zone Mapping Using GIS-based Analytical Hierarchy Process and Multi-Criteria Evaluation: Case Study of Greater Banjul Area”	Geology, land-use/cover, slope, drainage density, soil texture, groundwater fluctuation and aquifer transmissivity	India
9	(Suhail A. Lone *et.al*, 2016)	GIS & RS	Characterization of Groundwater Potential of Sindh Watershed Western Himalayas	Geomorphology, lithology, land use-land cover, lineaments density, drainage density, and slope	India/Nepal

10	(Shashank Shekhar & Arvind Chandra Pandey, 2014)	GIS& RS, AHP,WOA	Delineation of groundwater potential zone in hard rock terrain of India using remote sensing, geographical information system (GIS) and analytic hierarchy process (AHP) techniques	Geomorphology, lithology, soil, slope, lineament density, weathered zone thickness, drainage density and rainfall	India
11	(Dimple *et.al*, 2022)	GIS& RS, ,WOA, Boolean Logic	"Identification of Artificial Recharge Sites for Nand Samand Catchment"	Topographic elevation, post-monsoon groundwater level, recharge, slope, transmissivity and soils map	India
12	(Tanveer Dar *et.al*.,2020)	GIS& RS, AHP,WOA	"Delineation of potential groundwater recharge zones using analytical hierarchy process (AHP)"	Slope, soil texture, drainage density, land/land cover (LULC), lithology, geomorphology, lineament density, and rainfall	India
13	(C.D. Aju *et.al* 2021)	GIS& RS, AHP,WOA	"Identification of suitable sites and structures for artificial groundwater recharge for sustainable water resources management in Vamanapuram River Basin, South India"	Plan curvature, profile curvature, land use/land cover, aspect, distance from streams, relative relief, geology, geomorphology, slope angle, available space for recharge, lineament density, sand percent, rainfall and drainage density	India
14	(Omeed H. Al-Kakey *et.al* 2023)	GIS& RS, AHP,WOA	"Identifying potential sites for artificial groundwater recharge using GIS and AHP	Topographic position index, geomorphology, lithology, land cover, slope,	Iraq

			techniques: A case study of Erbil basin, Iraq”	drainage-length density, and lineament-length density.	
15	(M. Kirubakaran *et.al*, 2016)	GIS& RS, AHP,WOA	A geo statistical approach for delineating the potentialgroundwater recharge zones in the hard rock terrainof Tirunelveli taluk, Tamil Nadu, India	Geomorphology, lineament density, drainagedensity, topographic slope, land use/land cover, annual mean rainfall, soil, and subsurface geology	India
16	(I.P. Senanayake ,2015)	GIS& RS,WOA	An approach to delineate groundwater recharge potential sites in Ambalantota, Sri Lanka using GIS techniques	Rainfall, lineament, slope, drainage, land use/land cover, lithology, geomorphology and soil characteristics	Sri Lanka
17	(Manjunatha M.C, 2019)	GIS& RS, AHP,WOA	An approach to delineate artificial recharge structures for piriyapatna taluk of mysuru district, karnataka, india using geo informatics	Lithology, geomorphology, drainage & its density, lineament & its density, soil, slope, land use/ land cover	India
18	(Yahya Fathi Kamel Saleh, 2009)	GIS & WIOA	“Artificial groundwater recharge in Faria catchment A hydrogeological study”	Infiltration capacities of the sediments, type of the aquifer the fractures along study area, slope, Land use.	Palestine.
19	(Recep Çelik, 2019)	GIS& RS, AHP,WOA	“Evaluation of Groundwater Potential by GIS-Based Multicriteria Decision Making as a Spatial Prediction Tool: Case Study in the Tigris River Batman-Hasankeyf Sub-Basin, Turkey”	Geomorphology, geology, rainfall, drainage density, slope, lineament density, land use, and soil properties	Turkey

20	(José Pablo Bonilla Valverde *et a*l, 2019)	GIS Based Multi-Influencing Factor (MIF) and WLC	“Application of a GIS Multi-Criteria Decision Analysis for the Identification of Intrinsic Suitable Sites in Costa Rica for the Application of Managed Aquifer Recharge (MAR) through Spreading Methods”	Hydrogeological aptitude, terrain slope, top soil texture and drainage network density	Costa Rica
21	(Arunava Poddar *et.al,* 2020)	GIS& RS, MIF	Artificial Ground Water Recharge Planning Using Geospatial Techniques in Hamirpur Himachal Pradesh, India	Geology, Slope, land use/land cover, drainage density, geomorphology, , lineament density and soil texture	India
22	(Amanpreet Singh *et.al* 2013)	GIS& RS, AHP,WOA	“Artificial Groundwater Recharge Zones Mapping Using Remote Sensing and GIS: A Case Study in Indian Punjab”	Geomorphology, geology, land use/ land cover, drainage density, slope, soil texture, aquifer transmissivity, and specific yield.	India
23	(S. Kaliraj *et.al*, 2015)	GIS& RS, to unique scale weight value depending on its potential magnitude for groundwater recharge, WOA	Evaluation of multiple environmental factors for site-specific groundwater recharge structures in the Vaigai River upper basin, Tamil Nadu, India, using GIS-based weighted overlay analysis	Geomorphology, Geological settings, Topography, Soil type and its characteristics, Land use and land cover, Annual average rainfall, Lineament density, Drainage density, Aquifer transmissivity, Groundwater table fluctuation,	India

2.12.2 GIS, RS and MCDA Based Groundwater Studies in Ethiopia

Numerous studies have also been done in different basins and sub basins of Ethiopia with regards to groundwater potential zone evaluation and mapping using GIS, RS and MCDA but still the application of GIS and remote sensing is not widely used as in the case of other countries. Accordingly, few of selected studies among the 64 literature reviews are discussed below.

(Abebe Debele Tolche,2020) conducted groundwater potential mapping for the Dhungeta-Ramis subbasin in Ethiopia, utilizing geospatial techniques such as GIS, RS, and knowledge-based weighting, alongside Weighted Overlay Analysis (WOA). The findings categorized the sub-basin into five qualitative classes: very good, good, moderate, poor, and very poor, comprising 2.22%, 26.93%, 56.74%, 13.84%, and 0.26% of the landscape, respectively. Subsequently, the model's accuracy was assessed through cross-validation using spring, hand-dug, and deep well data. The analysis demonstrated that 89% of springs overlaid on areas classified as good or very good for groundwater potential, while 58% of deep wells showed a similar correlation. Conversely, 42% of deep wells were situated within the moderate zone.

(Tesfa Gebrie and Girum Getachew,2019) also conducted a study on Groundwater potential assessment of Guna tana landscape, upper blue Nile Basin using GIS and Remote sensing data and AHP was used to give weightage to 7 major groundwater potential influencing factors such as land cover, drainage density, lineament density, soil, geology, slope, and geomorphology. Soil (30×30m resolution) and DEM (30m resolution) data were sourced from the Ministry of Water, Irrigation, and Electricity of Ethiopia, with a land cover image obtained from the USGS Earth Explorer website for January 2018, featuring a resolution of 30 x 30 meters. The land cover map was created by classifying the satellite image and validating it with ground truth points. Geological and lineament maps (scaled at 1:250,000) were acquired from the Geological Survey of Ethiopia. Slope, drainage, and elevation maps were generated from the digital elevation model, while drainage density and lineament density maps were derived from the corresponding drainage and lineament maps. Utilizing ArcGIS 10.3.1 software, all necessary thematic maps were developed based on the collected datasets.

In their study titled "Determining Potential Aquifer Recharge Zones Using Geospatial Techniques with Proxy Data of Gilgel Gibe Catchment, Ethiopia," (Tarekegn Dejen et al.,2022) utilized various factors including slope, lithology, topographic position index, lineament density, rainfall, soil, elevation, land use/cover, topographic wetness index, and drainage density. Notably, lithology, rainfall, and land use/cover emerged as dominant factors, collectively weighted at 50%. The calculated consistency ratio (CR = 0.092, below 10%) and consistency index (CI = 0.1371) indicated the reliability of the input proxy layers in the analysis. Subsequently, a GIS-based weighted overlay analysis was conducted to delineate potential aquifer zones into categories of very high, high, moderate, low, and very low. The resulting map depicted proportions of the total area classified as very high (29%), high (25%), moderate (28%), low (13%), and very low (5%). Upon validation, the majority of inventory wells were found within the very high (57%), high (32%), and moderate (12%) zones. These validation outcomes underscored the method's capability in producing robust results supportive of sustainable development and groundwater utilization.

(Yisak Mohammed and Mikias Biazen, 2022) aimed to identify potential zones for artificial groundwater recharge in the Tikurwuha Watershed of Ethiopia. The suitability classification of the final potential artificial groundwater recharge zones revealed areas categorized as extremely high (0.5625 hectares, accounting for 0.001% of the total area), high (20,003.7 hectares, representing 30.959%), moderate (42,428.17 hectares, constituting 65.665%), poor (2,179.656 hectares, making up 3.373%), and very poor (1.312 hectares, accounting for 0.002%). The study also proposed that given the insignificance of the extremely high potential sites, decision-makers could utilize the high potential sites for the implementation of artificial groundwater recharge techniques.

2.12.3 Literature Summary on Related Works on Akaki Catchment Aquifer and Literature Findings

There are different Hydro geological, Impact Assessment, Hydro chemical and Numerical groundwater modeling studies of the Akaki Catchment developed by different researchers, governmental and non-governmental organizations and consultants. Well failure assessment and evaluation of hydraulic parameters are also among the common groundwater research studies conducted in the study area of Akaki Catchment.

The initial groundwater model for the well field was established in 2000 (BCEOM & Seureca Space JV in association with Tropics Consulting Engineers, September 2000) and underwent revision in 2004 to expand its scope. This model proposed a sustainable pumping rate from the well field and proposed for continuous monitoring of pumping rates and drawdown levels (Ayenew T, 2008). Furthermore, the subsurface hydrodynamics of the well field were examined through the calculation of groundwater fluxes using a steady-state MODFLOW model setup. According to the model findings, the proposed pumping rate could sustainably extract between 30,000m3/day to 35,000m3/day, with an anticipated drawdown ranging from 20 to 23 meters over a 20-year pumping period (BCEOM, 2000 and 2002).

A 2018 study by Yimer Mekonen on “Groundwater Depletion in Akaki Well Fields and Catchment Water Supply found that excessive groundwater extraction, surpassing the aquifers replenishment capacity, is a primary factor impacting the area's groundwater potential”. The study also noted that “changes in land use, temperature increase, and variability of precipitation, urbanization, and population density contribute to the alarming groundwater depletion in the catchment” (Yimer Mekonen, 2018). To address this, the author recommended “optimizing groundwater recharge mechanisms and implementing rainwater conservation and storage to mitigate water shortages” (Yimer Mekonen, 2018).

Abdrhman Berga,2011 conducted “an assessment on past and potential future changes in land cover and their influence on the hydrology of the Akaki catchment in their 2011 thesis titled Effect of Land Use Change on Hydrology of Akaki Catchment. “ The evaluation of the SWAT model's response to these land use/land cover (LU/LC) alterations revealed that annual stream flow increased by 9% from 1973 to 1986 and by 17% from 1986 to 2000” (Abdrhman Berga,2011). “Overall, the analysis indicated that stream flow during both wet and dry seasons increased by 16% and decreased by 4%, respectively. These findings suggest a correlation between changes in stream flow characteristics and alterations in land cover during the study period” (Abdrhman Berga, 2011).

In a 2006 numerical groundwater flow modeling study of the Akaki river catchment conducted by (Ebasa Oljira,2006) it was found that “changes in climatic conditions and ongoing construction activities have led to a reduction in groundwater recharge” (Ebasa Oljira, 2006). Additionally,” the increase in population size has resulted in a significant rise in water demand” (Ebasa Oljira, 2006). The author concluded that “prolonged and unregulated extraction could potentially lead to declines in water levels, causing imbalances in hydrological stresses” (Ebasa Oljira, 2006). The groundwater flow modeling conducted projected the risk associated with such unregulated extraction on the hydrological system, proposing necessary actions to mitigate such issues.

Furthermore, the thesis provided an understanding of “how the regional groundwater flow system of the Akaki River Catchment might respond to various potential sensitivity analysis” (Ebasa Oljira, 2006). The author suggested “implementing methods that enhance groundwater recharge from precipitation and decrease runoff i.e. afforestation, soil conservation, and capturing storm water runoff during heavy precipitation events, then directing it to aquifers for recharge to mitigate decreases in water levels” (Ebasa Oljira, 2006).

In 2018, Hawi Gudeta conducted a study on the “Aquifer Property Evaluations and Sensitivity Analysis of the Akaki Well Field.” The study “assessed aquifer properties by incorporating necessary corrections for unconfined aquifers and partial penetration, which account for well loss and borehole storage” (Hawi Gudeta,2018). Results indicated that “inefficient well pumping, exceeding safe yield, and parameter changes led to significant declines in groundwater levels” (Hawi Gudeta, 2018). The study concluded that “all Akaki well fields operated with poor efficiency, exceeded safe yields, and experienced well interference, which exacerbated drawdown of the water level” (Hawi Gudeta, 2018). Thus, the author concluded that this phenomenon led to “well drying and groundwater depletion and recommended that, recognizing the area's sensitivity to recharge, measures such as expanding artificial recharge and safeguarding existing recharge areas “(Hawi Gudeta, 2018).

In 2015, Mearg Belay conducted a study titled "A Geo-spatial Approach for Assessing the Impact of Land-Use and Land-Cover Change on Groundwater Recharge of Akaki Catchment." The study utilized “water balance modeling, Wetspass, and GIS to estimate past and present seasonal and annual groundwater recharge” (Mearg Belay, 2015). The results revealed “that the mean annual groundwater recharge decreased from 268.6 mm/year for the land-use map of 1986 to 264.9 mm/year and 260 mm/year for land-use maps of 2000 and 2015, respectively”, (Mearg Belay,2015).

A study by Debebe Muleta, 2020 on “assessment of groundwater hydraulics, hydrodynamics and sustainable utilization of Addis Ababa city”, indicated that “major sources of groundwater recharge for Akaki watershed well fields are regional as subsurface seepage from the fracture openings of the basaltic volcanic rocks of the adjacent Abay plateau watershed (WWDSE, 2008). And “in the case of Akaki watershed, the topographic water divide doesn’t concede with the groundwater divide”(Debebe Muleta, 2020). According to the study, “recharge within Akaki catchment without considering the inflow from the adjacent Abay plateau is estimated to be 99 Mm3/year and the estimated total volume of recharge on the portion of Abay plateau that considered for groundwater inflow is 77 Mm3/year” (Debebe Muleta, 2020). Hence, the study concluded that the entire recharge estimated with the assumed 50% inflow from the portion of Abay plateau is about 103Mm3/year. The study has also revealed that groundwater “production in the Akaki well fields deteriorated from 40,000 to 9,667meter cube per day within the last 18 years and suggested that groundwater management should be practiced through reliable aquifer characterization, sustainable development, planning of conjunctive use of surface water and artificial recharge”.

In conclusion despite the above cited literatures have suggested use of strategies of groundwater management such as artificial recharge of groundwater in response to the alarming depletion and high draw down rate of ground water table in the Akaki Catchment, the following gaps were identified to the best knowledge of the researcher.

- Lack of comprehensive groundwater recharge zone mapping incorporating nine critical factors largely utilizing remote sensing data and techniques and lack of model validation.
- Determination of the appropriate locations and methods/type of artificial recharge structures based on evaluation of determinant factors and backed by careful review of studies and manuals on artificial groundwater recharge.

Therefore, studies on assessing the potential recharge sites thereby determining the appropriate locations and methods to be used for artificial groundwater recharge in the Akaki aquifer shall be conducted.

MATERIALS AND METHODS

3.1 Study Area General Description

3.1.1 Location

The Akaki Catchment lies within the central Ethiopian Highlands, positioned along the western edge of the Main Ethiopian Rift (MER). It falls within the northwestern Awash River basin and is bounded by geographic coordinates ranging from 8°50‘00” to 9°10‘00”N latitude and 38°30’00” to 39°10’00”E longitude. The watershed boundary of the Akaki Catchment is characterized by mountains and diverse volcanic formations. To the north, the catchment is bordered by the Entoto ridge system, while to the west lie Mount Menagesha and the Wechecha volcanic range. Mount Furi marks its southwestern boundary, while Mount Bilbilo and Mount Guji define its southern limits. The Gara Bushu hills form the southeastern boundary, and to the east lies the Mount Yerer volcanic center. Covering a total area of approximately 1462 square kilometers, Addis Ababa is centrally located within the catchment. Notably, the topographic water divide of the Akaki catchment does not align with the groundwater divide, resulting in regional groundwater inflow from adjacent basins, particularly from the adjacent Abay Plateau watershed, predominantly flowing in a north-south direction into and out of the watershed. Both surface water and groundwater sources play pivotal roles in supplying water to Addis Ababa city and its surrounding areas.

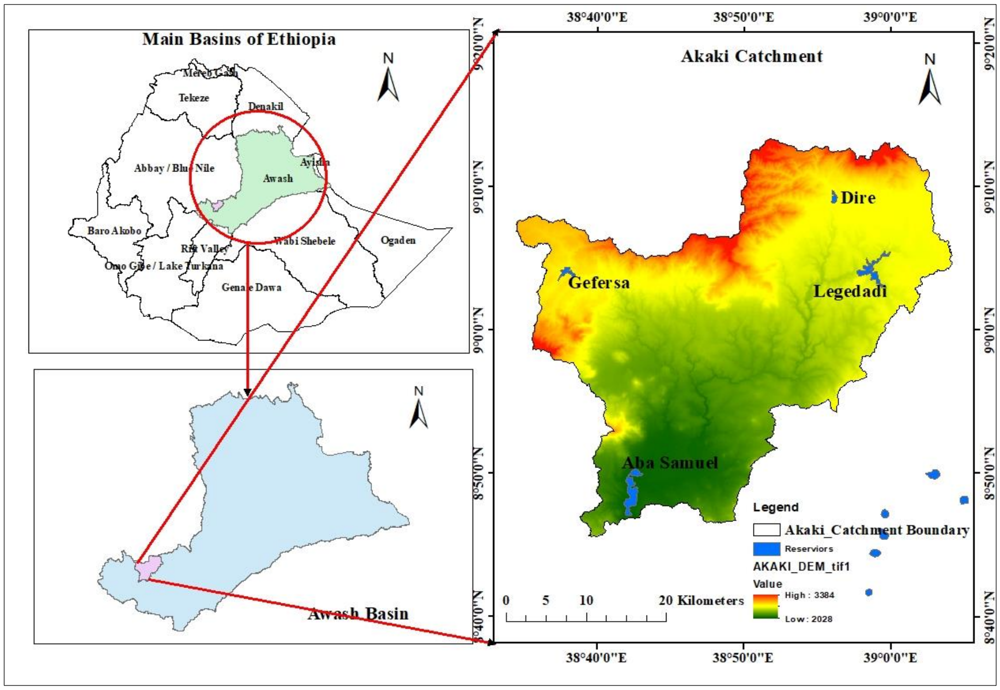

Figure 3: Study Area Location

3.1.2 Physiography and Topography of the study area

“Situated at the transition between the western Ethiopian plateau and the Main Ethiopian Rift (MER), the catchment specifically lies on the eastern edge of the western Ethiopian Plateau, gradually inclining towards the MER “(Dereje Nigussa, 2003).The physiographic setting of the catchment is the result of volcano ‐ tectonic activity that formed the plateau and rift followed by later erosion and river dissection that contributed to the existing rugged landform (Dereje Nigussa, 2003). “The elevation of the Akaki River catchment ranges from 2028 to 3,384 meters above sea level. It is enclosed by ridges, large mountain ranges, and individual volcanic centers” (Dereje Nigussa, 2003). “The central section of the catchment resembles a broad caldera and features undulating terrain, gradually decreasing in elevation towards the south, following the course of the river or outlet” (Dereje Nigussa, 2003). The topography of the catchment exhibits “steep slopes in the upstream region (such as Entoto and Sendafa) and gentler slopes in the downstream area (like Akaki)”(Dereje Nigussa, 2003).

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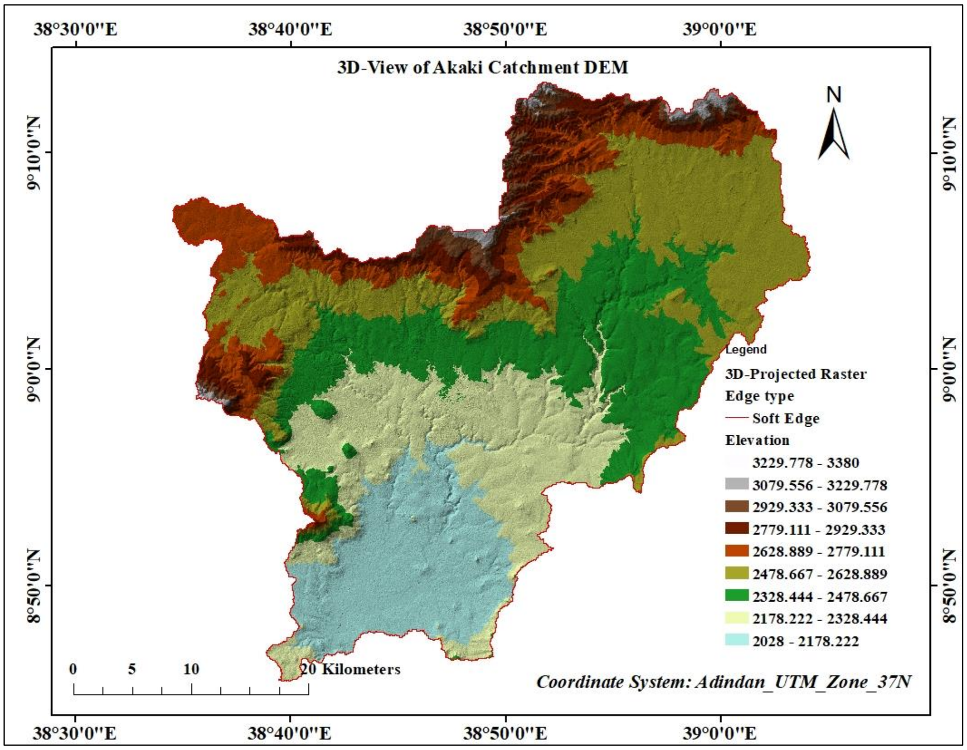

Figure 4: DEM 3D-View of Physiographic map of the study Area

3.1.3 Climate of Study Area

3.1.3.1 Climate

The study area is characterized by a warm temperate climate . It undergoes two seasonal weather patterns. “The primary wet season spans from June up to September, accounting for over 70% of the total annual rainfall and the 'Belg’ season occurs from mid-February to mid-May, contributing the remainder of the moisture to the catchment area “ (Demlie et al. 2007a). Consequently, the rainfall in the region follows a nearly bimodal distribution with two peaks, with the highest peak occurring in August.

3.1.3.2 Rainfall

Precipitation in the catchment exhibits seasonal fluctuations, influenced by factors such as the annual migration of the intertropical convergence zone (ITCZ), “a region of low pressure where dry tropical easterlies converge with moist equatorial westerlies” (HALCROW, 1989), as well as altitude variances across the catchment. The study area comprises five meteorological stations situated at Addis Ababa Bole, Addis Ababa Observatory, Akaki Mission, Entoto, and Sendafa.

The wet season, spanning from June to September, contributes approximately 75% of the annual rainfall, while the dry season which lasts from October to May, with sporadic rainfall in the remaining months. The mean annual rainfall across the stations from 1990 to 2021 G.C ranges between 961.73 mm at Akaki station and 1305.9 mm at Intoto station. Out of the rainy seasons, there is particularly high rainfall concentrations in July and August (recording the maximum monthly rainfall at 296.8 mm). The lowest mean monthly rainfall, with 9.0 mm and 6.6 mm respectively is exhibited on the month of November and December. Consequently, the watershed's average annual rainfall is estimated at 1,160.4 mm. Table 2 provides a summary of the rainfall data from 1990 to 2021 G.C.

Table 2: 31 years Mean monthly rainfall (1990-2021)

Stations	Jan	Feb	Mar	Apr	May	Jun	Jul	Aug	Sep	Oct	Nov	Dec
Addis Ababa bole	11.9	25.8	53.4	87.0	81.1	119.4	242.0	259.9	142.8	29.2	5.6	6.1
Addis Ababa Observatory	12.8	27.8	54.6	82.9	84.8	149.5	274.6	289.8	186.9	34.4	10.0	9.9
Akaki	9.7	22.3	47.9	76.8	66.3	111.1	236.4	236.9	116.2	26.3	6.5	5.2
Intoto	10.8	26.2	48.8	76.2	89.4	160.4	335.5	350.4	159.2	27.5	12.9	8.5
Sendafa	12.8	24.6	37.8	80.8	74.1	147.7	341.9	346.9	140.2	32.3	9.8	3.3
Average	11.6	25.3	48.5	80.7	79.1	137.6	286.1	296.8	149.1	30.0	9.0	6.6

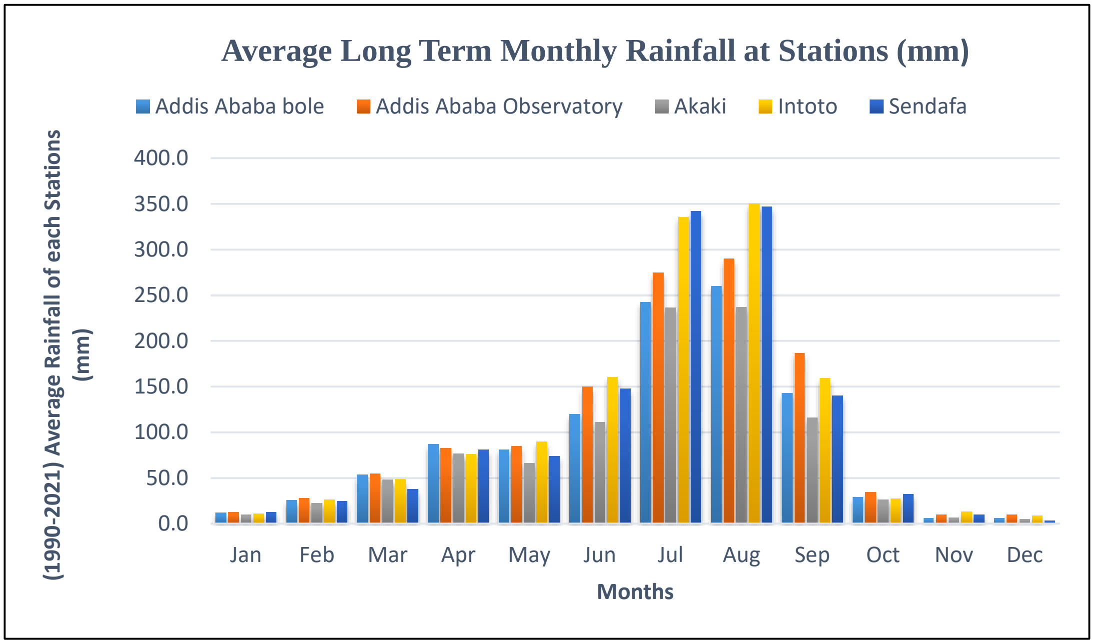

Figure 5: 31 years Mean monthly rainfall of 5 meteorological stations (1990-2021)

A trend line was plotted to establish the relationship between elevation and the annual rainfall of the catchment. As indicated by the trend line, there is a noticeable increase in annual rainfall with higher elevations (Fig 6).

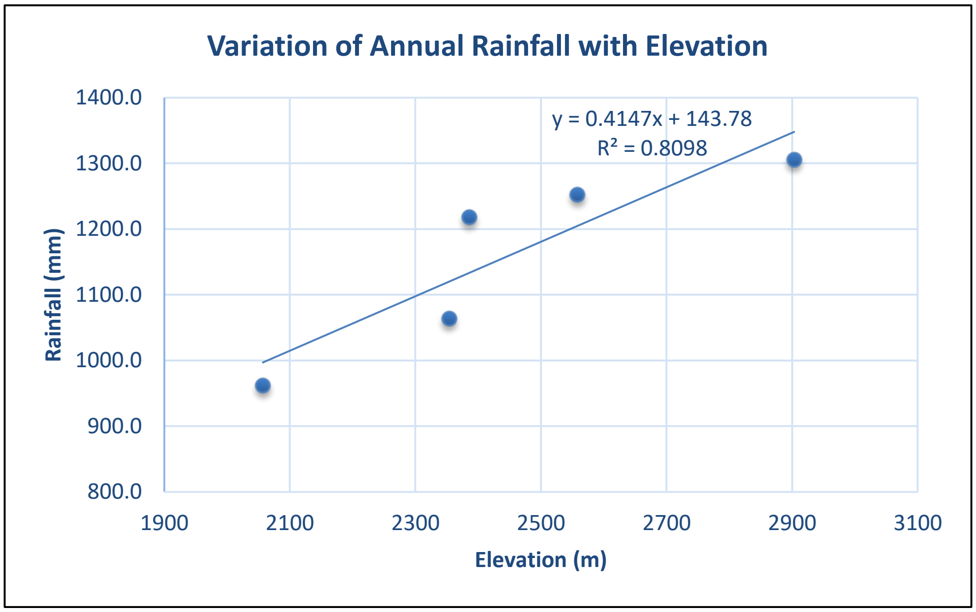

Figure 6: Annual Rainfall Variation with Elevation

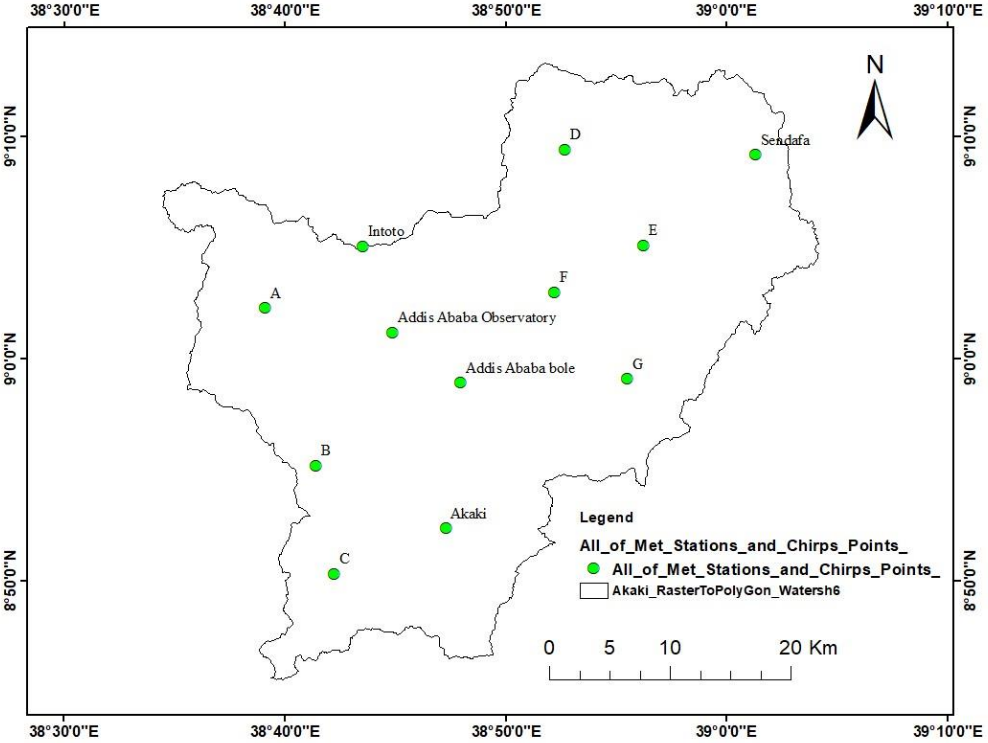

Figure 7: Locations of the meteorological stations and Chirps data points

3.1.3.3 Temperature

Temperature, another significant climatic factor, displays a strong correlation with elevation and exhibits notable variation across the catchment. Generally, temperature decreases with increasing elevation. Data on temperature in the study area were sourced from the Ethiopian National Meteorological Agency (ENMA) for the years 1990 to 2021. The mean annual temperature of the area ranges from 14.3°C to 17.1°C, as detailed in Table 3 and illustrated in Figure 8. The mean annual maximum temperature in the study area ranges from 18.1°C to 22.1°C, while the mean minimum temperature varies from 8.3°C to 12.3°C.

Table 3: Maximum and Minimum average temperature of the study area

Temp	Jan	Feb	Mar	Apr	May	Jun	Jul	Aug	Sep	Oct	Nov	Dec
Max.	20.9	21.8	22.1	21.7	21.8	20.4	18.3	18.1	19.0	20.1	20.3	20.2
Min.	9.1	9.4	11.5	11.8	12.3	11.6	11.9	11.8	11.3	10.3	8.9	8.3
Mean	15.0	15.6	16.8	16.8	17.1	16.0	15.1	15.0	15.1	15.2	14.6	14.3

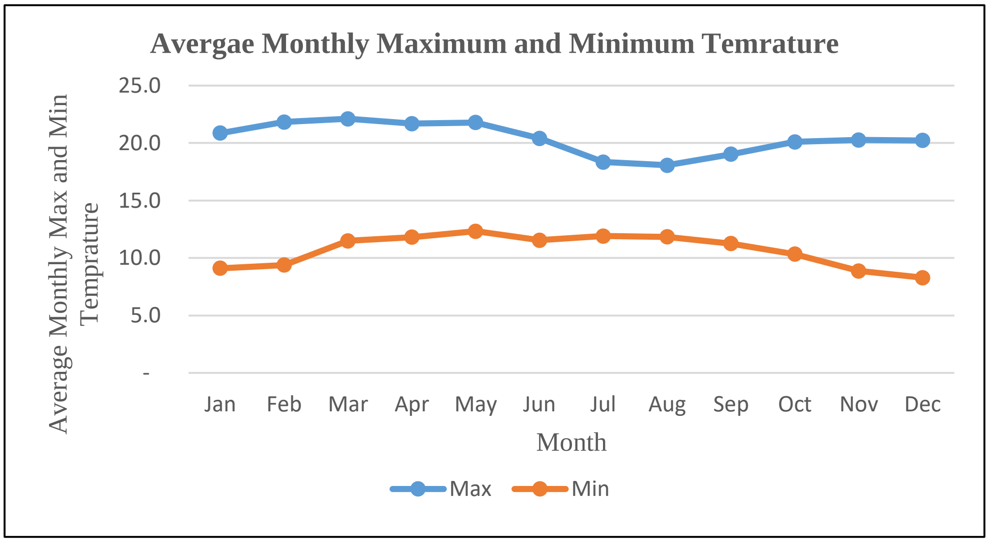

Figure 8: Maximum and Minimum average temperature of the study area (1990-2021)

3.1.3.4 Wind speed, sunshine hours and relative humidity

In the study area maximum wind speeds are typically recorded during the months of October, November, December, February, and March, while minimum values occur in July, August, and September and they area has mean annual wind speed of 1.31. Stations, maximum sunshine hours are typically observed during October up to February, with minimum values occurring in July - August. The monthly average sunshine hours are 6.85 hours. Relative humidity data show that maximum mean relative humidity values during August and minimum relative humidity values are on the months of February.

Table 4: Monthly average Rh, Sunshine hours and Wind speed of Akaki catchment (1990–2021)

Monthly Average	Jan	Feb	Mar	Apr	May	Jun	Jul	Aug	Sep	Oct	Nov	Dec
Wind speed (m/s)	1.4	1.5	1.5	1.4	1.4	1.1	1.0	1.0	1.0	1.5	1.5	1.5
Sunshine hours (hr)	9.1	8.9	8.1	6.8	6.9	5.2	3.1	3.3	4.8	8.2	8.8	9.1
Relative humidity (%)	57.0	48.3	55.6	57.2	59.6	70.1	81.1	86.4	75.6	58.5	55.1	56.9

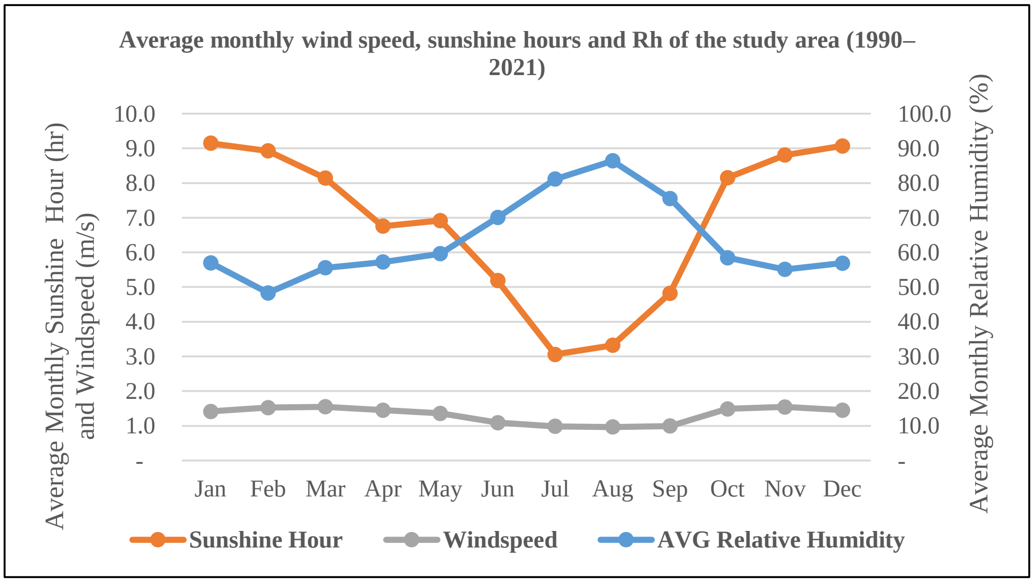

Figure 9: Monthly average Rh, Sunshine hours and Wind speed of Akaki catchment (1990–2021)

3.1.4 Drainage

The Akaki River basin catchment area, which encompasses the entirety of the Addis Ababa region, has two primary sub-basins: the Big Akaki River (Eastern) sub-basin and the Little Akaki River (Western) sub-basin. These two rivers collectively constitute one of the major tributaries feeding into the Awash River, known as the Akaki River. The Akaki River flows into Abba Samuel Lake, exits the lake, and navigates through a gorge reaching depths of up to 100 meters, spanning approximately 8 kilometers, before converging with the Awash River. Additionally, the catchment area includes numerous small rivers along with their respective tributaries. The primary tributaries of the Big Akaki River include the Bulbula and Kebena rivers. The Bulbula River collects water from the northeast peri-urban region of the catchment, while the Kebena River drains the northern sector, encompassing the older section of Addis Ababa city. Originating from the upstream area, the Bulbula River receives water from the Legedadi River, which flows through the towns of Dire, Legedadi, and Sendefa. Floodwaters released from the Legedadi and Dire reservoirs follow the course of the Legedadi River towards the Bulbula River, eventually reaching the floodplain of the Big Akaki River. On the other hand, the Little Akaki River drains the northwest portion of the catchment, channeling water from the Gefersa reservoir to the floodplains and subsequently replenishing the Aba Samuel reservoir.

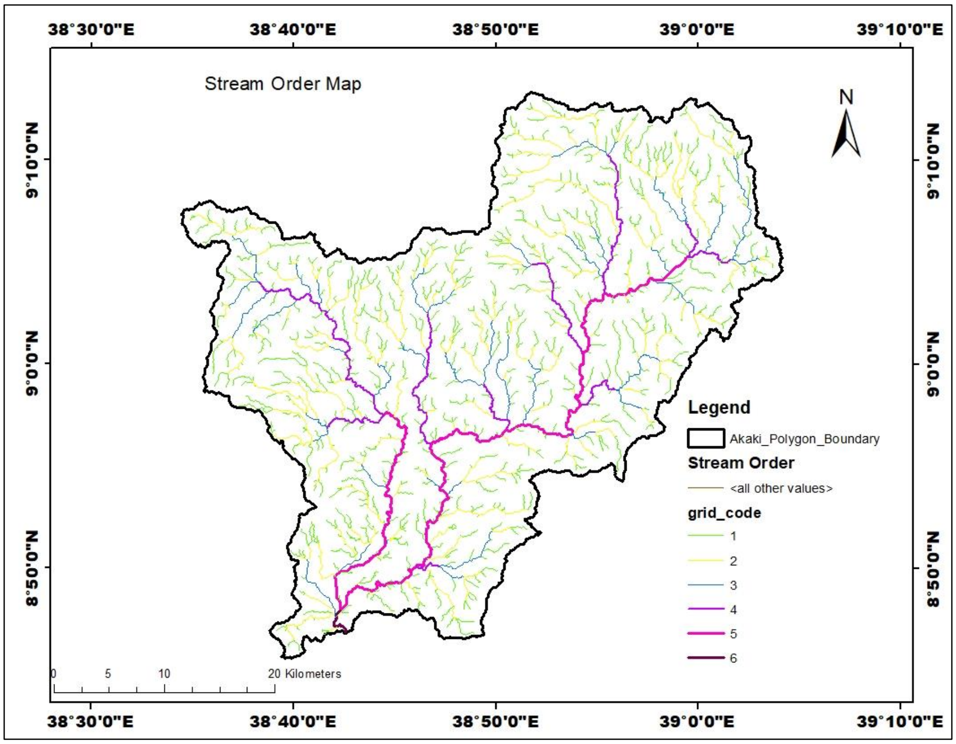

Figure 10: Drainage *pattern map of Akaki catchment (Strahaler Stream Order)*

3.1.5 Land use / Land cover

The Akaki catchment exhibits a diverse range of land use and land cover (LULC). The predominant LULC pattern within the catchment can be broadly categorized into four main groups: forested areas, urban zones (comprising various infrastructural and built-up uses), agricultural or open expanses, and water bodies. Large portions of the Intoto Range and its slopes have forest cover, primarily consisting of eucalyptus trees. The mountain range's elevated plateau facilitates rainfall interception and rapid infiltration of rainwater into the soil. Urban areas, particularly Addis Ababa city, feature extensive paved surfaces due to infrastructure such as asphalt roads, residential, commercial, and industrial developments, hindering precipitation infiltration into the ground. Storm drainage networks swiftly channel rainfall runoff to nearby drainage pathways." Despite the prevalence of elevation peaks (hills, ridges) unsuitable for farming across the catchment, agricultural or open areas occupy substantial portions, particularly in the east, south, and southwest directions" (BCEOM-seureca, 2000). These zones experience minimal human interference in terms of altering soil permeability, allowing rainwater to naturally infiltrate at a steady rate" B(CEOM-seureca,2000).

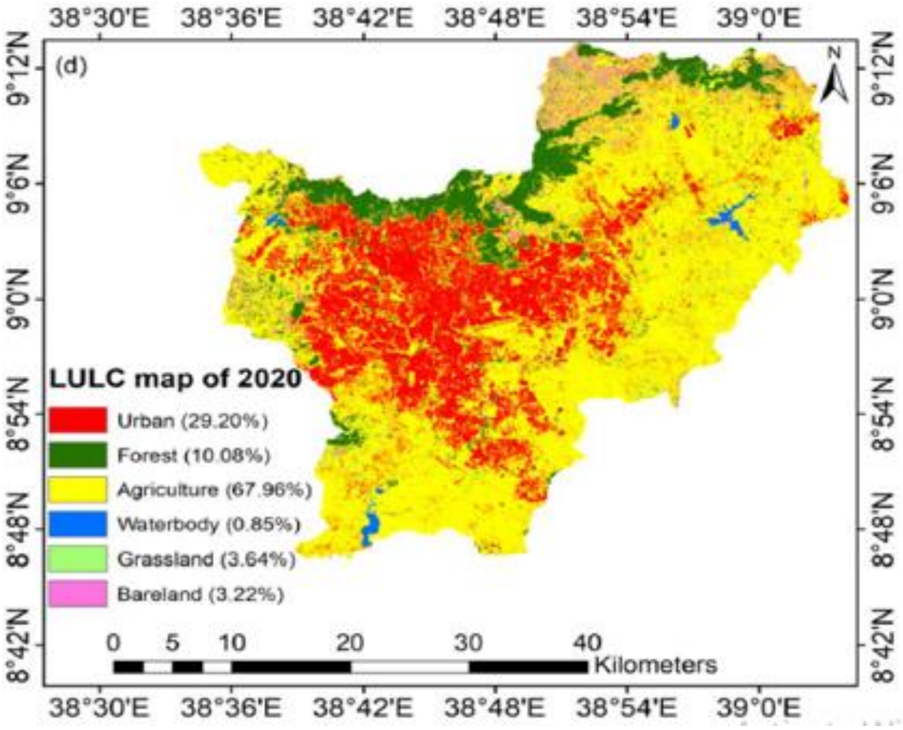

Figure 11: *Land use land cover map of the catchment (Adopted from Ephrem Derso Negah et.al, 2023)*

3.1.6. Geology Setting

3.1.6.1 Regional Geology

Typically, the geological composition of the Upper Awash River Basin, where the Akaki Catchment is located, spans from the “Upper Miocene to the Holocene epochs” Ebasa Oljira 2006. It comprises consolidated formations of volcanic origin (including Plateau and Rift volcanic deposits), lacustrine sediments, and alluvial deposits. Ebasa Oljira's 2006 summary regarding the geological characteristics of the regionally referenced area can be outlined as follows:

3.1.6.1.1 Rift and Plateau Volcanics

Alaji Basalt:

“Alaji Basalts are primarily exposed in the Addis Ababa region. These basalts are characterized by flood basalt formations, displaying texture variations ranging from aphanitic to highly porphyritic. Additionally, within this unit, there are layers of welded tuff “(Ebasa Oljira,2006).

Termaber Formation:

“The Termaber basalt is located in the plateau region stretching from Addis Ababa to the Guder valley. It consists of basalt formations with textures ranging from aphanitic to porphyritic”(Ebasa Oljira, 2006).

Anchar Basalt and Arba Gurracha Silicics:

“In the Anchar area, the geological formations consist of approximately 400 meters of basalt, interspersed with several layers of ignimbrites. The ignimbrite layer at the base dates back to 12.4 million years ago” (Ebasa Oljira, 2006).

Arba Gugu Basalt:

“This unit is a succession of lava flows piled up to 300m thick, composed of porphyritic pyroxene and/ or plagioclase basalt, erupted Arba Gugu shield volcano” (Ebasa Oljira, 2006).

Nazareth Group and Associated Unit:

“The Nazareth Group comprises a substantial sequence of geological formations, including ignimbrites, unwelded tuffs, ash flows, rhyolites, aphanitic basalt, and trachytes. These formations are predominant in the rift floor and are also visible along the escarpment and adjacent plateau margins” (Ebasa Oljira, 2006).

Bishoftu Basalt:

“The Bishoftu Basalt unit is visible in the Akaki-Debrezeit region, beginning approximately 15 kilometers south of Addis Ababa and extending to a thickness of approximately 10 meters at Akaki” (Ebasa Oljira, 2006).

Recent to Sub-recent Basalt, and Rhyolitic and Trachytic lava:

“The recent basalt outcrop located south of Debrezeit comprises scoriaceous and vesicular basalt, along with scoriaceous and porphyritic trachy-andesite, phonolite, and trachytic tuffs” (Ebasa Oljira, 2006).

3.1.6.1.2 Volcano- Sedimentary Deposits

“These deposits consist of lacustrine and alluvial formations. The lacustrine sediments are dense and largely composed of welded tuffs, ashes, silts, clays, and diatomaceous sediments. Alluvial deposits, on the other hand, are loose materials comprising sand, silt, and clay” (Ebasa Oljira, 2006).

3.1.6.2 Local Geology

The catchment is covered by range of volcanic rocks overlain by fluvial and residual soils, in which black cotton soils are predominant, varying in thickness from a few centimeters to about 20 m (AAWSA et al., 2000). The main lithology/volcanic formations include basalts, rhyolites, trachytes, scoria, trachy-basalts, ignimbrites and tuff .These highly weathered, and fractured lithology favor the circulation and storage of subsurface water (Demlie et.al. 2007a).

According to AAWSA-Seureca (1991) the following lithostratigraphic units can be identified in the catchment.

Alaji Formation:

This geological unit comprises rhyolites, trachytes, tuff, agglomerate, and aphanitic basalt. It is predominantly found in the northern and central regions. Previous studies have further categorized this series into Alaji rhyolites and Intoto Silicics (Zanettin and Justin-Visentin, 1974). The Intoto trachyte overlays the Alaji basalts. The Intoto Silicics consist of extensive Oligocene fissure-basalt, rhyolites, and trachytes, with minor occurrences of welded tuff and obsidian (Morton et al., 1979).

Addis Ababa Basalts:

These basalt formations lie above the Intoto Silicics and extend across the central and southern regions of Addis Ababa. It is common to observe distinct individual lava flows, and in many areas, remnants of ancient soils and scoriaceous layers are present. Olivine porphyritic basalt formations are particularly visible in central Addis Ababa, varying in thickness across different locations.

Younger Volcanics

This category encompasses the Nazareth Group and Bishoftu Formations, primarily situated south of the Filwuha Fault. The Nazareth Group comprises a variety of rock types, including aphanitic basalts, welded tuffs, ignimbrites, trachytes, and rhyolites. It is overlaid by aphanitic basalt and underlain by porphyritic basalt. The Bishoftu Formation consists of olivine porphyritic basalt, scoria, vesicular and scoriaceous basalt, and occasional trachy-basalt lava flows. These formations are localized in the southern region and typically have a thickness ranging from 20 to 40 meters in the Akaki well field. In some areas, they are covered by scoria, tuff, sand, and gravel. This unit constitutes the primary aquifer in the area.

Recent Deposits

These deposits encompass alluvial, residual, and lacustrine formations. Their thickness ranges from 5 meters to 50 meters near riverbanks in the southern region (AAWSA, 2000). Often, these deposits are covered by younger dark black cotton clayey soils. Alluvial deposits are present in certain areas along the little and Big Akaki rivers, primarily in the south and southwest of Addis Ababa. Residual soils are situated in the central, southeast, northeast, and western flat plains.

3.1.7 Geological Structures

The catchment which is situated at the edge of the Main Ethiopian Rift, has passed through volcano-tectonic activity forming the main Ethiopian rift which also resulted in major diastrophic and non-diastrophic structures such as lineaments, faults, bedding and volcanic layering. these structures generally align with the orientation of the rift system, running northeast to southwest, although some faults other orientations. “One prominent regional fault extends east-west from the Kassam River through the north of Addis Ababa to Ambo in the west, crossing the western rift escarpment and uplifting its northern block” (Zennettin et al., 1978). “This lineament extends further to Wollega “(Mengesha et al., 1996). Another significant fault is the Filwuha Fault, which is a notable normal fault in the area

3.1.8 Hydrogeology

The Akaki River Catchment contains both intergranular and fracture-type aquifers (Ebassa Olijira, 2006). “Essentially, the volcanic aquifers can be seen as having a dual porosity, as both the matrix and fracture porosity play roles in the movement and retention of subsurface water”(Ebassa Olijira, 2006). The intergranular porosity aquifers consist of alluvial sediments as well as pyroclastic and scoraceous volcanic rocks, which form the upper, more permeable layer. Meanwhile, the fractured aquifers are made up of basalts, ignimbrites, trachytes, and rhyolites, comprising a relatively less permeable secondary aquifer system below.

“Basalts and ignimbrites are typically highly fractured and permeable, thus categorized as good aquifers” (Tesfaye Alema, 2009). The author notes that faulted ignimbrites and basalts also serve as good aquifers, whereas basalts with fewer fractures and joints, such as the alkaline flood basalts found in the Addis Ababa area, form moderate aquifers with yields reaching up to 432 m3/day and 260 m3/day, respectively”. Additionally, “confined aquifers are also present in Addis Ababa, particularly consisting of hot waters along the Filwoha fault, which are regarded as isolated and lacking direct connection with the unconfined system” (Tesfaye Alema, 2009).Accordingly, the main aquifers in the Akaki catchment can be categorized into three groups:

1. “Shallow aquifer: made of weathered volcanic rocks and alluvial sediments along the river valleys”
2. “Deep aquifers: made of fractured volcanic rocks at which boreholes are drilled for drinking water supply purpose”
3. “Thermal aquifer: that is located at depth greater than 300m”.

Scoria deposits stand out as the most significant aquifer unit from a hydrogeological perspective. The interconnected voids within these deposits lead to their notably high permeability (Tesfaye Alema, 2009).

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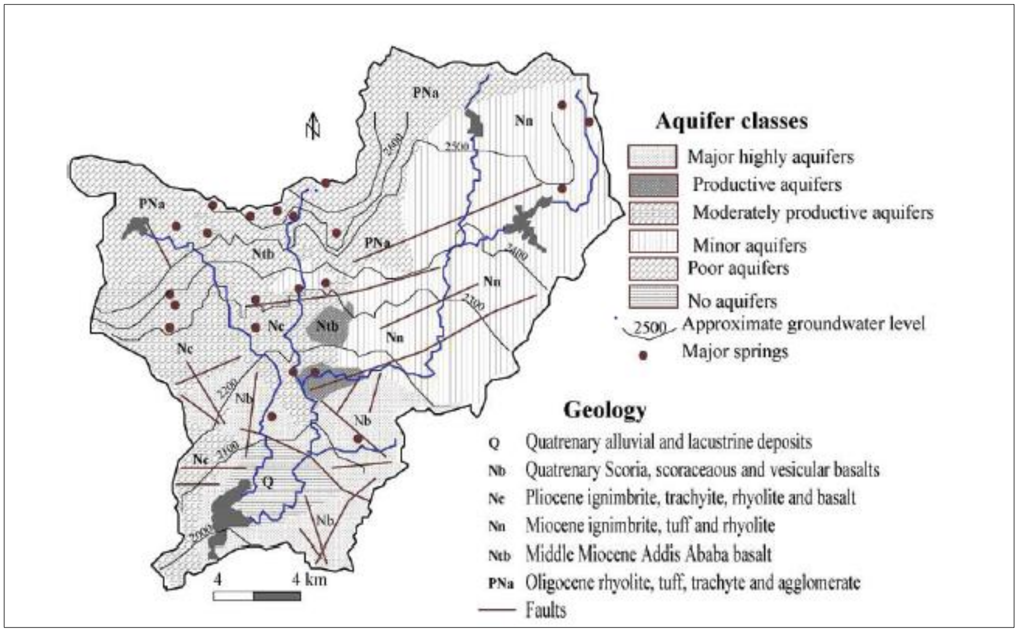


Figure 12: Hydrogeological map of Akaki catchment (Adopted from Ayenew et.al, 2008)

3.1.9 Soil

Soil formation in the study area primarily results from the physical breakdown and chemical alteration of volcanic rocks. The resultant weathering products either remain in situ, forming residual soils, or are transported and deposited in low-lying flatlands and depressions. Alluvial deposits, prevalent in the middle reaches of the Akaki River, predominantly consist of black cotton soil, known for its exceptionally low permeability. Another soil type present in the area is residual soil, located in the northern and northeastern sectors of the catchment. Additionally, lacustrine sediments are found along the Akaki Rivers and lake areas in the southern and southeastern parts. The majority of soil types in the catchment exhibit a compacted clayey texture, characterized by very low permeability and minimal percolation rates.

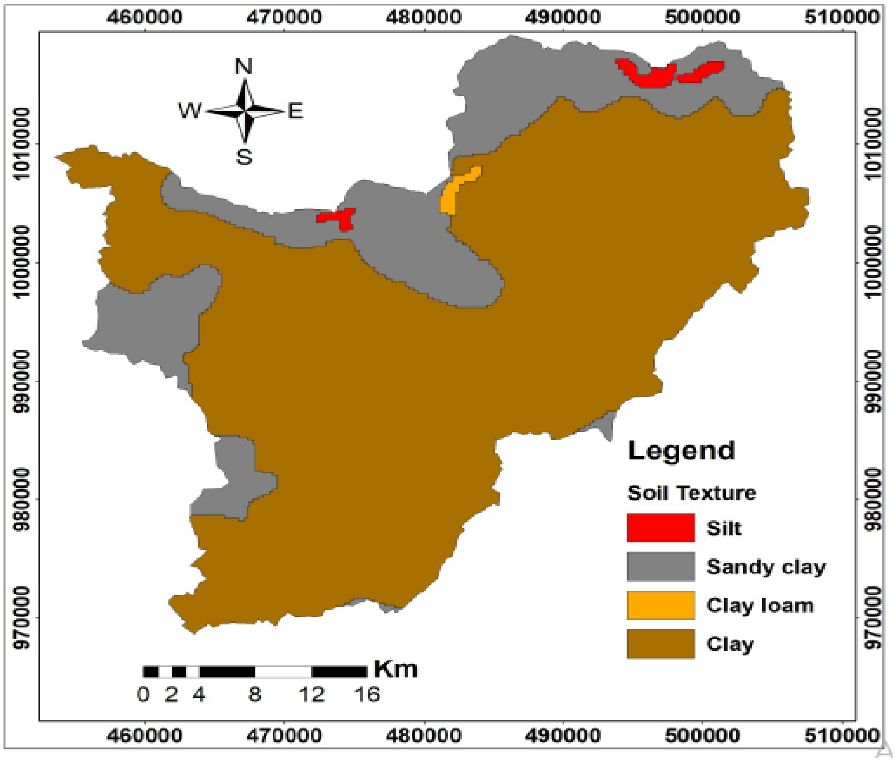


Figure 13 : *Soil texture map of the catchment (Adopted from Worknesh..J, 2021)*

3.1.10 Surface Hydrology of the Area

Since 1981, the Addis Ababa - Debre Zeit Road Bridge has served as a monitoring point for the Akaki River, covering a drainage area of 885 square kilometers (Tesfaye Alema, 2009). Notably, this station does not track the flow data of the smaller Akaki River. Analyzing the records from 1981 to 2005, the average annual discharge at this site is determined to be 9517 liters per second (l/s), translating to 10.75 l/s per square kilometer, with an average annual yield of 339 mm (Tesfaye Alema, 2009). "The majority of the yearly runoff, about 82%, is concentrated in the months of July, August, and September, highlighting the predominance of surface runoff over groundwater contribution during the wet season " (Tesfaye Alema ,2009). "The Akaki River's estimated low flow, excluding wastewater effluent, ranges between 600 and 1000 l/s "(MoWE, 2011).

3.1.11 Demography of the study area

Addis Ababa grew from a settlement of an estimated 15,000 people in 1888 to more than 3.6 million in 2020. According to the Central Statistical Agency, the population is estimated to surpass 5 million in 2036 (see Figure 14). However, the city's growth rate has declined in the last couple of decades – from 6.9% annually over the 1961-62 period to 2% from 2007 to 2013. Along with population growth, the administrative boundary of Addis Ababa expanded from an estimated 32 km^2 in 1929 to 218 km^2 in 1984 and 527 km^2 in 1994. Built-up areas of the city and the larger metropolitan region also expanded.

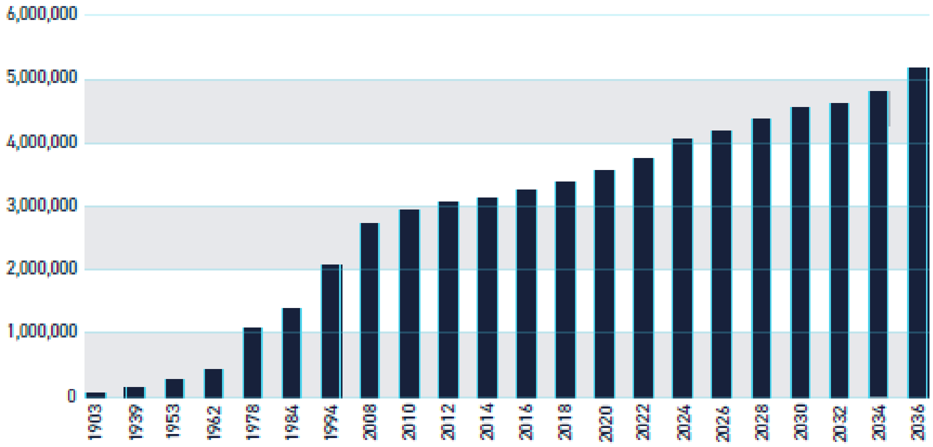


Figure 14: Projected Addis Ababa population (1903-2037)

3.2 Materials and Methods Used

GIS and remote sensing methodologies were utilized to assess the groundwater recharge potential of the Akaki Catchment using the Analytical Hierarchy Process. The research methodology involved several stages: i) identifying and evaluating criteria; ii) collecting data; iii) preprocessing the collected data; iv) preparing the input dataset; v) reclassifying input layers; vi) conducting pairwise comparisons of criteria and assigning weights using the Analytical Hierarchy Process (AHP); vii) performing overlay analysis with weighted sum overlay analysis using ArcGIS tools; and viii) ranking the final values obtained from the analysis..

Software such as GIS (ArcGIS 10.4.1), PC Geomatica, Published and Unpublished literatures, Google Earth Pro, Ms excel, and Maps: Such as Geological map, etc. were used.

3.3 Description of Data Used and Source

Various forms of primary and secondary data related to hydrology, topography, geology, and existing conventional maps were identified and utilized as parameter factors in the process of delineating the groundwater recharge zone map within the study area. Chirps V2.0 was selected for this study (to supplement the rainfall data) since it provides high spatial resolution rainfall estimates (at a spatial resolution of approximately 0.05 degrees or about 5 km), which is higher than many other satellite-based rainfall datasets and covers the entire globe. Chirps V 2.0 also has long-term consistency & near real-time availability i.e. it has long-term temporal coverage starting from 1981 to near real-time and is updated regularly. According to studies, compared with other satellite-based rainfall datasets, such as TRMM (Tropical Rainfall Measuring Mission) and the

Global Precipitation Measurement (GPM), CHIRPS is found to be competitive in terms of accuracy and spatial resolution, with advantages in certain regions i.e. studies have shown that CHIRPS performs well in regions like East Africa, where gauge networks are sparse and hence selected for the current study.

while other DEM sources like JAXA's Global ALOS 3D World (in 12.5-meter resolution), ASTER and LiDAR may offer higher resolution in certain cases or better performance in specific environments, the SRTM 30-meter Digital Elevation Model (DEM) is preferred for this research due to its global coverage, and open access nature (free of charge). Despite unavailability of finer resolutions (less than 30 meter) on the USGS Earth explorer data source, the 30-meter resolution SRTM DEM was adequate for achieving the specific objectives of the study since it captures the essential topographic characteristics necessary for the overlay analysis by providing sufficient detail at the watershed scale for delineating boundaries and deriving relevant topographic variables. Plus, since all layers were resampled to match the soil texture layer (which is 250m resolution) using the 30m resolution DEM was satisfactory.

Table 5: Data type used for the study and source

Data Type	Source of Data	Purpose of Data
Meteorological Data	Ethiopian National Meteorological Agency (ENMA)	To create rainfall map and other weather data
CHIRPS v.20	https://www.chc.ucsb.edu/data/chirps	To widen the areal coverage of rainfall data and supplement the rainfall data.
Shuttle and Radar Topographic Mission (SRTM) 30x30m Digital Elevation Model (DEM)	https://earthexplorer.usgs.gov	To Delineate watershed boundary of the catchment, to create Drainage Density, slope map, Topographic Position Index(TPI) and Topographic Wetness Index (TWI)
ISRIC Soil Data Hub (250mx250m)	https://www.isric.org/	To prepare Soil Texture Map
Satellite data/ FAO's WaPOR 2.1 open database.	https://wapor.apps.fao.org/	To Prepare Land Use Land cover Map
Satellite Data/ Landsat 8-9 OLI/TIRS C2 L1	https://earthexplorer.usgs.gov	To Prepare Lineament Density Map
Conventional Geological data	Geological Survey of Ethiopia	To Create Lithological Map

Existing bore wells data in Akaki catchment	Addis Ababa Water and Sewerage Authority (AAWSA)	for validation of the groundwater recharge zone potential of the study area
online INOWAS (**Innovative Groundwater Solutions)** platform	https://www.inowas.com	For Recommendation of the suitable Artificial Recharge methods

Table 6: Software used and purpose

No	Type of Software	Purpose
1	ArcGIS 10.4.1	To develop thematic map of parameters that affect groundwater recharge zone using weighted overlay analysis
2	PC Geomatica 17	For lineament features digitization/generation and mapping using Landsat 8-9 OLI/TIRS C2 L1.
3	Google Earth Pro	Ground truth For Land Use Land Cover Classification
4	Ms-Excel	For Linear and Multiple Regression to fill rainfall data gaps, for AHP analysis and borehole water inventory data points conversion to CSV

3.4 Method of Thematic Map Preparation

In the study area, the groundwater recharge potential zone was identified by considering nine key factors: rainfall, land use land cover, soil texture, lithology, lineament density, slope, topographic position index (TPI), drainage density and topographic wetness index (TWI). These factors were frequently used in previous multi-criteria analysis (MCA) studies, as referenced in Table 1. The research activities encompassed several key steps such as data collection and analysis, preparation of thematic maps from remote sensing and conventional sources. The thematic maps were also resampled to common resolution and reclassified. Following pairwise comparisons using the Analytical Hierarchy Process (AHP) was performed, and ultimately the groundwater recharge potential zone was developed by conducting weighted overlay analysis with ArcGIS tools. The thematic maps, representing various characteristics of the selected parameters for groundwater recharge, were used as input layers for delineating these zones. The detailed procedures for preparing the thematic layers for the nine selected factors are described below.

Thematic Map Preparation

Rainfall map: Long term precipitation data taken from the ENMA was used to prepare the rainfall map of the study area using Inverse Distance Weighting Method of Interpolation. First Annual Rainfall of each stations (starting from 1991-2021) was taken (before analysis missing rainfall data was filled using Regression) and the **31** years Annual rainfall data was averaged. Similarly CHIRPS rainfall data was also used to widen the coverage and supplement the rainfall data.

Accordingly, for the Inverse Distance Weighting (**IDW**) Interpolation, first the excel file containing the Latitude, Longitude and Annual Rainfall (Mean) of the meteorological stations and the CHIRPS data were imported to the GIS. Next using the display X, Y data tool, the X and Y data are displayed assigning the Z fields to the Annual Rainfall on the Excel. Accordingly, all meteorological stations and CHIRPS data points are displayed and this data is exported to the map as a layer. Finally using the IDW tool in the interpolation of spatial analyst, the input point features were used assigning the mean annual rainfall to their Z value field The rainfall map of the study area, depicted in Figure 15, was created using the mean annual rainfall (mm) recorded in the region.

Table 7: Mean annual rainfall data from 5 meteorological stations and CHIRPS data points

Mean Annual Rainfall Data From 5 Meteorological Stations				
Gauge station Name	Elevation (m)	Lat. (N)	Long. (E)	Mean annual RF (mm)
Addis Ababa bole	2354	992766.61	477874.22	1064.2
Addis Ababa Observatory	2386	996952.4	472248.08	1217.9
Akaki	2057	980707.55	476690.05	961.7
Intoto	2903	1004113.64	469780.52	1305.9
Sendafa	2558	1011675.48	502362.15	1252.4
Mean Annual Rainfall Data From CHIRPS based on selected X and Y Coordinates				
A	-	998961.12	461676.67	1124.4
B	-	985911.38	465885.98	1060.1
C	-	976910.73	467395.96	1012.0
D	-	1012134.62	486585.3	1091.7
E	-	1004194.89	493066.04	1026.0
F	-	1000294.16	485669.15	1111.3
G	-	993095.17	491712.12	1023.8
Average areal annual rainfall				**1104.3**

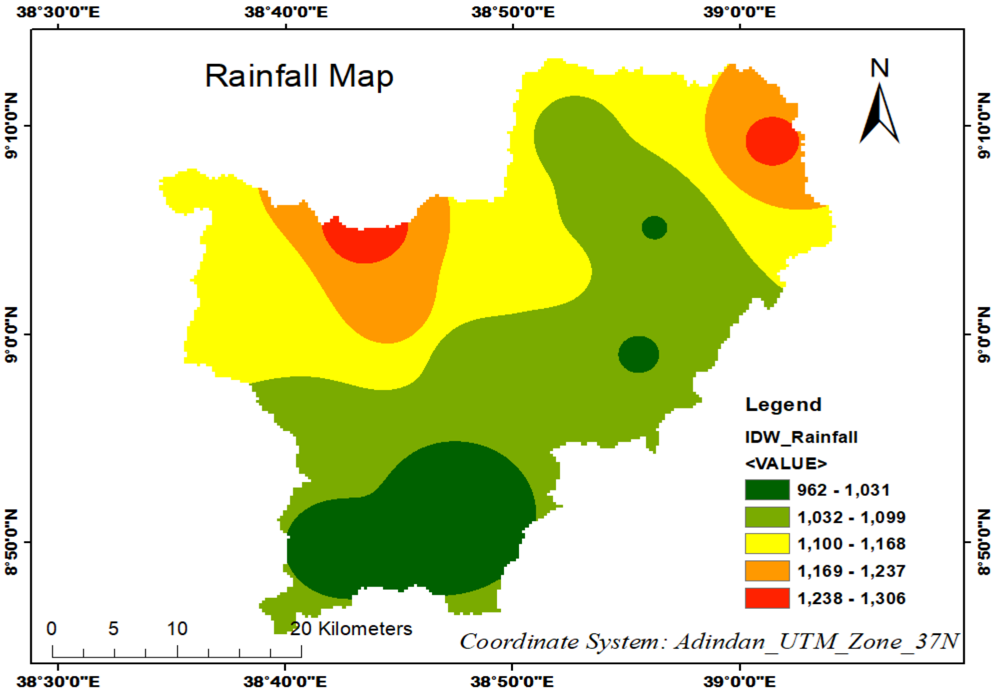


Figure 15: *IDW Rainfall map of Akaki Catchment*

Drainage Density: the drainage density map is generated from the shuttle and radar topographic mission (SRTM) 30m digital elevation model (DEM) using ESRI's hydrology tool in spatial analyst tool. The drainage map was initially generated from the digital elevation model (DEM) of the watershed boundary in the study area using the Hydrology tool in ArcGIS for spatial analysis. First the Clipped DEM for the watershed boundary was filled, then Flow Direction and Flow Accumulation was generated consecutively. The flow accumulation was adjusted by conditional tool in spatial analyst tools and by setting set cell values > 500 for the stream definition threshold in query builder. Following the adjustment the stream order and stream to feature of study area was generated as per Figure 16. Finally, the drainage density of the study area was determined using the drainage line density tool in ArcGIS 10.4.1. The densities were then categorized into five classes using the natural break method.

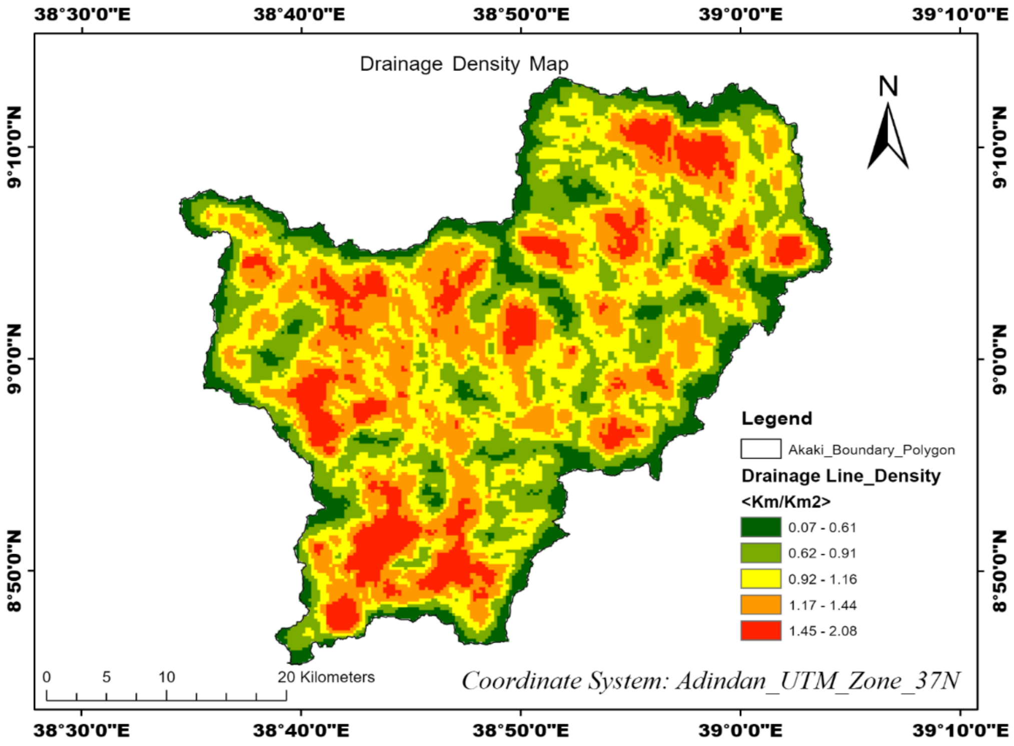


Figure 16: Drainage density map of Akaki Catchment

Land Use Land Cover (LULC)*:* LULC map of the study area was generated using FAO's WaPOR 2.1 open database. WaPOR (Water Productivity Open-access Portal) is a web-based platform developed by the Food and Agriculture Organization of the United Nations (FAO) and uses satellite remote sensing data and ground-based measurements. Accordingly, continental data was downloaded for Ethiopia in 100m spatial resolution for the year 2022 G.C. Then the spatial resolution was resampled to 250 m resolution and projected to Adindan UTM Zone 37 since the Spatial Reference System (SRS) of the data was in WGS84 - Geographic Coordinate System (lat/long) . The classification applied is based on the Land Cover Classification System (LCCS) that was developed by FAO. After the Downloaded data is imported to Arcgis it was extracted by extract by mask tool in spatial analyst of arc map to extract the LULC classes for the study area. After extraction the result was aggregated to 7 major classes by the reclassify tool in arcgis as per table 8: Accordingly, the LULC Map is prepared based on the Aggregated Classes and the 7 major LULC classes in the study area are Grass Land, Crop Land/Cultivated Land, Urban/Built-up, Bare / sparse vegetation, Water bodies, Shrub or herbaceous cover, flooded and Forest as per the below figure 17 LULC map.

Table 8: Land Cover Classification System (LCCS) developed by FAO and New Aggregated Classes.

No	Class	Caption	**Reclassification**	**New Class**
1	20	Shrub land	**Grass Land**	**30**
2	**30**	Grassland		
3	**41**	Cropland, rainfed	**Crop Land/Cultivated Land**	**41**
3	42	Cropland, irrigated or under water management		
5	43	Cropland, fallow		
6	**50**	Built-up	**Urban/Built-up**	**50**
7	**60**	Bare / sparse vegetation	**Bare / sparse vegetation**	**60**
8	**80**	Water bodies	**Water bodies**	**80**
9	**90**	Shrub or herbaceous cover, flooded	**Shrub or herbaceous cover, flooded**	**90**
10	112	Tree cover: closed, evergreen broadleaved	**Forest**	**126**
11	114	Tree cover: closed, deciduous broadleaved		
12	116	Tree cover: closed, unknown type		
13	124	Tree cover: open, deciduous broadleaved		
14	**126**	Tree cover: open, unknown type		

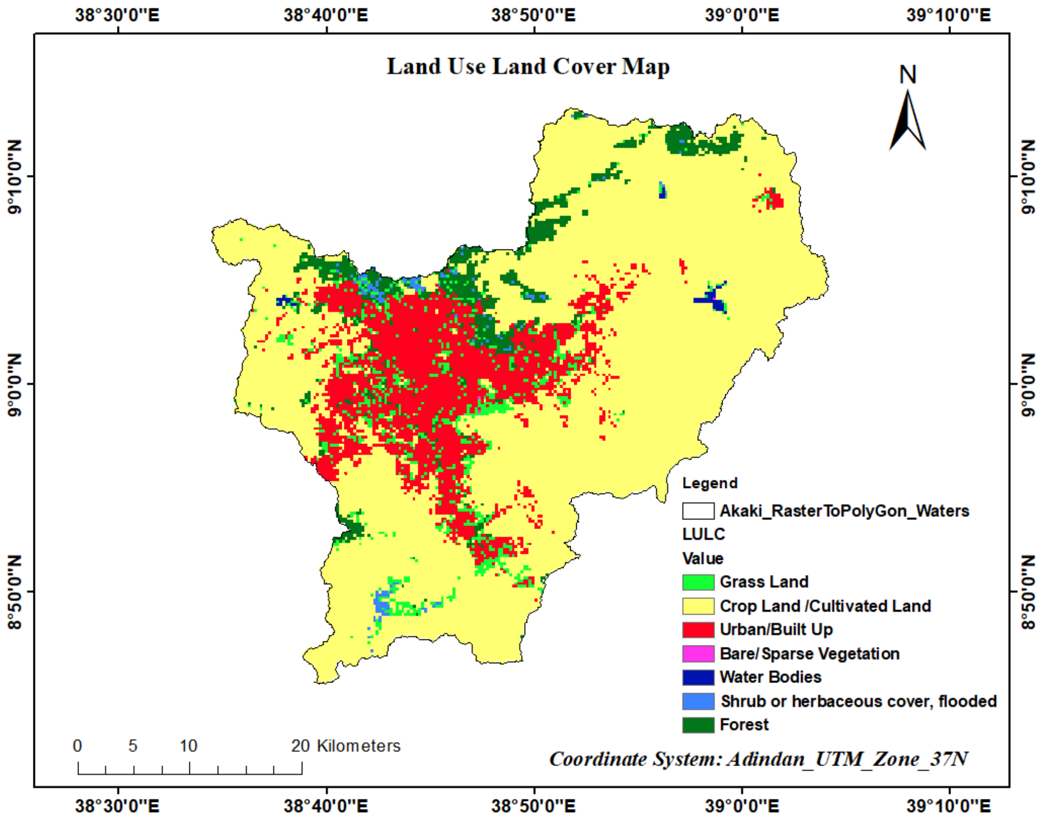


Figure 17: LULC map of the study area

Lineament Density Map: Lineaments for Akaki catchment were extracted automatically from a cloud free Landsat 8-9 OLI/TIRS C2 L1 Band 8 (band 8 is used due to its better clarity and resolution of spatial features) using the ProPCI Geomatica 2013 software. PCI Geomatica is a remote sensing and image processing software developed by PCI Geomatica and is used for processing, analyzing, and visualizing satellite and aerial imagery for various applications including GIS. The primary benefits of the automatic lineament extraction method compared to the manual extraction method (which is done by digitizing the DEM of the study area in arcgis environment) are its ability to uniform approach to different images; processing operations are performed in a short time and its ability to extract lineaments which are not recognized by the human eyes (Mustafa, 2014).

The steps followed for the extraction of lineaments on PCI Geomatcia and Generation of Lineament density for the Akaki Catchment is listed as follows:

1. The raster Landsat Band 8 Layer was imported to PCI Geomatica and the Landsat image was enhanced using the Enhance tool.
2. Next in the tools option clipping/sub setting is used to clip the area around the study area i.e Akaki catchment by clipping and saving the imported Band 8 Landsat Image.
3. The lineaments are then extracted using the tool option > Algorithm Librarian > Line: Lineament Extraction and using the clipped and enhanced Landsat Band 8 image as an input. Various input parameter adjustment were used to control the Edge Granite Threshold (50), Curve Length, Angular Difference and density of the Lineaments.
4. Next the extracted lineament was saved as Arcview shape file to be exported to the Arcgis Environment.
5. Following that the Extracted Lineaments shape file are imported to the Arcgis
6. Next the Compound Lines composed of different line segments were split using the split line at vertices of tool of Arcmap.
7. The lineament density thematic map of the Akaki Catchment was ultimately produced using the Line Density tool within ArcGIS spatial analysis. To do this. First the extracted lineaments shape file was imported to the GIS and Split .following that the split lineament shape file was clipped to the study area and re-projected. Finally the clipped and re-projected lineament map (Figure 18) was used as an input polyline feature for the lineament density generation Figure 19.

Table 9: Source/data of Landsat image input for Lineament Density map

No.	Type of Data	Path and Row	Date of Acquisition	Sensor Type	Spatial Resolution (m)	Bands	Source
1	Landsat 8-9 OLI/TIRS C2 L1	168/054	2021/12/07	OLI/TIRS	30 (M)	Band 1-Band 11	USGS

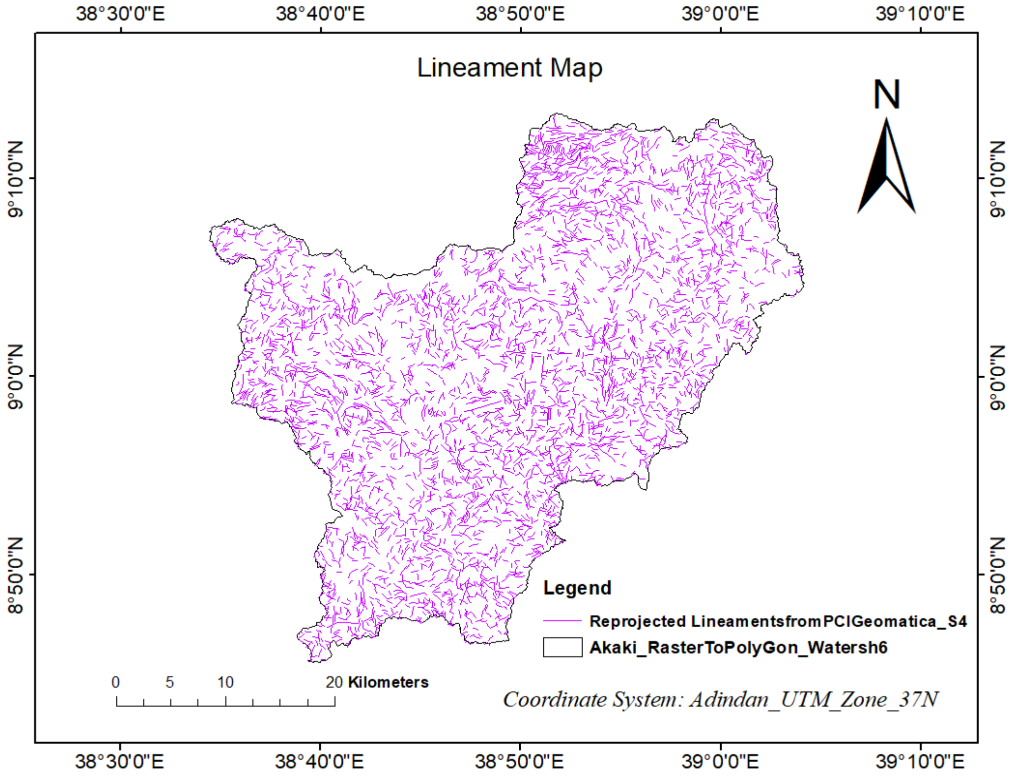


Figure 18: Lineament Extracted from Landsat 8 Band 8 using PCI Geomatcia

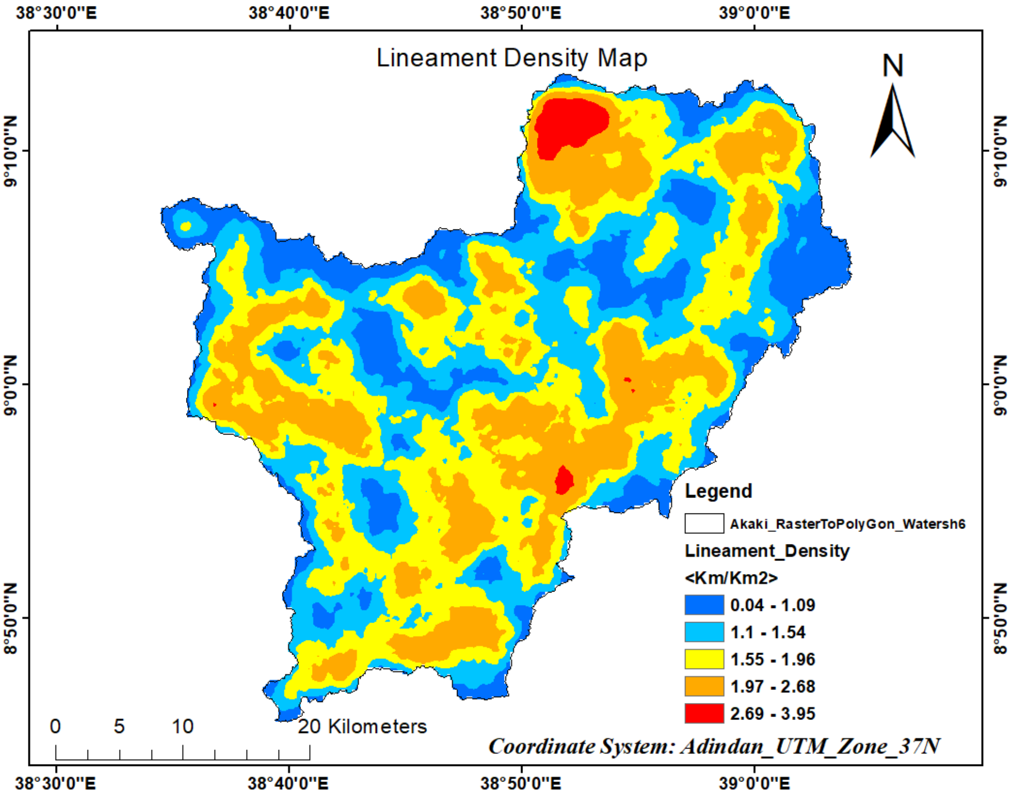


Figure 19: Lineament density map for Akaki Catchment

Slope Map: The slope map for the Akaki Catchment, shown in Figure 20, was derived from the 30-meter resolution digital elevation model (DEM) provided by the Shuttle Radar Topography Mission (SRTM). This data was obtained from the freely accessible open-source products of the United States Geological Survey (USGS). First, the necessary spatial dataset was projected to the Adindan UTM Zone 37 coordinate system. Next, the slope map was generated using the spatial analysis tools available in the GIS environment. The resulting slope map, measured in degrees, was then resampled to a 250-meter resolution. Finally, it was reclassified and ranked into five distinct classes for further analysis.

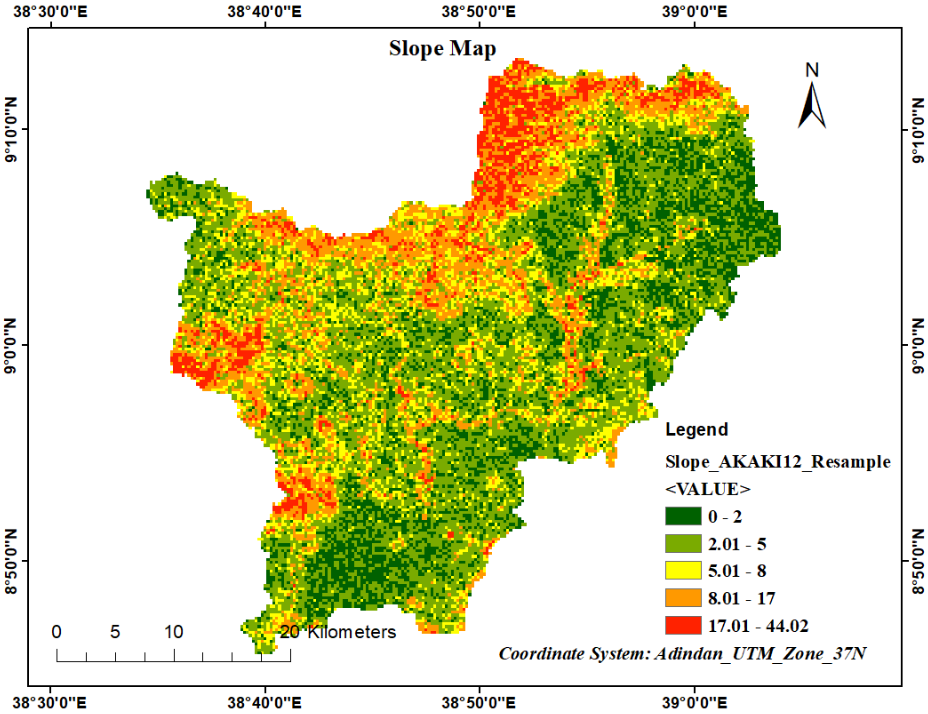


Figure 20: Akaki Catchment Slope Map

Soil Texture Map: Soil Texture map for the akaki catchment is acquired from **ISRIC** soil data hub. ISRIC Soil Data Hub is a web-based platform that provides access to global soil data and information. It offers a wide range of soil-related data, including soil properties, maps, and profiles, as well as information on soil use and management. It is maintained by the International Soil Reference and Information Centre (ISRIC), an independent non-profit organization that specializes in soil research and information management. The soil texture data which is based on United States Department of Agriculture (USDA) soil texture classification system and was downloaded with 250 m resolution for the top 15-30CM .To prepare the soil texture map first the 250meter resolution soil texture data was downloaded from the ISRIC data hub/website. After projection of the raster data it is then extracted using the extract by mask tool in the spatial analysis for the study area and reclassified according to the soil texture class identified using the USDA Classification system code. According to the ISRIC data, the study area has three major soil texture types for the top 15-30 cm (Figure 21): Clay, Clay Loam, and Silty Clay Loam. As depicted in Figure 21, the majority of the study area consists of clay soil texture, encompassing 88% of the total study area. Clay soils are often characterized by slow infiltration rates, which can result in surface runoff and waterlogging during wet conditions. Clay loam soil, comprising a mixture of clay, silt, and sand particles with a moderate clay content, typically exhibits improved infiltration capacity compared to pure clay soil due to the presence of sand and silt particles, which create larger soil pores. However, infiltration rates in clay loam soil can still vary from moderate to slow, influenced by factors such as soil structure, compaction, and organic matter content.

On the other hand, silty clay loam soil contains a higher proportion of silt particles and a lower clay content compared to clay loam soil. The presence of silt particles in silty clay loam soil enhances its infiltration capacity by improving soil structure and increasing pore spaces. Generally, silty clay loam soil demonstrates better infiltration rates than clay and clay loam soils but may still exhibit slower infiltration compared to soils with higher sand content.

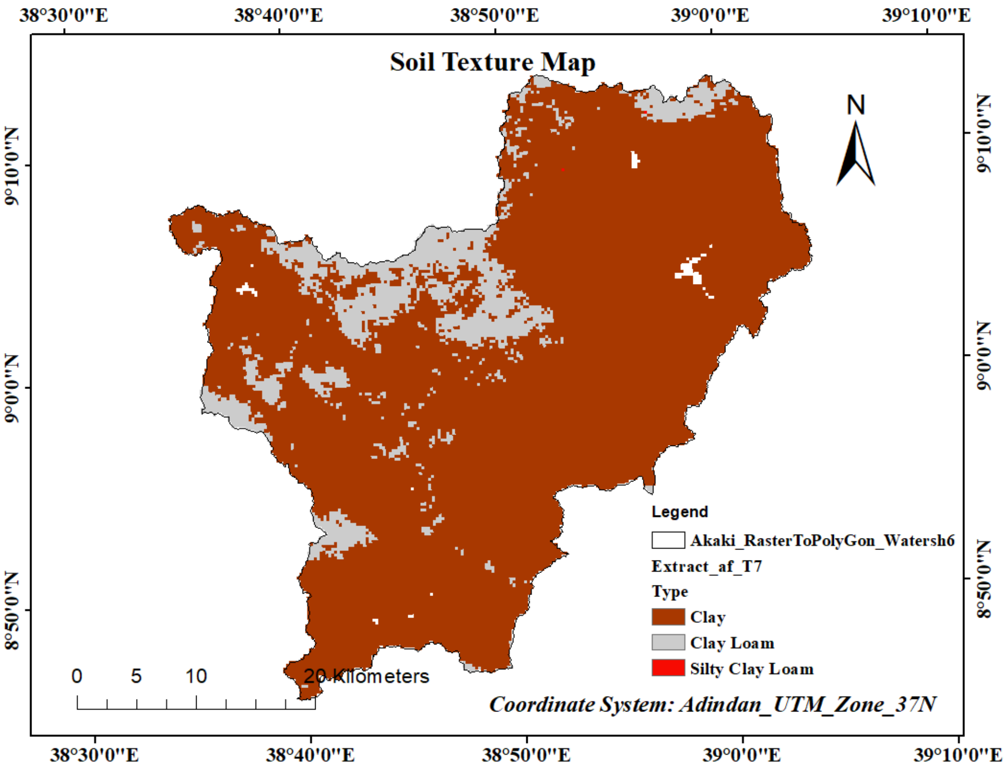


Figure 21: Soil Map of Akaki Catchment

Geological Map: Lithology map of the Akaki Catchment was prepared from three map sheets obtained from Geological Survey of Ethiopia, GSE (Geological map of Addis Ababa: NC37-10, Geological Map of Akaki Beseka: NC37-14 and Geological Map of Debre birhane NC37-11). The scanned maps were first Geo referenced using the Coordinates on the maps as control points and rectified. Following that the three maps were mosaicked (by first converting to a graphics and extracting the desired areas) using Mosaic to new raster in data management tools. Lithology of the study area was then extracted for the catchment using the extract by mask tool in spatial analyst tools. Next the Lithology of the study area is digitized manually to a polygon format and areas having similar lithological codes were dissolved. Once the polygon format is completed it was converted to raster using conversion tool of feature to raster.

The raster lithology map underwent reclassification through the "Reclass" command within the spatial analysis tools available in ArcGIS. Detailed descriptions of the characteristics of each lithological unit identified in the study area are provided in Appendix Table 11.Accordingly, within the lithological units identified in the study area, pyroclastic rocks (welded pyroclastic flows, welded tuff, ash, ignimbrites with interlayers of ryholitic flow, basalts, tuffaceous sediment) and Alluvium cover large portion of the study area (25.48% and 15.20% respectively). The pyroclastic rocks particularly dominate the North eastern and central parts of the study area while the Alluvium dominates the southern parts of the catchment.

Table 10: Lithology of Study Area

Sn.No	Description of Lithology	Lithological Code	Area in Km^2	Areal _Percentage (%)
1	Addis Ababa Basalts	Eaa	61.63	4.22
2	Lakes	Lake	17.81	1.22
3	Welded to Partially Welded Pyroclastic Flows	Npp	49.19	3.37
4	Welded Pyroclastic Flows	Nwp	36.75	2.52
5	Wechecha Trachytes	Nwt	17.50	1.20
6	Wechecha Trachytes	Nwt(a)	54.50	3.73
7	Quaternary Basalt: olivine phyric and vesicular basalt	Qb	82.44	5.65

8	Eluvial: Silt to Clay sized, light/dark gray to reddish brown and fertile	Qel	8.81	0.60
9	Quaternary Superficial Sediments; Mostly of eluvial soil	Qs	3.25	0.22
10	Pyroclastics and pumice fall deposits	Qtp	22.06	1.51
11	Scoria Fallouts	Qts	24.00	1.64
12	Alluvium	Qus	221.88	15.20
13	Cheleka basalt:aphanitic and porphyritic basalts with minor pyroclastics (Tcb)	Tcb+Ttb	182.00	12.47
	Tarmaber megezeze basalt:plagioclase phyric basalt and olivine-plagioclase phyric basalt with minor olivine phyric, pyroxene phyric, plagioclase-pyroxene-olivine phyric basalt and aphanetic basalt(Ttb)			
14	Trachytes: porphyritic trachytic lava flow	Tetr	20.13	1.38
15	Entoto Volcanics: trachyte lava flow with pyroclastic rocks interlayer with sediments	Tev	105.94	7.26
16	Pyroclastic rocks: welded tuff, ash, ignimbrite with interlayers of rhyolitic flow(Tpx)	Tpx+Nwp+Tdig	371.81	25.48
	Welded Pyroclastic Flows(Nwp)			
	Sela Dingay-Debre birhan-Goro ignimbrite:ignimbrite,tuff,rhyolite,basalt,tuff aceous sediment, ash and agglomerate (Tdig)			
17	Lower Basalts: phyric (olivine-plagioclase and pyroxene-plagioclase) basalts. they are fractured and jointed	Tv1	34.81	2.39
18	Middle Basalts: phyric (olivine-plagioclase, plagioclase-olivine and olivine phyric) basalts and minor aphanitic basalts	Tv2	4.50	0.31
19	Upper Basalt: grayish, black, light to dark gray, aphanitic to porphyritic	Tv3	41.63	2.85
20	Wechecha Trachytes: trachytic lava flows and domes (Twtr)	Twtr+Nwt(a)	98.69	6.76
	Wechecha Trachytes (Nwt(a))			

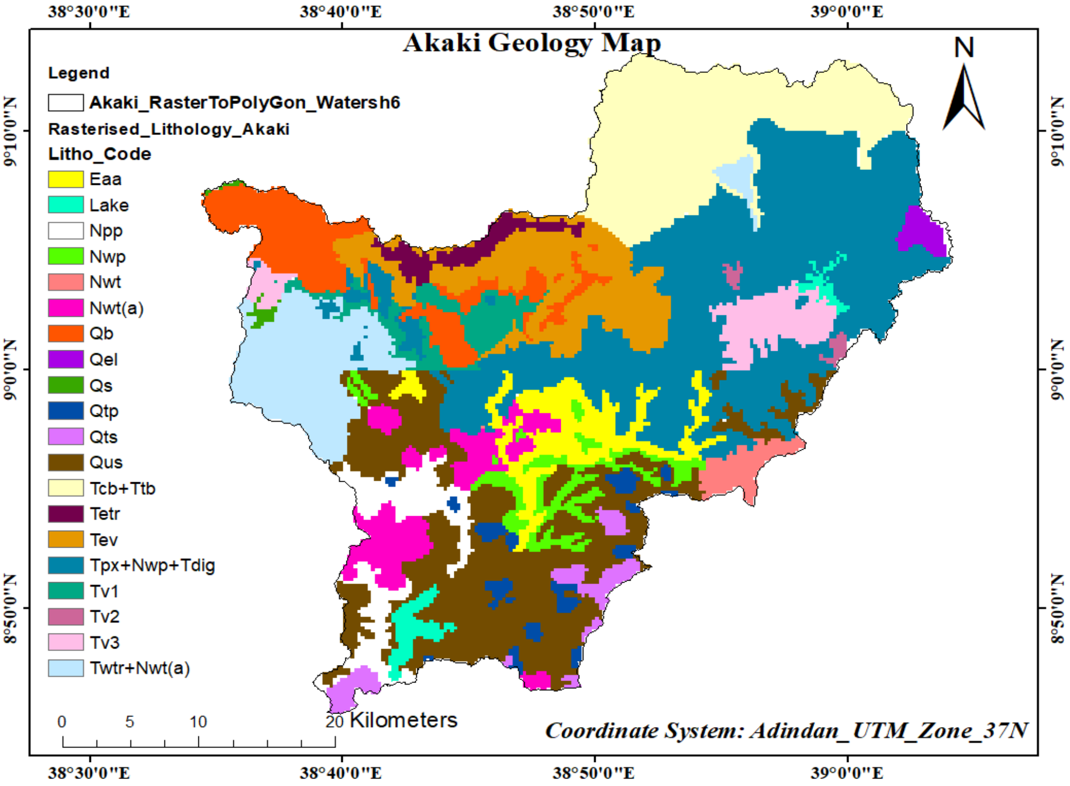


Figure 22: Digitized Lithological map of Akaki Catchment

Topographic Position Index (TPI): TPI is a widely utilized algorithm for quantifying topographic positions and classifying land surfaces (De Reu et al., 2013). TPI plays a substantial role in determining water retention time within a watershed, thereby influencing the connectivity of water sources. (Singh et al. 2009). It calculates the difference in elevation between the central cell and the average elevation of neighboring cells within a specified radius (Wilson &Gallant, 2000). Consequently, TPI reflects the height difference of the central pixel compared to its surrounding cells, with values being either negative or positive. A positive TPI indicates that the central point is higher than the average surroundings (Weiss, 2001), suggesting proximity to a ridge or hill, while a negative value suggests proximity to a valley bottom. A zero value may indicate either a mid-slope area or flat terrain (Tagil &Jenness, 2008). For this study, the TPI map was generated from the 30m SRTM DEM using Focal Statistics and Minus Tools (to subtract the focal mean from the DEM) in ArcGIS Spatial Analyst Tool. The generated TPI map was classified into five classes, ranging from -94.21 to 114.91, with a particular emphasis on assigning high recharge suitability weight to high negative TPI values.

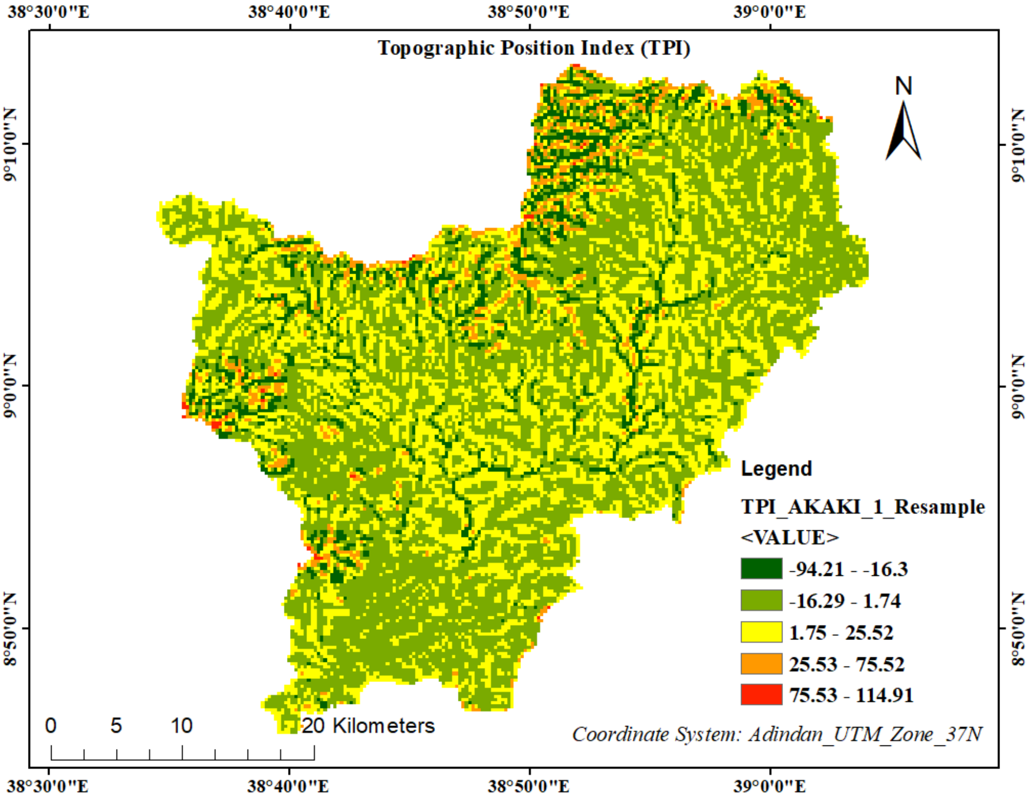


Figure 23: (TPI) Topographic Position Index ***of*** *Akaki Catchment*

Topographic Wetness Index (TWI): Topography plays an important role in the distribution and flux of water and energy within the natural landscape. TWI assesses the degree to which the topography supports the recharge process through precipitation and correlates directly with groundwater potential (Bisrat et al., 2020). The topographic wetness index (TWI) gauges the disparities in soil moisture driven by terrain, lateral transmissivity in the subsurface, and integrates the upslope catchment area of the aquifer system with the downslope drainage for each cell in a digital elevation model (DEM) (Bisrat et al., 2020).By taking into account both local slope geometry and site location in the landscape, combining data on gradient and specific drainage area, TWI provides a description of the spatial distribution of the soil moisture and can be used to identify areas that relatively much contribute runoff to a watershed outlet. Generally TWI uses the topographic elements of a landscape to determine where water may flow or accumulate. The index which is a function of both slope and upstream contributing area per unit width orthogonal to flow direction is computed as:

$$\text{TWI}=\ln\left(\frac{As}{tanB}\right) \ldots\ldots\ldots\ldots\ldots\ldots\ldots\ldots\ldots\ldots\ldots\ldots\ldots\ldots\ldots\ldots\ldots\ldots\ldots\ldots \text{(5)}$$

Where **As** is the local upslope area draining through a certain point per unit contour length and tan B is the local slope in radians. The TWI has been used to study spatial scale effects on hydrological processes and is unit less. Landscapes with larger upslope drainage areas and shallower slopes will produce larger TWI values, indicating higher propensity for runoff. The TWI for the Akaki catchment was developed using the projected 30m SRTM DEM as follows : Fill DEM>Flow Direction >Flow Accumulation>Slope in Degree> Slope in Radian calculated in raster calculator as (Slope in degree*1.570796)/90> then in raster calculator the Tan Slope is calculated as Tan Slope= con(slope>0, tan(slope), 0.001)> scale the flow accumulation in raster calculator as (flow accumulation +1)*cell size >finally the Topographic Wetness Index is calculated in raster calculator as **TWI**=Ln(scaled Flow Accumulation/Tan Slope).at last the TWI was resampled to 250m resolution for weighted overlay analysis. In the Akaki Catchment, the TWI varies from 3.88 – 21.16 and most of the area exhibits TWI values ranging from 6.47 to 7.88, with the mountainous regions displaying lower TWI values.

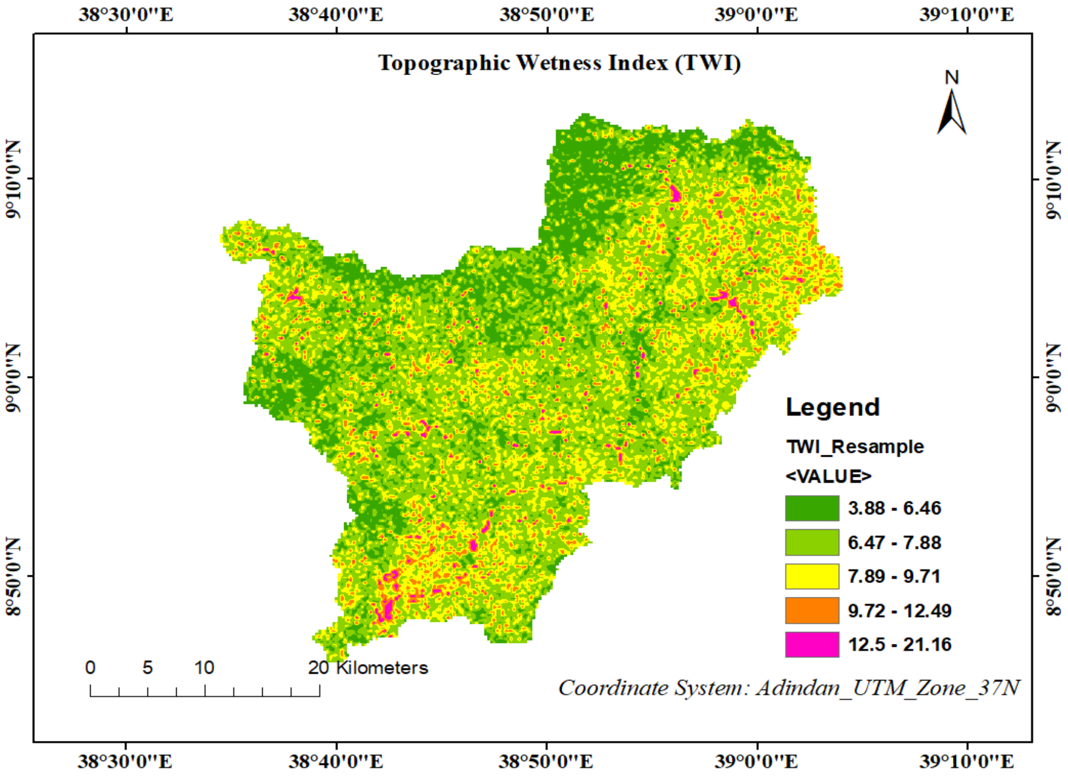


*Figure 24**:** Topographic Wetness Index (TWI)* ***of*** *Akaki Catchment*

3.5. Method of Data Analysis

3.5.1 Factors Selection

In this study, factors impacting groundwater recharge were chosen by referencing previous studies and conducting a literature review across various research sources. Criteria were established to refine the selection of these factors. Accordingly number of times the factor is used, data accessibility and significance of the factor has been used as a base for selection of the factors among the reviewed literatures done on GIS and RS based Groundwater Potential and Recharge Studies.

3.5.2 Analytic Hierarchy Process (AHP)

MCA/MCDA, particularly Analytic Hierarchy Process (AHP), has been widely used in groundwater recharge studies and are relatively straightforward to implement and interpret compared to SCA techniques like ANN or fuzzy logic. **On the other hand,** SCA methods often involve complex algorithms making it challenging to understand how input data translate into output predictions. **Additionally,** SCA methods like ANN& Fuzzy Logic typically require large amounts of training data to effectively learn and generalize patterns. **More importantly,** implementing and training SCA models like ANN can be computationally intensive and require significant computational resources. In contrast, MCA methods are generally less computationally demanding and can be applied using readily available software tools, making them more accessible and practical for many decision-making scenarios and hence chosen for this study.

Among the various Multi-Criteria Analysis (MCA) methods, the Analytic Hierarchy Process (AHP), developed by Saaty in 1980, was employed as a decision-aiding tool to assign weights to different themes and their features utilized in the artificial groundwater recharge zoning process. AHP is a mathematical approach for structuring and analyzing intricate decisions involving multiple attributes. It breaks down complex multi-criteria decision problems into a multi-dimensional hierarchical structure of criteria, objectives, and alternatives, as outlined by Al-Abadi & Al-Shamma'a (2014) and Stojanovic et al. (2015).

The AHP relies on the creation of a pairwise comparison matrix, which is developed for weight assignment of each thematic map utilizing a nine-point (1-9) scale of importance or a 9-point rating scale. After resolving the matrix, weights are assigned to the thematic map, thereby establishing a rank for the factors that determine the groundwater recharge suitability (Solomon T, 2020).

The AHP also includes systematic assessments to ensure the consistency of judgments, giving it an advantage over other methods for multi-attribute valuation (such as MIF). However, in this study, the AHP weights for various thematic layers were determined through thorough reviews of existing literature and consultation with expert (hydro geologist from the Ethiopian Engineering Corporation's Water and Energy Design and Supervision Works Sector (EEC - WEDSWS)).

3.5.2.1 Assigning weights

Following the compilation of the thematic layers, each thematic map was allocated an appropriate score based on its relative significance in groundwater recharge. Simplifying the process into pairwise comparisons, where only two criteria are evaluated at a time, can greatly streamline the weighting process and is likely to yield a more resilient set of criteria weights.

In the present study, the GIS-based AHP method was applied to integrate different thematic layers based on the assigned weights for suitable site selection. The weights for each factor were designated based on Saaty's scale of relative importance values (1–9), as presented in Table 12. In Saaty's scale, the numbers 1-9 indicate the degree to which one factor is considered more important than other factors.

Table 11: Saaty's,1-9 scale (Adopted and Modified from Solomon T,2020)

Relative Importance and Its Value								
Less Importance		←	←	Equal Importance	→	→	More Importance	
Extremely	**Very Strong**	**Strong**	**Moderate**	**Equal**	**Moderate**	**Strong**	**Very Strong**	**Extremely**
1/9	**1/7**	**1/5**	**1/3**	**1**	**3**	**5**	**7**	**9**

Note: intermediate values= 2, 4, 6 and 8 are mid values denoting compromise.

Reciprocal numbers (1/9, 1/7, 1/5, and 1/3) denote values used for inverse comparison.

3.5.2.2. Pairwise Comparison Matrix (PCM). A diagonal matrix is prepared by placing the values in the upper triangle and their reciprocal values used to fill the triangular matrix. Extensive previous literature reviews and weights suggested by expert were used to establish the PCM in this study.

Table 12:Pair-wise comparison Matrix ***(PCM).***

Factors	**F1**	**F2**	**F3**	**…..**	**Fn**
F1	a11	a12	a13		a1n
F2	a21	a22	a23		a2n
F3	a31	a32	a33		a3n
…	…	….	…		…
Fn	an1	an2	an3		ann

Where, aij = relative weight given on scale of 1-9.

Saaty method computes weights vector W = (W1, W2,…,Wn), where W is a column vector as the principal right eigenvector of matrix A, that is,

$AW = \lambda max W$…………………………………………………… (6)

Next the matrix will be normalized, i.e.each number in the column is divided by the sum of each column (Equation 7).

$$A = [a\ ij\ ] = \begin{bmatrix} a_{11'} & a_{12'} & \dots & a_{1n'} \\ a_{21'} & a_{22'} & \dots & a_{2n'} \\ \vdots & \vdots & \ddots & \vdots \\ a_{n1'} & a_{n2'} & \dots & a_{nn'} \end{bmatrix}$$

$\boldsymbol{aij'} = \frac{\boldsymbol{aij}}{\sum_1^N \boldsymbol{aij}}$ *for i,j=1,2…..,n* ……………………………………………………..(7)

Where, ***aij'*** is the value of the normalized matrix and N =total number of factors. Weight of the thematic layers i.e. **Wj** is then computed from the matrix which is normalized i.e. by dividing the sum of each row in the normalized matrix table by the number of factor according to (Equation 8).

$\boldsymbol{Wj} = \frac{\sum_1^n aij'}{n}$ and $\boldsymbol{W} = \begin{bmatrix} w1 \\ w2 \\ \vdots \\ wn \end{bmatrix}$………………………………………………………… (8)

To verify the correctness and consistency of the comparison, a consistency check can be conducted using the equations provided below. The consistency index (CI) can be computed using the following formula (Equation 9) as outlined by Saaty (1987).

$$CI=\frac{\lambda\text{max}-\text{n}}{n-1} \text{ .... (9)}$$

Where CI = consistency index, n = number of factors and λmax = highest eigenvalue of the pairwise comparison matrix

Following Saaty's recommendation (1987), the maximum Eigenvalue (λmax) of the comparison matrix can be determined using the following method:

1. Multiply each value in the column (matrix before normalization) by the criteria weight.
2. Calculate the weighted sum value by summing the values in the rows.
3. Compute the ratio of each weighted sum value to the sum value of the respective criteria weight.
4. Average the ratios of the weighted sum value to the criteria weight.

$$\boldsymbol{\lambda max}=\frac{1}{N}\left(\sum_{i-1}^{N}.\frac{aij.wj}{wj}\right) \text{.. (10)}$$

Finally, the consistency ratio (CR) can be calculated using the following formula (Equation 11)

$$CR=\frac{\mathbf{CI}}{\mathbf{RI}} \text{.. (11)}$$

Where, RI is the random index, which is the consistency index of a randomly generated pair wise comparison matrix. It depends on the number of elements being compared and takes on the following values..

Table 13: Random Index value for N ≤ 10

N	**1**	**2**	**3**	**4**	**5**	**6**	**7**	**8**	**9**	**10**
RI	0.00	0.00	0.88	0.90	1.12	1.24	1.32	1.41	1.45	1.49

(Source: Saaty, 1980)

If the CR is less than 0.1, it indicates that the pairwise comparison matrix has acceptable consistency. However, if the CR exceeds 0.1, it signifies inadequate consistency in the pairwise comparison, and the comparison process must be repeated until the CR value is below 0.1 (Saaty 1987).

.3.6 Data Analysis and Quality test

Ethiopian National Metrological Agency was the major source of weather data in this study. Meteorological stations were situated both within and outside the catchment boundary. Based on the following three conditions i.e. (i) availability of long-term data, (ii) percentage of missing data, and (iii) their representativeness to the basin the met stations A.A observatory, A.A bole, Entoto, Akaki and Sendafa were selected for this study. Daily rainfall data of 31 years (i.e. 1990-2021) were collected from these 5 meteorological stations and daily maximum and minimum temperature, relative humidity, wind speed and sunshine hours were collected spanning 20 to 30 years, depending on data availability. For the rainfall data if the percent of missed data is less than 20% or in other word if the recorded data for total length of record is 80% full the station was used in the study.

other met stations (such as ILCA) were not used for rainfall analysis since there were substantial missing data . The rainfall and temperature data had a daily temporal resolution and were summed and averaged to obtain the yearly mean annual values. Checking consistency, data quality and filling of the missing data were also required for the rainfall data.

Table 14: Percentage of Missed Rainfall Data

S/N	Station	Lat. (N)	Long. (E)	Elevation (m)	Record Length Taken	% of Missed Data
1	Addis Ababa bole	8.981081	38.79871	2354	(1990-2021)	**2.75%**
2	Addis Ababa Observatory	9.01891	38.7475	2386	(1990-2021)	**0.72%**
3	Akaki	8.872	38.788	2057	(1990-2021)	**0.47%**
4	Intoto	9.083667	38.725	2903	(1990-2021)	**0.53%**
5	Sendafa	9.152167	39.0215	2558	(1990-2021)	**19.22%**

3.6.1 Estimation and Missing Rainfall Data Filling

When undertaking an analysis of precipitation data from gauges where daily observations are made, it is often to find days where no observations are recorded at one or more gauges. The nearby stations within the basin were used to fill in the missing data, based on the assumption of hydro-meteorological similarity among the group of stations. Several approaches are used to estimate the missing values. Station Average, Normal Ratio, Inverse Distance Weighting, and Regression methods are commonly used to fill the missing records.

Linear Regression (LR)

Linear regression is a statistical method used to estimate missing weather data at any gauge station with similar climatological conditions. The LR method in statistics is a technique to find a relationship between a dependent variable Y and one independent variable X. The LR method is a regression analysis and is commonly used in practical applications.

$$\mathbf{Yi=a+(b.Xi)} \ldots\ldots\ldots\ldots\ldots\ldots\ldots\ldots \text{(12)}$$

where Yi is the estimated rainfall data, and Xi is the observed rainfall value of the neighboring station; a is the intercept, and b is the regression coefficient.

Multiple Linear Regression (MLR)

In the MLR method, the missing rainfall data are estimated by computing the regression coefficient between the target station and the most highly correlated nearby stations

$$\boldsymbol{Yi = bo + \sum_{i=1}^{n} biXi} \ldots\ldots\ldots\ldots \text{(13)}$$

Where Yi is the estimated rainfall data, Xi is the observed rainfall value of the i^{th} surrounding station, bi are the regression coefficients of the i^{th} surrounding stations, and n is the number of nearest stations included in the calculation method.

In this research because of the gaps in the annual rainfall to estimate the normal rainfall, which is a necessary condition for the normal ratio and Arithmetic Mean methods, the regression methods i.e. Linear and Multiple Regression methods were used to fill in the gaps. The procedure is detailed as follows:

1. Daily data was arranged in chronological order using excel V-look up.
2. After estimation of the percentage of missing data from each of the 5 stations, the stations were arranged in ascending order based on the missing percentage.
3. The gaps at the station with the lowest missing data i.e. Akaki station with 0.47% missing for the years (1990-2021) were filled by averaging the data for the specific date on the same station.

4. Next the gaps at Intoto station were filled using linear regression on excel and by using the corresponding complete daily rainfall data at akaki station as the independent variable X.eg.(y = 2.7128x + 0.0733).
5. For the remaining stations multiple regression was used to estimate the missing records using the daily records at the already filled stations as independent variables X1, X2… etc. and as per the ascending order of their missing percentage using excel data analysis add-in.

Table 15: *Data Filling Methods used for each station*

Rank.	Stations	Percent of missing data	**Filling Method**
1	Akaki	0.47%	**Station Wise Average**
2	Intoto	0.53%	**Linear Regression**
3	Addis Ababa Observatory	0.72%	**Multiple Regression**
4	Addis Ababa Bole	2.75%	**Multiple Regression**
5	Sendafa	19.22%	**Multiple Regression**

3.6.2 Checking Consistency of Rainfall Records

After all of the missing data were filled, the consistency of the rainfall records were checked. A record is considered consistent if its characteristics have remained unchanged over time. The Double-Mass Curve (DMC) analysis is a graphical technique used to detect or rectify inconsistencies in a station's record by comparing its temporal patterns with those of neighboring stations. This method relies on the principle that plotting the cumulative sum of one variable (dependent variable) against the cumulative sum of another variable (independent variable) over the same period will result in a straight line, indicating the proportionality of the data. In this method, the accumulated annual rainfall of a particular station is compared with the concurrent accumulated values of mean rainfall of groups. The line's gradient signifies the constant proportionality between the variables. Alterations in this proportionality between the measurements at the station under scrutiny and those in the vicinity are evidenced by changes in slope. In this study, annual precipitation data for each year were initially tabulated and then cumulated chronologically. Subsequently, the cumulative precipitation for each station was plotted against the cumulative precipitation of the group of stations. If a significant change in the regime of the curve is observed, it should be corrected by using Equation 14.

$$Pc = Px * \frac{Mc}{Ma} \qquad (14)$$

Where: **Pc**= corrected precipitation at any time period T1 at station x

Px= original recorded precipitation at time period T1 at station x

Mc= Corrected slope of the double mass curve

Ma= Original slope of the double mass curve

According to the double mass curve analysis, all five stations were found to be consistent and needed no correction of data. Figure 25 shows a double mass curve of each stations.

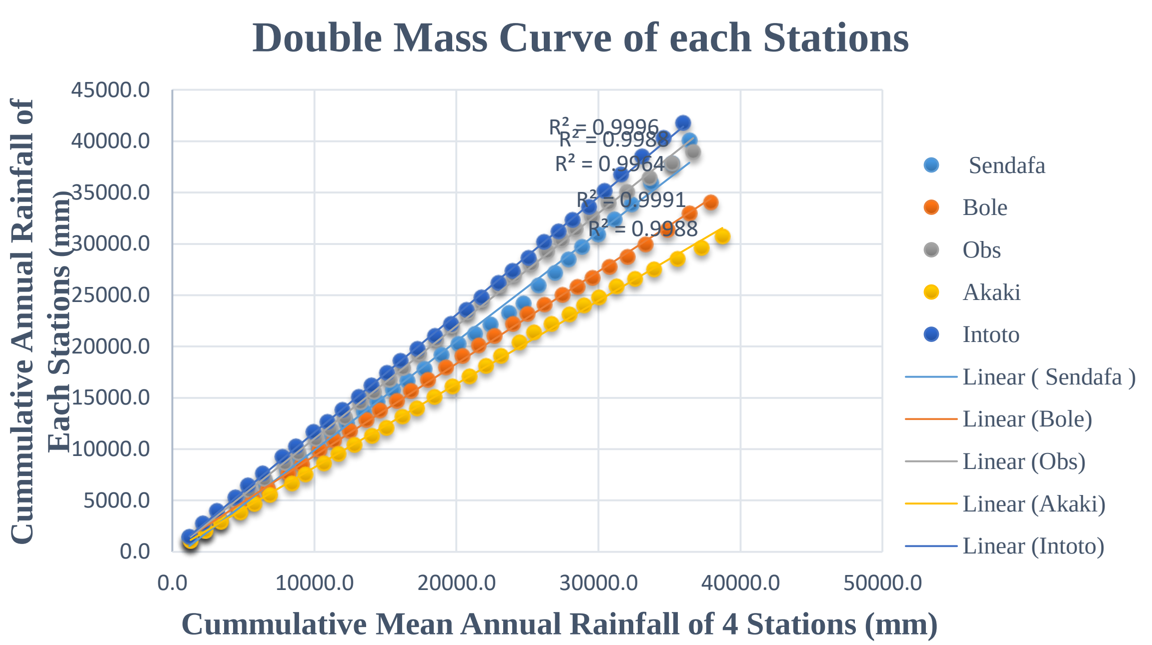


Figure 25: Double mass curve of each precipitation stations

3.6.3 Testing for Rainfall Data Outliers

The approach recommended by the Water Resources Council suggests adjusting for outliers, which are data points that significantly deviate from trend of the rest of the data. Determining whether to retain or remove outliers can significantly impact the statistical parameters derived from the data, especially when dealing with small sample sizes. Addressing outliers requires a combination of mathematical analysis and hydrological expertise. According to the Water Resources Council (1981), if the skewness of the station exceeds +0.4, evaluations prioritize high outliers; conversely, if the skewness is below -0.4, assessments focus on low outliers. For station skewness between ±0.4, it's advisable to conduct tests for both high and low outliers before considering their removal from the dataset. The following frequency equation can be employed to identify high outliers:

$$y_H = \overline{y} \pm K_n s_y$$

Where: YH is the high (+) / low (-) outlier threshold in log units and Kn is given from sample size n. The Kn values are used in one-sided tests that detect outliers at the 10-percent level of significance in normally distributed data. If the logarithms of the values in a sample are greater than Yh in the above equation, then they are considered high outliers. Accordingly, rainfall data was checked for outliers in all of 5 meteorological stations within the catchment and had no outliers present (Appendix Figure 3).

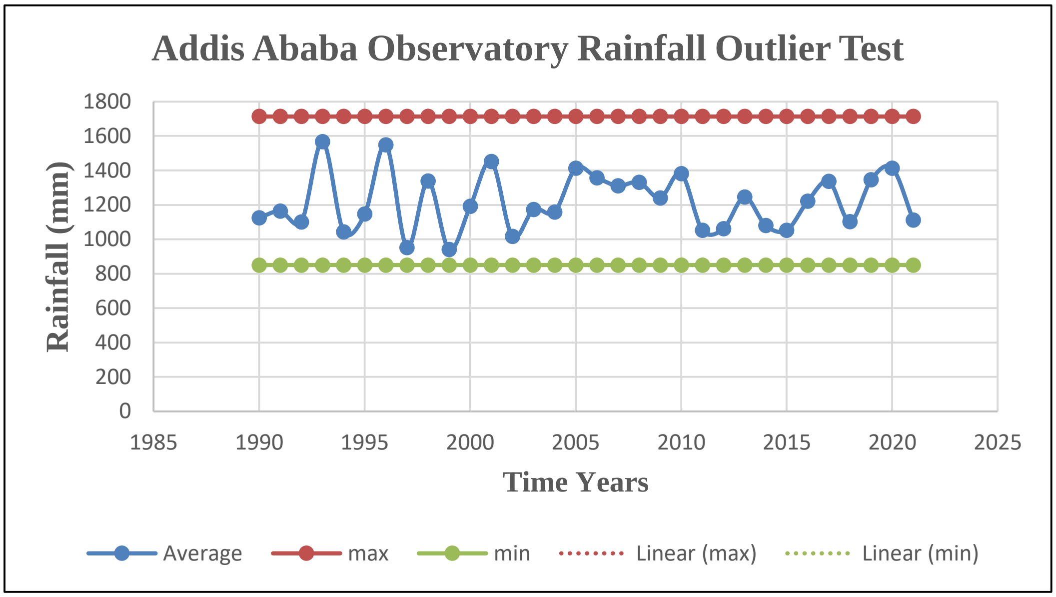


Figure 26: Outlier test on Addis Ababa Observatory Rainfall Data (1990-2021)

3.6.4 Areal Depth of Rainfall Determination

Various methodologies are available for calculating the areal rainfall across a watershed based on rain gauge measurements including Arithmetic Mean, Thiessen Polygon, Isohyetal, Grid Point, Percent Normal, and Hypsometric Methods, as documented by Tegine (2018).For this study in addition to rainfall data that was obtained from the Ethiopian National Meteorological Agency i.e. for A.A Observatory, AA bole, Intoto, Akaki and Sendafa, CHIRPS rainfall data was also used to widen the coverage(taking in to account unevenly distributed ground rain gage stations) and augment the rainfall data. Accordingly after identifying Geographical location of points whereby by the gaps are present. Annual rainfall data was downloaded from CHIRPS v.20 website in NETCDF data format. Following that using the Make Netcdf Table View tool on Arc Gis and by inserting the Latitude and Longitude of Chosen Points it was possible to extract the annual time series rainfall data and for this study rainfall data starting from 1990-2021 was selected.

Thiessen polygon method

In order to achieve accurate estimation of the spatial distribution of rainfall the Thiessen polygon method was considered. In this process, areas and lines connecting adjacent stations were delineated on a map of the study area using ArcGIS 10.4 software with the Arc toolbox extension. This was achieved by selecting analysis tools within the proximity category and subsequently generating Thiessen polygons. Accordingly, areal rainfall amount of each stations (including the CHIRPS X, Y Points which were considered as station points) was obtained by multiplying the area of each polygon and the point precipitation amount and the sum of those products are divided by total area of the catchment. The areal rainfall is computed by (Chow et al., 1988):

$$\overline{P} = \frac{1}{A}\sum_{j=1}^{J} A_j P_j , \qquad A = \sum_{j=1}^{J} A_J \qquad \text{..................................}(15)$$

Where: Aj = the area of polygon j in the watershed (km2)

Pj = rainfall amount in polygon j (mm)

$\overline{P}$= average rainfall (mm)

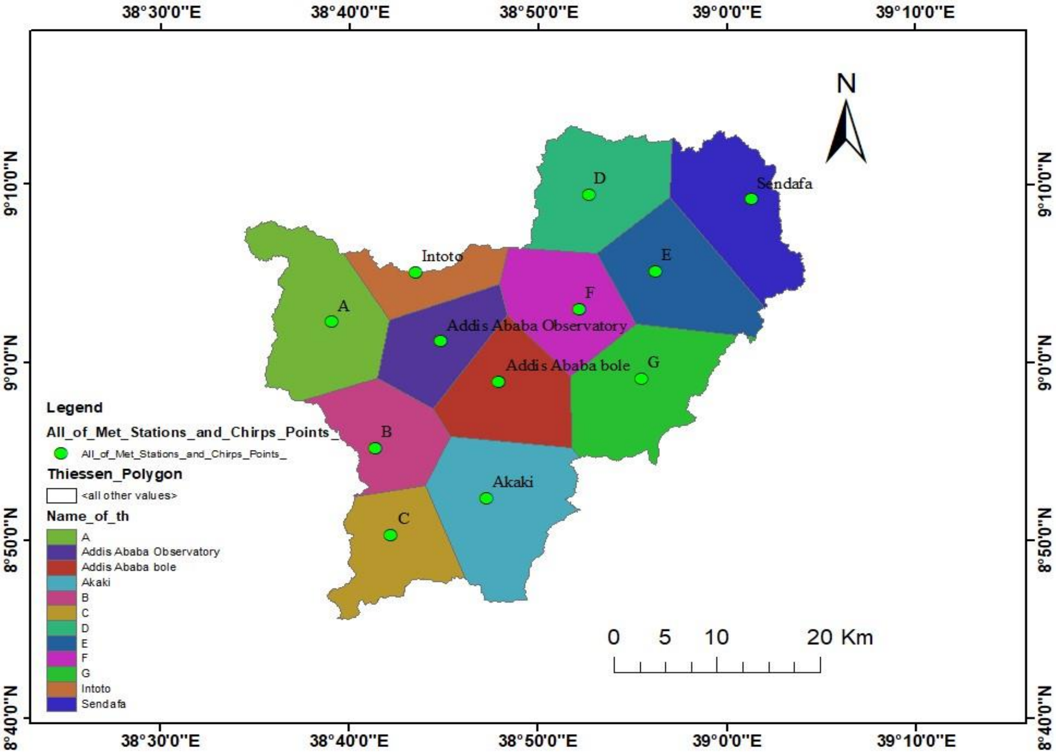


Figure 27: Thiessen Polygons of Akaki Catchment

As indicated on table16 the average areal annual rainfall in the catchment is estimated to be 1089.5 mm.

*Table 16**:** Thiessen Polygon result for Rainfall Data*

Thiessen Polygon result for Rainfall Data From 5 Meteorological Stations						
Gauge station Name	Lat. (N)	Long. (E)	Mean annual RF (mm)	Area of each polygon_skm	Area Percentage	Aj*Pj
Addis Ababa bole	992766.61	477874.22	1064.2	118.2	8.1	125767.2
Addis Ababa Observatory	996952.4	472248.08	1217.9	90.4	6.2	110102.2
Akaki	980707.55	476690.05	961.7	171.6	11.7	164984.4
Intoto	1004113.64	469780.52	1305.9	60.1	4.1	78540.61
Sendafa	1011675.48	502362.15	1252.4	130.8	8.9	163866.5
Thiessen Polygon result for Rainfall Data From CHIRPS based on selected X,Y Coordinates						
A	998961.12	461676.67	1124.4	159.1	10.9	178929.1
B	985911.38	465885.98	1060.1	96.4	6.6	102154.4
C	976910.73	467395.96	1012.0	103.7	7.1	104948.4
D	1012134.62	486585.3	1091.7	133.4	9.1	145653.5
E	1004194.89	493066.04	1026.0	135.5	9.3	139005.6
F	1000294.16	485669.15	1111.3	113.6	7.8	126217
G	993095.17	491712.12	1023.8	149.4	10.2	152930.1
Average areal annual rainfall =(1593099)/1462.2 =**1089.5mm**						

3.6.5 Construction of pairwise comparison matrix (PCM) for nine influencing factors

A pairwise comparison matrix was constructed for the nine factors that influence Groundwater Recharge Zones (GWRZs). Each entry in the comparison matrix denotes the influence of the row layer on the column layer. Saaty's 1–9 scale was used to fill in the entries. For instance a value entry of 1 indicates equal impact between the two layers, and 9 signifies the highest impact of a row layer compared to a column layer. As such all of the entries on the pairwise comparison matrix was filled and analyzed using AHP techniques. To determine the overall weight of the primary criteria, the relative weights of their corresponding classes were taken into account. After filling of the values on excel the consistency was checked to assure CR<0.1 by iteration and adjustment of the values entered in each elements of the matrix

The pairwise comparison matrices were developed based on detailed review of previous literature that utilized these controlling factors for mapping aquifer recharge zones, along with discussion held with expert (hyrdogeologist from EEC - WEDSWS). The AHP analysis followed, matrix construction, criteria weightage, normalizing the matric and calculate the normalized Principal Eigen Vectors, and finally consistency ratio were computed to assign final weightage to each thematic maps.

Table 17: Saaty's scale of preferences in the pair-wise comparison process (Saaty 1980)

Numerical rating	**Verbal judgments of preferences between alternative i and alternative j**
1	i is equally important to j
3	i is slightly more important than j
5	i is strongly more important than j
7	i is very strongly more important than j
9	i is extremely important than j
2, 4, 6, 8	Intermediate values

3.6.6 Weight assignment for factors affecting groundwater recharge

The pairwise comparison, normalized relative weight, and Principal Eigen Vector were computed, as illustrated in (Table 18-Table 20) respectively, while the consistency ratio was determined using equation 11.

Table 18: Pairwise comparison matrix (PCM) for factor weightage

Factors	**R.F**	**LULC**	**ST**	**Li**	**LD**	**Sl**	**TPI**	**D.D**	**TWI**
R.F	1	2	3	2	3	2	3	4	5
LULC	1/2	1	2	3	4	3	4	3	4
ST	1/3	1	1	2	3	4	5	6	7
Li	1/2	1/3	1/2	1	2	3	4	5	6
LD	1/3	1/4	1/3	1/2	1	2	3	4	7
Sl	1/2	1/3	1/4	1/3	1/2	1	1	3	4
TPI	1/3	1/4	1/5	1/4	1/3	1	1	2	3
D.D	1/4	1/3	1/6	1/5	1/4	1/3	1	1	2
TWI	1/5	1/4	1/7	1/6	1/7	1/4	1/3	1/2	1
Sum	**3.95**	**5.25**	**7.59**	**9.45**	**14.23**	**16.58**	**21.83**	**28.50**	**39.00**

Where, R.F =Rainfall, LULC =Land Use Land Cover, ST=Soil Texture, Li=Lithology, L.D=Lineament Density, Sl =Slope, TPI=Topographic Position Index, D.D=Drainage Density TWI=Topographic Wetness Index.

Normalized Criterion Weight

Following the normalization (i.e. division of each element by the sum of column) the criteria weights are calculated by summing the normalized rows and dividing them by the total number of factors (Table 19). Accordingly Rainfall had the highest value and TWI had the lowest rank.

Table 19: Selected Factors Normalized weight

Factors	***R.F***	***LULC***	***ST***	***Li***	***LD***	***Sl***	***TPI***	***D.D***	***TWI***	***Sum***	***Criteria Weights***	***Criteria weight (%)***
R.F	0.25	0.38	0.40	0.21	0.21	0.12	0.14	0.14	0.13	***1.98***	***0.22***	***21.98***
LULC	0.13	0.19	0.26	0.32	0.28	0.18	0.18	0.11	0.10	***1.75***	***0.19***	***19.46***
ST	0.08	0.10	0.13	0.21	0.21	0.24	0.23	0.21	0.18	***1.59***	***0.18***	***17.71***
Li	0.13	0.06	0.07	0.11	0.14	0.18	0.18	0.18	0.15	***1.20***	***0.13***	***13.29***
LD	0.08	0.05	0.04	0.05	0.07	0.12	0.14	0.14	0.18	***0.88***	***0.10***	***9.74***
Sl	0.13	0.06	0.03	0.04	0.04	0.06	0.05	0.11	0.10	***0.61***	***0.07***	***6.75***
TPI	0.08	0.05	0.03	0.03	0.02	0.06	0.05	0.07	0.08	***0.46***	***0.05***	***5.13***
D.D	0.06	0.06	0.02	0.02	0.02	0.02	0.02	0.04	0.05	***0.32***	***0.04***	***3.52***
TWI	0.05	0.05	0.02	0.02	0.01	0.02	0.02	0.02	0.03	***0.22***	***0.02***	***2.43***
Total	1	1	1	1	1	1	1	1	1	***9***	***1***	***100%***

Where, R.F =Rainfall, LULC =Land Use Land Cover, ST=Soil Texture, Li=Lithology, L.D=Lineament Density, Sl =Slope, TPI=Topographic Position Index, D.D=Drainage Density TWI=Topographic Wetness Index.

Weight Sum: the weighted sum is obtained by multiplying each value in the column (in the matric table which is not normalized) by the criteria weight.

CRITERIA .WEIGHT	**0.22**	**0.19**	**0.18**	**0.13**	**0.10**	**0.07**	**0.05**	**0.04**	**0.02**	
FACTORS	**R.F**	**LULC**	**ST**	**Li**	**LD**	**Sl**	**TPI**	**D.D**	**TWI**	**Weighted sum value**
R.F	0.22	0.39	0.53	0.27	0.29	0.13	0.15	0.14	0.12	**2.25**
LULC	0.11	0.19	0.35	0.40	0.39	0.20	0.21	0.11	0.10	**2.06**
ST	0.07	0.10	0.18	0.27	0.29	0.27	0.26	0.21	0.17	**1.81**
LI	0.11	0.06	0.09	0.13	0.19	0.20	0.21	0.18	0.15	**1.32**
LD	0.07	0.05	0.06	0.07	0.10	0.13	0.15	0.14	0.17	**0.94**
SL	0.11	0.06	0.04	0.04	0.05	0.07	0.05	0.11	0.10	**0.63**
TPI	0.07	0.05	0.04	0.03	0.03	0.07	0.05	0.07	0.07	**0.48**
D.D	0.05	0.06	0.03	0.03	0.02	0.02	0.03	0.04	0.05	**0.33**
TWI	0.04	0.05	0.03	0.02	0.01	0.02	0.02	0.02	0.02	**0.23**

Principal/ Highest Eigen Vectors (λmax)

To verify the weights assigned to each parameter in Table 19, the normalized Principal Eigen vector value (λmax) was calculated. Principal Eigen vectors are the normalized weight Eigen vectors computed to ensure that the assigned relative weights to each factor are evenly distributed, contributing to the calculation of the consistency ratio (equation 11). This calculation involves dividing the weighted sum value by the criteria weight.

Table 20: Selected factors weighed ratio (R)

C.W	**0.22**	**0.19**	**0.18**	**0.13**	**0.10**	**0.07**	**0.05**	**0.04**	**0.02**		**Weighted ratio (R)**
Factors	**R.F**	**LULC**	**ST**	**Li**	**LD**	**Sl**	**TPI**	**D.D**	**TWI**	**Criteria Weight**	**WSV/CW**
R.F	0.22	0.39	0.53	0.27	0.29	0.13	0.15	0.14	0.12	0.22	**10.23**
LULC	0.11	0.19	0.35	0.40	0.39	0.20	0.21	0.11	0.10	0.19	**10.57**
ST	0.07	0.10	0.18	0.27	0.29	0.27	0.26	0.21	0.17	0.18	**10.24**
Li	0.11	0.06	0.09	0.13	0.19	0.20	0.21	0.18	0.15	0.13	**9.94**
LD	0.07	0.05	0.06	0.07	0.10	0.13	0.15	0.14	0.17	0.10	**9.69**
Sl	0.11	0.06	0.04	0.04	0.05	0.07	0.05	0.11	0.10	0.07	**9.39**
TPI	0.07	0.05	0.04	0.03	0.03	0.07	0.05	0.07	0.07	0.05	**9.46**
D.D	0.05	0.06	0.03	0.03	0.02	0.02	0.03	0.04	0.05	0.04	**9.43**
TWI	0.04	0.05	0.03	0.02	0.01	0.02	0.02	0.02	0.02	0.02	**9.47**

Where, R.F =Rainfall, LULC =Land Use Land Cover, ST=Soil Texture, Li=Lithology, L.D=Lineament Density, Sl =Slope, TPI=Topographic Position Index, D.D=Drainage Density TWI=Topographic Wetness Index.

From above computation of Table 20, the principal Eigen Vector is calculated using equation 16 and tabulated in Table 23.

Principal Eigen Vector $\boldsymbol{\lambda max}=\frac{1}{N}\left(\sum_{i-1}^{N}.\frac{aij.wj}{wj}\right)$……………………………(16)

$$=\left(\frac{R1+R2+R3+R4+R5+R6+R7+R8+R9}{n}\right)$$

*Table 21**:** Principal Eigenvector (Normalized)*

Parameters	**Normalized principal Eigen vectors**
R.F	10.23
L.D	10.57
Li	10.24
Sl	9.94
D.D	9.69
ST	9.39
LULC	9.46
TPI	9.43
TWI	9.47
λmax	9.82

Consistency Ratio (CR)

As per table 15 Random Index(RI), for nine factors is 1.45

Consistency Index = (λmax – n)/ (n-1)………………………………………….. (17)

CI = (9.82 – 9)/ (9-1)

= 0.10

Consistency Ratio = CI/RI …………………………………………………….……. (18)

CR = 0.10/1.45, where RI for n = 9 is 1.45

= 0.07

According to Saaty's criteria, a favorable decision requires a consistency ratio (CR) of ≤ 0.1. In this case, the CR is calculated as 0.07, which is below 0.1. This indicates that the assigned weights for each factor were consistent, and the relative weights from the pairwise comparison were suitable and satisfactory for decision-making. Consequently, the evaluation of consistency ratio suggests that the map developed using MCDA is reasonably accurate.

3.6.7 Weighted overlay analysis (WOA)

In the raster overlay analysis, each cell of each layer must reference the same geographic location to make it well suited to combining characteristics for numerous layers into a single layer (Malczewski2006). Additionally, all of the thematic layers must be converted to raster format must have the same spatial resolution through resampling before usage of WOA in ArcGIS.

In this assessment, each pixel (cell) of feature classes within a specific thematic layer is allocated numeric weight values, which are mathematically combined to generate new values for the corresponding pixels in the output layer. The weighted overlay analysis employs a standardized scale of values across multiple thematic layers to generate an output layer, with weight values ranging from 1 to 10. In this study, feature classes with the highest recharge potential are assigned a higher weight value, such as 5, while those with minimal influence are assigned lower weight values, typically 1.

The remaining feature classes are categorized within an intermediate range and typically receive weight values within this range based on their suitability to recharge. Subsequently, the total weighted index value is computed by multiplying the scale weight by the criteria weight .

$$W=\sum_{i=0}^{n} Xi * Wi \ldots\ldots\ldots\ldots\ldots\ldots\ldots\ldots\ldots\ldots\ldots \text{(19)}$$

Where *W* is the weighted overlay, n is the number of factors, *xi* is the standardized/reclassified cell value, and *wi* is criteria weight. In other words, the pixel values of the raster layers are multiplied by the criteria weight determined through AHP analysis, and the outcomes are summed to generate the groundwater recharge potential output raster map.

3.7 Development of Groundwater Recharge Zone Map

In this research, the identification and demarcation of potential groundwater recharge sites are executed through weighted overlay procedures through integration of the nine thematic layers within the ArcGIS platform. According to Salar et al. (2018), weighted linear combination is the most commonly employed technique for multi-criteria evaluation. The assigned weights for these nine themes are detailed in Table 24. The resulting map delineates potential groundwater recharge zones (PGWRZ) in the Akaki catchment by linear combination of weighted overlay of all thematic maps according to equation 20.

GWRZ = {[(RFw) (RFr)] + [(LuLcw) (LuLcr)] + [(Stw) (Str)] + [(Liw) (Lir)] + [(Ldw) (Ldr)] + [(Slw) (Slr)] +[(Tpw)(Tpr)] + [(Ddw) (Ddr)] + [(Tww)(Twi)]}…………………. (20)

Where, GWRZ – Groundwater recharge zone, RF – Rainfall, LuLc – Land use land cover, St-Soil Texture, Li –Lithology, Ld – Lineament density, Sl– Slope, Tpw-Topographic Position Index, Dd – Drainage density, and Tww– Topographic Wetness Index. The letters "w" & "r" refers to criteria weight and standardized/reclassified cell value of a specific thematic map respectively.

Table 22: Weight of Factors and λ

Factors	Weight	λ
Rainfall	21.98	10.23
Land Use Land Cover	19.46	10.57
Soil texture	17.71	10.24
Lithology	13.29	9.94
Lineament Density	9.74	9.69
Slope	6.75	9.39
Topographic Position Index	5.13	9.46
Drainage Density	3.52	9.43
Topographic Wetness Index	2.43	9.47
Total	100	λ max= 9.82

3.8 Validation of Groundwater Recharge Potential Map

Validating the groundwater spatial recharge model is essential to assess the accuracy of the obtained results. To accomplish this, the final recharge potential map was compared with the locations of existing groundwater wells to establish the model's validity. For quantitative validation, many researchers commonly employ the receiver operating characteristics (ROC) curve method to evaluate the efficiency of groundwater recharge potential mapping. The existing 230 wells located in the Akaki Catchment Appendix Table 8 (i.e. well fields of Akaki Phase-4(Koye), Akaki Phase 2, Akaki Phase 3A, Akaki Phase 3B, Legedadi Phase-1 Works, Legedadi Phase- 2 South Ayat North Fanta (SANF) and Addis Ababa Pocket.) are used to validate the groundwater recharge potential map. The quality of well data which was collected from AAWSA was checked through assessment of consistency in the format and precision of the geographic coordinates of the wells across the dataset and also checked for any anomalies or outliers that may indicate errors in data entry or recording. Additionally the dataset was crosschecked with other similar studies conducted in the study area (review of similarity of data and metadata for verification).

In the ROC curve, the model's sensitivity, representing the percentage of well pixels correctly predicted by the model, is plotted on the x-axis, while 1-specificity, indicating the percentage of predicted well pixels over the total, is plotted on the y-axis. The area under the curve (AUC) assesses the forecast system's quality by measuring its ability to accurately predict the occurrence or non-occurrence of predefined events, as described by Devkota et al. (2013).

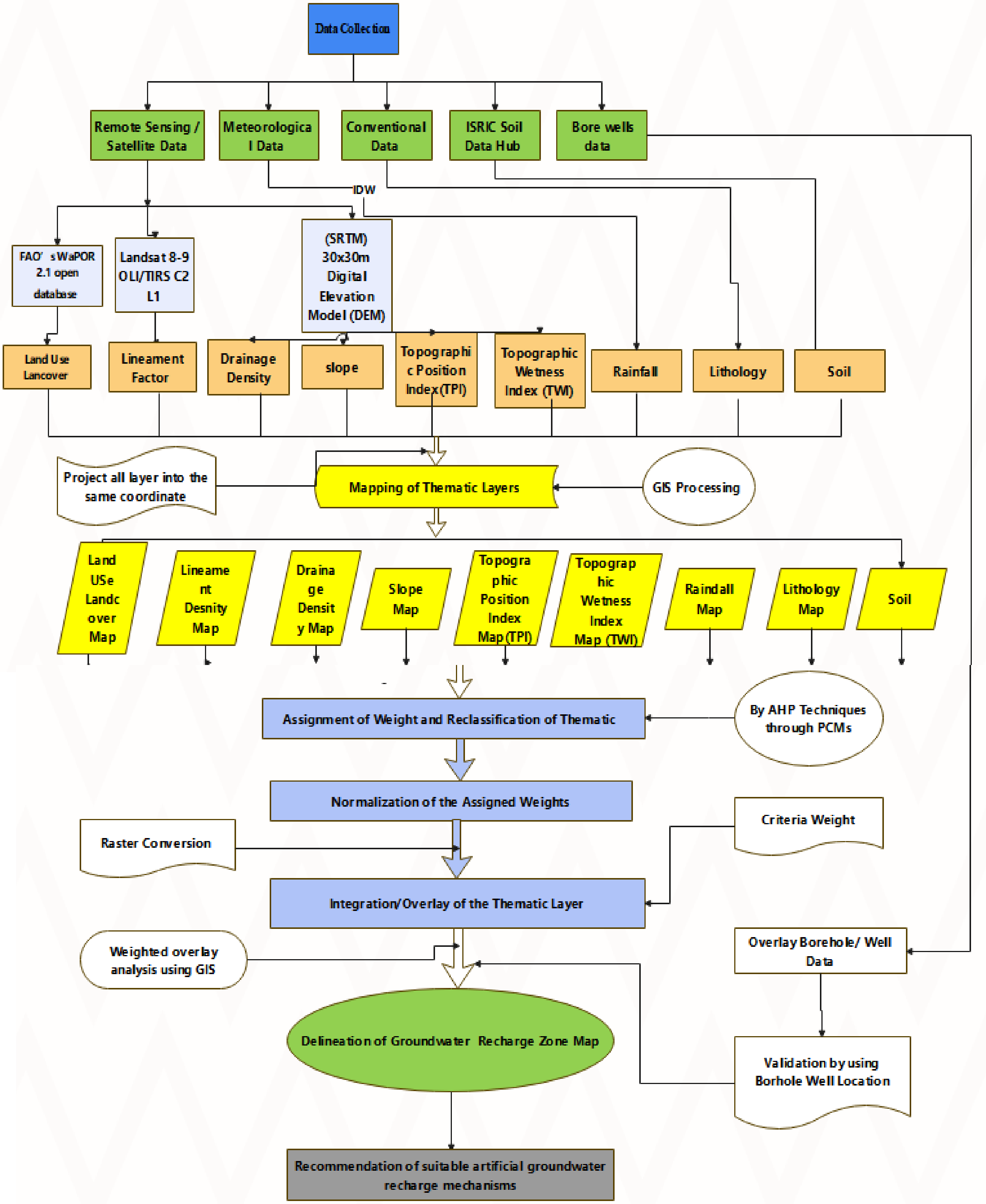


Figure 28: *Research methodology Framework*

4. RESULTS AND DISCUSSION

4.1 Selection of Factors Influencing Recharge of Groundwater

Factors affecting groundwater recharge were identified by reviewing various past literature and considering the conditions specific to the study area, ultimately narrowing them down to nine key factors.

Frequency of usage: for this study more than 64 research papers /literatures were thoroughly reviewed. Out of the 64 reviewed literatures 42 studies related to Identification of Potential Groundwater Recharge Zone were selected. Accordingly, Rainfall was used=25 times, Lineament Density=18 times, Lithology= 39 times, Slope=37 times, Drainage Density =24 times, Soil Texture=30 times, LuLc =24 times, TPI=3 times and TWI =3 times.

Ease/difficult of data access: due to difficulty in obtaining or accessing the data, geomorphological data was not considered in this study.

Significance of the factor: Informed by previous scholarly research and fundamental scientific principles, the selected nine factors i.e. Rainfall, Lineament Density, Lithology, Slope, Drainage Density, Soil Texture, Land Use Land Cover (LULC), TPI and TWI were found to be critical and important to groundwater recharge of an area.

4.2 Reclassified Thematic Map

The thematic layers underwent reclassification, standardization, weighting and ranking based on their contribution to occurrence of groundwater recharge. Moreover, various studies present varying numbers and classifications of ranges or attributes for suitability classes, reflecting differences in expert opinions and published guidelines. Many studies adopt five suitability classes with differing terms but similar meanings. For example, Ignacio and Willem (2020) utilized very low, low, moderate, high, and very high suitability, whereas Guigui et al. (2021) and Yonas and Tesfa (2021) employed very poor, poor, moderate, good, and very good suitability classes in their suitability mapping. The reclassified maps in this study were categorized in to 5 classes, representing very high, high, moderate, low and very low, recharge potentiality. A higher value (5) was assigned to areas with a significant contribution to recharge, while the lowest value (1) was assigned to areas causing minimal groundwater recharge.

4.2.1. Reclassified Rainfall Map (RF)

The IDW interpolation method was utilized to produce spatial data representing the mean annual rainfall across the study area, which was then categorized into classes using manual breakpoints. As illustrated in Figure 15, the mean annual rainfall in the study area varies from 962 mm/year to 1306 mm/year. The northern and northeastern regions experience notably high rainfall, ranging from 1195 to 1305.87 mm/year and 1100 to 1195 mm/year, respectively. Moderate rainfall, ranging from 1046 to 1100 mm/year, is observed in the western, central, northern, and northeastern parts. Conversely, the southern areas, receive lower rainfall, ranging from 999 to 1046 mm/year and 961.82 to 999 mm/year. Consequently, there is an observable decrease in annual rainfall values with increasing elevation.

The classification of rainfall can vary depending on the local conditions, such as the region's climate, topography, and hydrological characteristics. However, generally speaking, in many temperate and tropical regions, an annual rainfall amount exceeding 1100 millimeters (mm) is often considered relatively high. Hence, rainfall amount exceeding this threshold was classified as high during the manual reclassification. Table 25 and Figure 25 depict the classified and ranked rainfall ranges into five suitability classes, assigning 1 (very low suitability) to rainfall of ranges 961.82-999 mm/year and 5 assigned to rainfall in the range of 1195-1305.87 mm/year, indicating very high recharge suitability. These classifications were reached by reviewing existing literature and studies related to rainfall classification for groundwater recharge mapping and by identifying common established thresholds used in similar local studies having proximity to the study area such as; (Solomon T., 2020) which conducted on “Groundwater Potential and Recharge Zone Mapping Using GIS and Remote Sensing techniques: a case study of Melka Kunture Watershed in the Upper Awash River Basin in Ethiopia” and (Yishak and Mikias , 2022) which conducted on “Identification of Potential Artificial Groundwater Recharge Zones in Tikurwuha Watershed of Ethiopia”

Table 23: Classified and ranked rainfall ranges

Thematic map	Annual RF (mm)	Area(km^2)	Area (%)	Rank	Suitability Classification
Rainfall	961.82-999	39.3	2.7	1	Very Low
	999-1046	276.6	18.9	2	Low
	1046-1100	503.6	34.5	3	Moderate
	1100-1195	525.1	35.9	4	High
	1195-1305.87	116.9	8.0	5	Very High

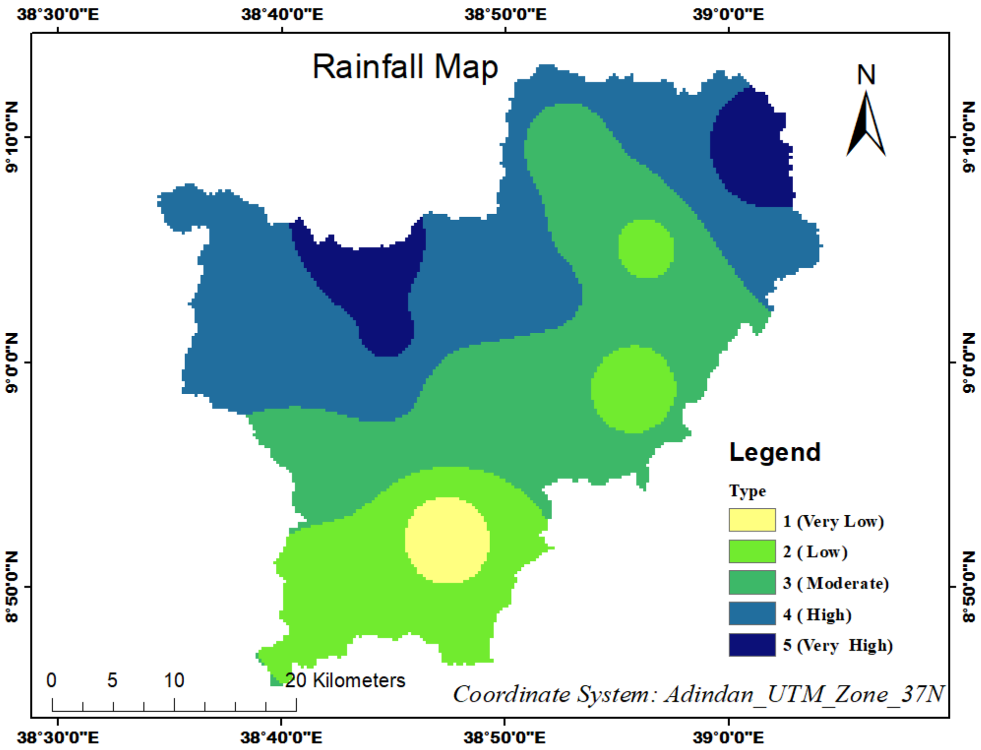


Figure 29: Classified and ranked rainfall map

4.2.2 Reclassified Drainage Density (DD)

The generated Drainage Density shown in Fig 16 reveals the density values ranges from 0.07 to 2.08 km/km2.According to Agarwal et al. (2016), there is an inverse relationship between drainage density and permeability. Increased drainage density indicates reduced water infiltration into the subsurface. Conversely, areas with the lowest drainage density diminish runoff potential and bolster water infiltration capacity into groundwater, leading to the highest suitability for groundwater recharge. Therefore, the drainage density map of the study area, as depicted in Figure 30, was categorized into five classes based on their suitability for groundwater recharge zones, with particular emphasis on assigning the highest weight/rank to areas with very low drainage density. Similarly, these drainage density reclassification were based on review of existing literature and studies related to drainage density classification for groundwater recharge mapping and by identifying frequently used thresholds/classes for ranking the drainage density emphasizing on similar local studies having proximity to the study area and similar setting (Yishak and Mikias , 2022)

Accordingly , very low drainage density areas (0.07-0.09 km/km2) covered 0% and were given rank of 5, low drainage density areas (0.09-0.5 km/km2) covered 6.8%, moderate drainage density areas (0.5-1.0 km/km2) covered 38.0% ,high drainage density areas (1.-1.43 km/km2) Covered 43.2% and very high drainage density areas (1.43-2.08 km/km2) covered 11.9% of the total area and given rank of 1.

Table 24: Classified and ranked drainage density ranges

Thematic map	Drainage Density Km/Km2	Description	Area (Km2)	Area (%)	Rank	Suitability Classification
Drainage Density	0.07 - 0.09	Very Low density	0.2	0.0	5	Very High
	0.09 - 0.5	Low density	100.0	6.8	4	High
	0.5 - 1	Moderate density	556.1	38.0	3	Moderate
	1 - 1.43	High density	631.7	43.2	2	Low
	1.43 - 2.08	Very High density	173.5	11.9	1	Very Low

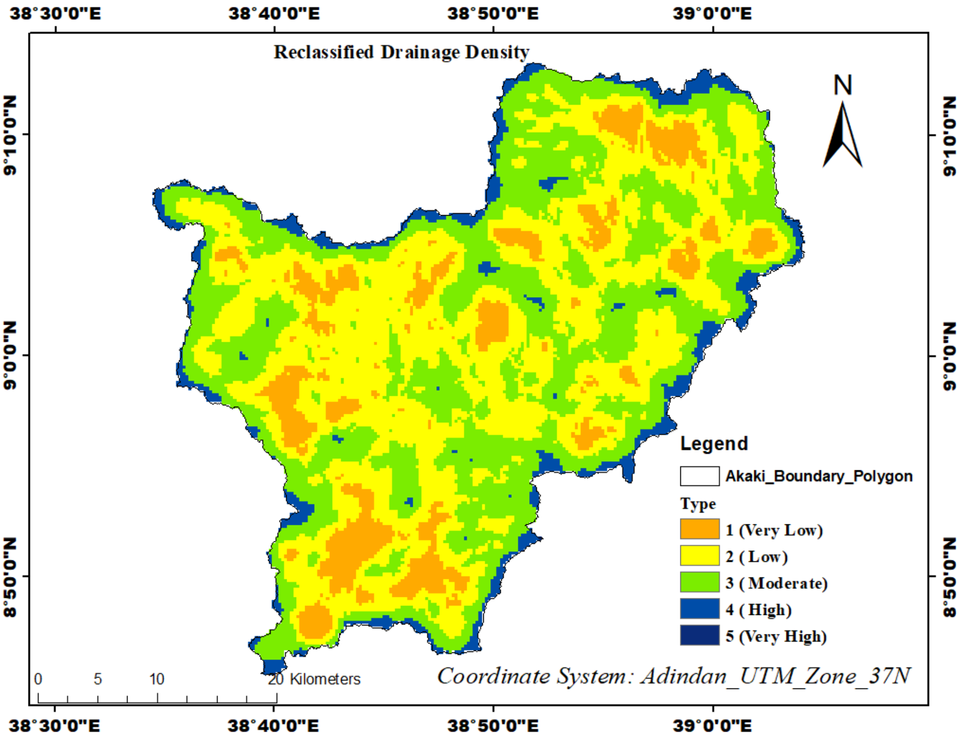


Figure 30: Classified and ranked drainage density

4.2.3 Reclassified Land Use Land Cover:

seven types of LULC (Figure 17) dominate the study area namely; Urban/Built-Up, Bare/Sparse Vegetation, Crop Land/ Cultivated Land and Grass Land, Shrub or herbaceous cover/ flooded & Forest, and Water Bodies which cover 16.67%,0.02%,76.79%,6.27% & 0.26% respectively. As depicted in the map, the study area is predominantly characterized by Crop Land/Cultivated Land and Grassland, with a smaller proportion of Bare/Sparse Vegetation compared to other land cover types (see Figure 14).

Given that different land use and land cover (LULC) types exhibit varying rates of groundwater recharge due to differences in infiltration capacity, the LULC classification in the study area was adjusted based on suitability rankings, as depicted in Table 27. Urban/Built-Up areas were assigned 1 due to their low infiltration rates and high runoff in very low potential for groundwater recharge zones. Conversely, Water Bodies received rank of 5 due to their continuous recharge effects and high infiltration rates, indicating very high potential for groundwater recharge zones (refer to Figure 31). The classified and ranked LULC map (Figure 31) indicates that approximately 76.8% of the total study area is moderately suitable for groundwater recharge. This classification aligns with the findings of previous research studies such as those conducted by Kibrit and Samuel (2020), Tarekegn et al. (2022), and Tadele and Tatek (2021).

Table 25 : Classified and ranked Land use land cover

Thematic map	LULC Types	Area(km2)	Area (%)	Rank	Suitability Classification
Land Use Land Cover	1 (Urban/ Built Up)	243.56	16.67	1	Very Low
	2 (Bare/Sparse Vegetation)	0.25	0.02	2	Low
	3 (Crop Land/Cultivated Land and Grass Land)	1,122.19	76.79	3	Moderate
	4 (Shrub or herbaceous cover, flooded and Forest)	91.63	6.27	4	High
	5 (Water Bodies)	3.81	0.26	5	Very High

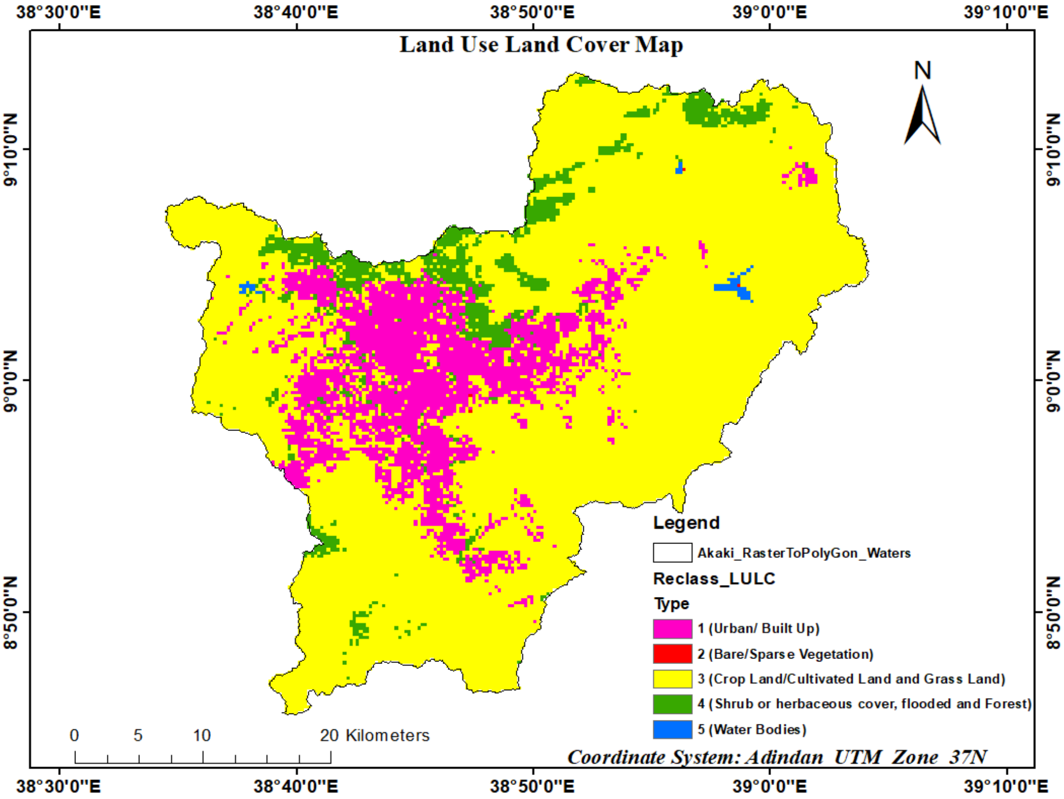


Figure 31: *Re-classified and ranked Land use land cover*

4.2.4 Reclassified Lineament Density Map:

Suganthi et al. (2013) suggest that areas with high lineament density values indicate greater suitability for groundwater recharge, while areas with low lineament density values have lower suitability. In this study, areas with the highest lineament density are considered most suitable for recharge due to the presence of numerous joints and faults that facilitate water infiltration to the groundwater table. Conversely, areas with the lowest lineament density are deemed less suitable for groundwater recharge as they have fewer joints and faults, limiting water permeability to the groundwater table. Therefore, lineament density is directly correlated with groundwater recharge zones.

The reclassified lineament density map of the study area was derived from the lineament map displayed in Figure 19. The suitability of these lineaments was assessed and categorized into five classes based on their impact on groundwater recharge, as illustrated in Figure 32 and table 26. The table indicates that lineament density in the study area ranges from 0 to 3.95 km/km². Specifically, very high lineament density falls within the range of 2.51-3.95 km/km², high density ranges from 1.78-2.51 km/km², moderate density ranges from 1.21-1.78 km/km², low density ranges from 0.46-1.21 km/km², and very low density is less than 0.46 km/km². These categories cover 2.4%, 34.7%, 40.9%, 20.9%, and 1.1% of the study area, respectively, as indicated in Table 28. The reclassification of lineament density was backed by a review of existing literature and studies pertaining to lineament density classification for groundwater recharge mapping. This process involved identifying commonly used thresholds and classes by considering similar local studies in close proximity to the study area and with comparable geological settings (Yishak and Mikias, 2022 and Solomon T.,2020).

Table 26: Classified and ranked Lineament density

Thematic map	Lineament Density. Km/km2	Area in km2	Area in %	Value/Rank	Recharge Suitability Classification Rank
Lineament Density	0 - 0.46	15.6	1.1	1	Very Low
	0.46 - 1.21	305.2	20.9	2	Low
	1.21 - 1.78	598.5	40.9	3	Moderate
	1.78 - 2.51	507.3	34.7	4	High
	2.51 - 3.95	35.1	2.4	5	Very High Suitability

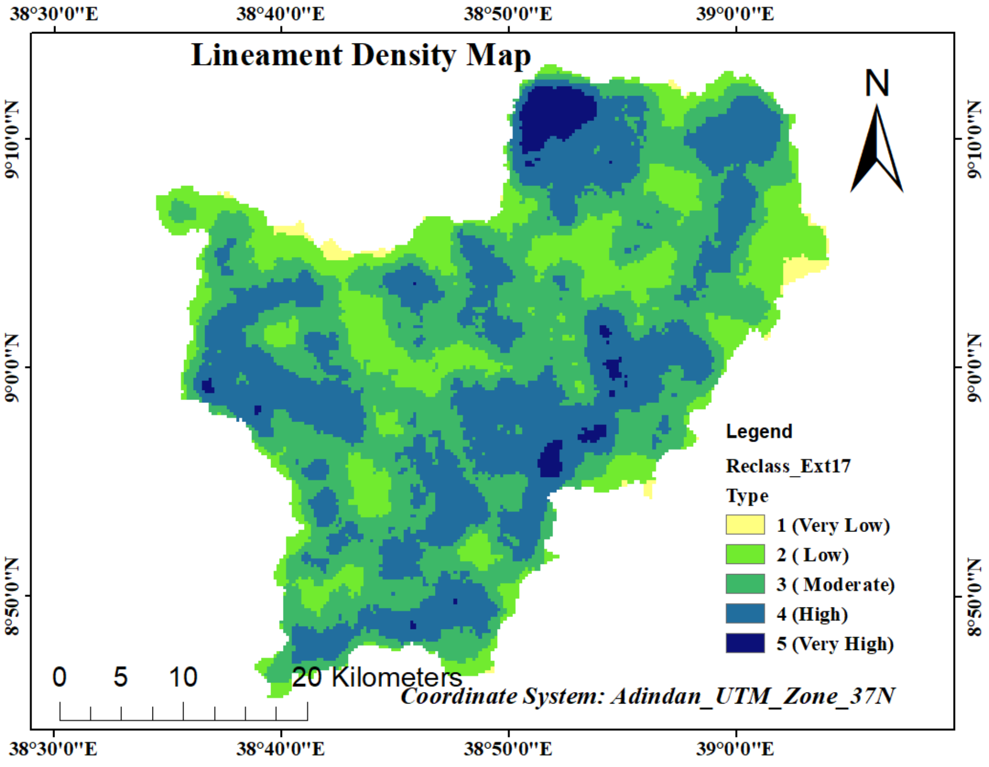
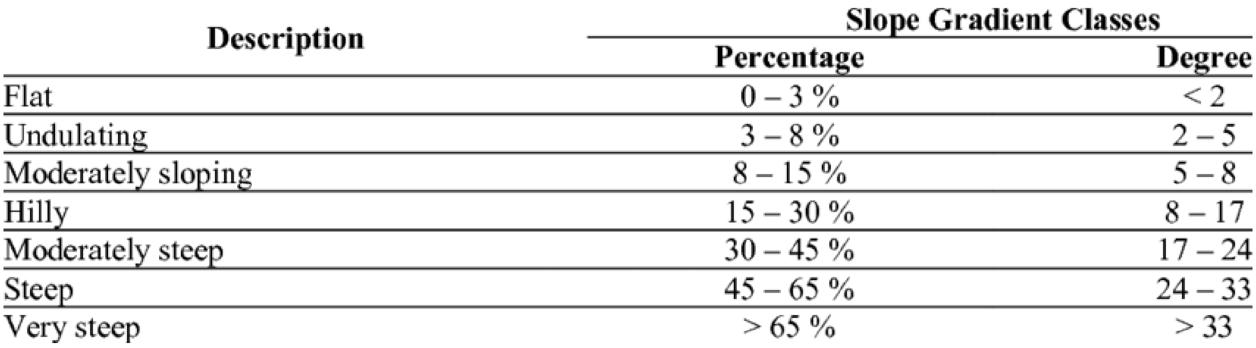


Figure 32: Classified and ranked Lineament density

4.2.5 Reclassified Slope Map: The slope of an area is intricately linked to its geomorphology, playing a pivotal role in regulating groundwater infiltration into the subsurface and recharge processes (Kadam et al., 2017). Regions with high slopes typically experience increased runoff and diminished infiltration rates, rendering them unsuitable for effective groundwater recharge (Chenini et al., 2010). In the study area depicted in Figure 20, slopes range from 0° to 44°. Consequently, the slope is categorized into five classes based on their potential for recharge and infiltration rates. The classification prioritizes lower slope values, such as flat or undulating slope terrain, assigning them the maximum rank due to their significant contribution to groundwater occurrence and recharge. Conversely, areas with steeper slopes are assigned lower ranks, indicative of their reduced potential for groundwater recharge.

The slope in the Akaki catchment was classified based on USDA (United States Department of Agriculture) Slope gradient classification .According to USDA slope classification (Table 27) the slopes in the study area were classified as 0^{o} –2^{o} (Flat), 2^{o} -5^{o} (undulating), 5^{o} –8^{o} (moderately sloping), 8^{o} -17^{o} (hill), and 17^{o} –44^{o} (Moderately Steep -Very Steep) with very high, high, moderate, low, and very low recharging potential . According to the classification, most of the catchment was dominated with undulating slope of 2^{o} to 5^{o} covering a total area of 40.12%.

Table 27: Slope gradient classes based on USDA (United States Department of Agriculture) classification



Description	Slope Gradient Classes	
	Percentage	Degree
Flat	0 – 3 %	< 2
Undulating	3 – 8 %	2 – 5
Moderately sloping	8 – 15 %	5 – 8
Hilly	15 – 30 %	8 – 17
Moderately steep	30 – 45 %	17 – 24
Steep	45 – 65 %	24 – 33
Very steep	> 65 %	> 33

Table 28: Classified and ranked Slope

Thematic map	Slope in Degree	USDA Classification	Area in km^2	Area in %	Value Rank	Recharge Suitability Rank
Slope	0° - 2°	Flat	270.38	18.50	5	Very High Suitability
	2° - 5°	Undulating	586.44	40.12	4	High Suitability
	5° - 8°	Moderately Sloping	248.19	16.98	3	Moderate Suitability
	8° - 17°	Hilly	262.13	17.93	2	Low Suitability
	17° - 44°	Moderately Steep -Very Steep	94.50	6.47	1	Very Low Suitability

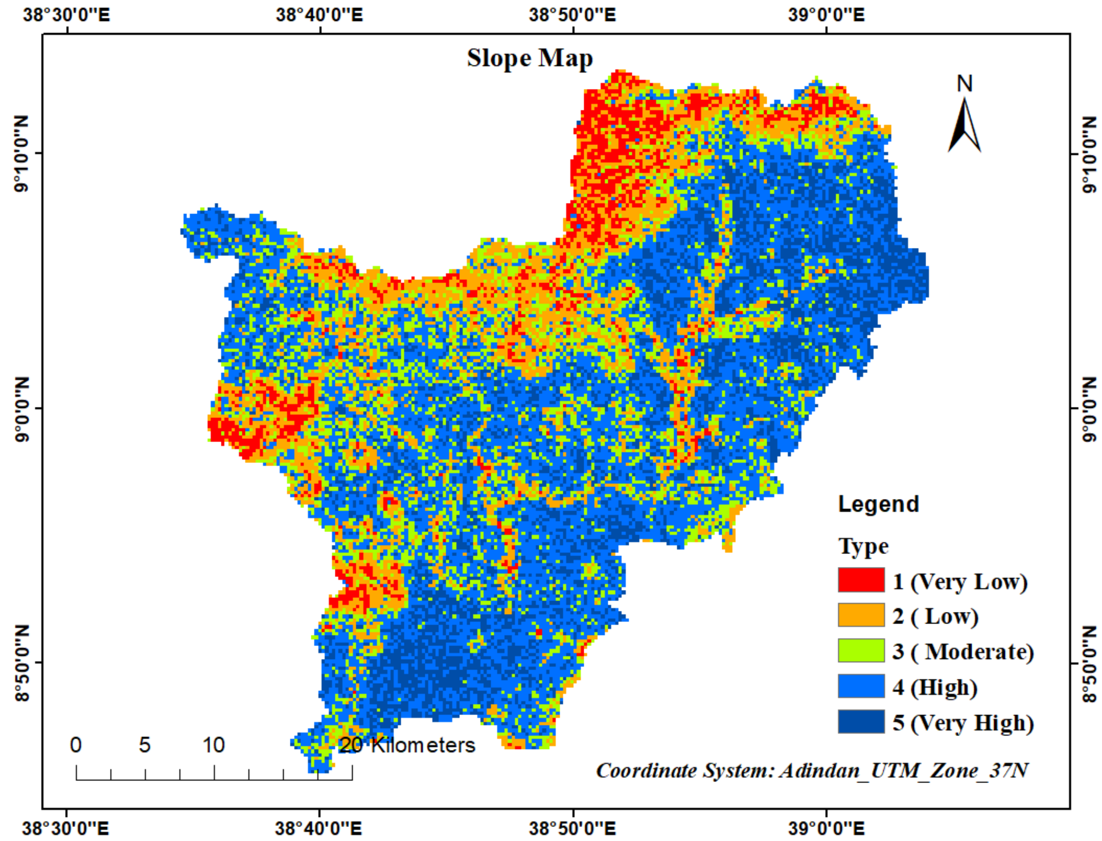


Figure 33: Classified and ranked Slope

4.2.6 Reclassified Soil Map: oil plays a crucial role in influencing groundwater recharge through its impact on infiltration and percolation processes (Anuraga et al., 2006; Kumar et al., 2016; Rukundo and Dogan, 2019). The permeability of various soil types is largely determined by their texture. As discussed in previous section, the dominant soil types of the study area were Clay, Clay Loam and Silty Clay Loam which covered 88.01%, 11.98 % and 0.01% of the total area of Akaki

Catchment, respectively. These soil types are characterized by Very Low to Moderate infiltration property. Therefore, ranks were assigned for clay (Very Low), Clay loam (Low) and Silty clay loam (moderate), based on infiltration and recharge potentiality. Groundwater recharge and infiltration potential are greater in coarse-grained soil structures and significantly lower in fine-grained soil types. Consequently, clayey soil was assigned the lowest weight due to its substantial limitation on percolation and low permeability.

Table 29: Soil Texture Suitability Class for Groundwater Recharge Zone Identification

Thematic Map	Texture of Soil	Area(km2)	Area (%)	Rank	Suitability Classification
Soil Texture	Clay	1,281.88	88.01	1	Very Low
	Clay Loam	174.56	11.98	2	Low
	Silty Clay Loam	0.13	0.01	3	Moderate

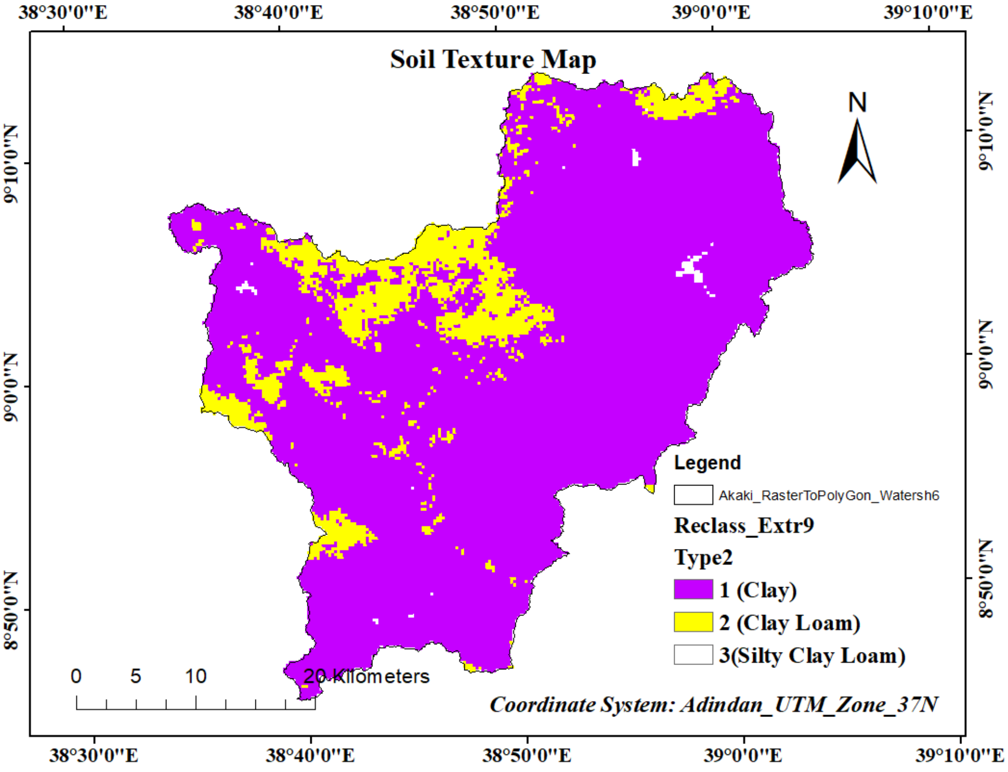


Figure 34: Reclassified Map of Soil Texture

4.2.7 Reclassified Geological/Lithological Map: Situated at the western margin of the Main Ethiopian Rift, the Akaki catchment area is intricately linked to the formation and evolution of both the Ethiopian plateau and the Rift system. The geological composition of the catchment comprises volcanic rocks overlaid by alluvial deposits, with black cotton soil being the predominant component of the alluvium. Among the volcanic rocks present, basalts, rhyolites, trachytes, scoria, trachybasalts, ignimbrites, and tuff of various ages prevail, many of which exhibit significant weathering and fracturing (Demlie et al., 2007a).Detailed descriptions of the major lithological formations within the catchment area, extracted from three map sheets, are provided in Appendix Table 11. Each geological unit exerts a distinct influence on groundwater recharge. Therefore, they were assessed, ranked, and reclassified based on their inherent properties and their capacity for aquifer recharge and permeable. The lithological map was classified and ranked into five distinct classes, as illustrated in Figure 35, with each class being ranked according to its suitability for groundwater recharge. Scoria fallout, Alluvium, and Entoto Volcanics, covering 2.87%, 15.2%, and 7.26% of the area, were given higher ranks of 5 and 4. These geological formations facilitate very high to high levels of water infiltration into the ground, rendering them moderately to highly productive aquifers.

The findings of the suitability classification for the study area align with the geological studies conducted in the catchment and other research studies, as documented by Solomon (2020), Yisak and Mikiyas (2022), and Tarekegn et al. (2022).

Table 30: Classified and ranked Lithology of Akaki Catchment

Thematic Map	Lithological Groups	Area(km2)	Area (%)	Rank	Suitability Classification
Lithology	**Qel**	8.8	0.6	1	Very Low
	Nwt/Nwt(a)/Qtp/Tetr/Tv2/Tv3/Twtr +Nwt(a)	259.0	17.7	2	Low
	Eaa/Npp/Nwp/Qb/Qs/Tcb+Ttb/Tpx +Nwp+Tdig/Tv1	821.9	56.3	3	Moderate
	Qus/Tev	327.8	22.5	4	High
	Lake/Qts	41.8	2.9	5	Very High

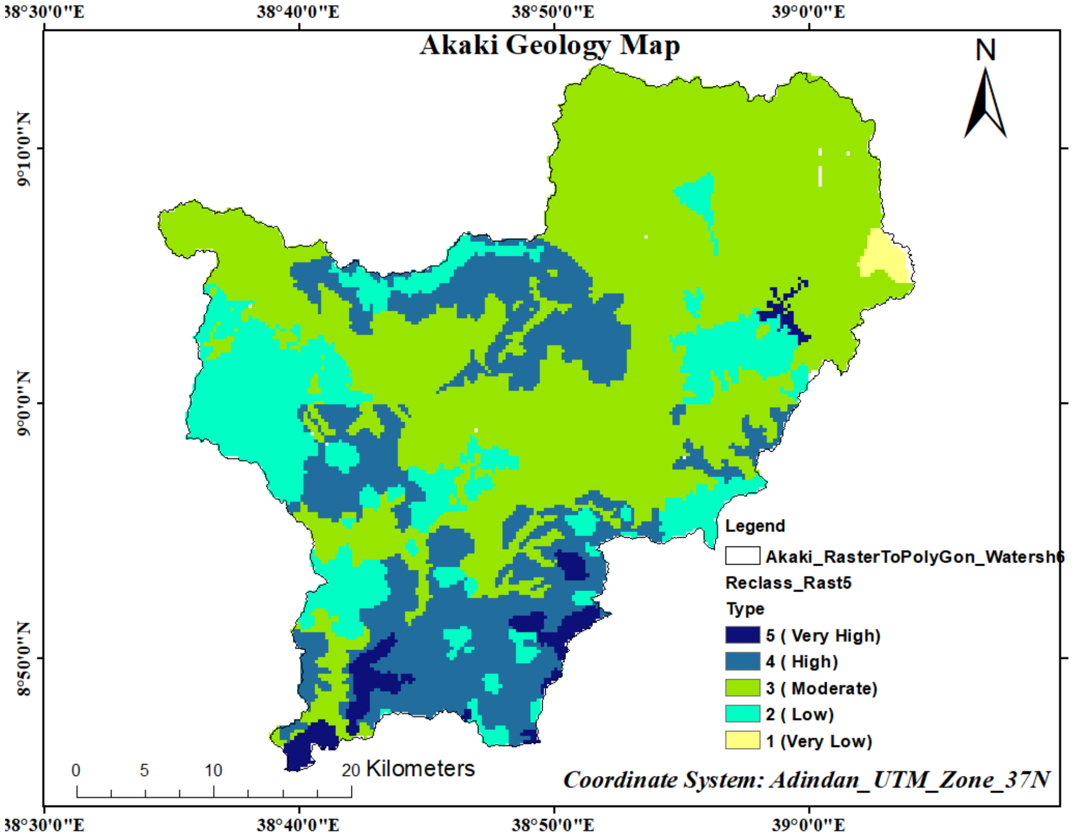


Figure 35: *Classified and ranked Lithology of Akaki Catchment*

4.2.8 Reclassified Topographic Position Index (TPI): The generated Akaki catchment TPI shown in Figure 23 Illustrates that the TPI ranges from -94.21 – 114.91. A positive TPI value indicates that the point of interest is situated higher than its surrounding areas, whereas a negative value signifies a lower position, and a TPI of zero indicates flat terrain (Sajad et al., 2021). TPI values are inversely related to surface water accumulation, thus prioritizing negative TPI values (Omid et al., 2019). The distribution illustrated in Figure 20 indicates a predominance of low recharge potential across the study area. Higher TPI values tend to occur near hill summits, while lower values are typically found in valley bottoms (Nair et al., 2017). TPI of the study area was classified (Table 31) as -94.21 to -16.3 (very high suitability), -16.29 to 1.74 (high suitability), 1.759 to 25.52 (moderate suitability), 25.53 to 75.52 (low suitability), and 75.53 to 114.91 (very low suitability). The TPI reclassification were based on existing literature or studies that have utilized TPI in similar contexts to gain insights into commonly used class breaks or thresholds (such as Bisrat et al.2020 and Yisak and Mikiyas (2022). Additionally the result of the TPI classification has been compared with other relevant spatial dataset, such as slope map of the study area (high slope areas had similar spatial distribution with very high TPI values i.e. northern part of the catchment and also similar spatial patterns to the remaining classes) which also assisted to identify patterns and relationships that validated the classification thresholds.

*Table 31: Topographic Position Index (TPI**)** Suitability Class for Groundwater Recharge Zone Identification*

Factor	**TPI (Index)**	**Area(km2)**	**Area (%)**	**Rank**	**Suitability Classification**
Topographic Position Index	**-94.21--16.3**	**2.9**	**0.2**	**5**	**Very High**
	-16.29-1.74	**63.3**	**4.3**	**4**	**High**
	1.75-25.52	**522.8**	**35.8**	**3**	**Moderate**
	25.53-75.52	**757.7**	**51.8**	**2**	**Low**
	75.53-114.91	**115.1**	**7.9**	**1**	**Very Low**

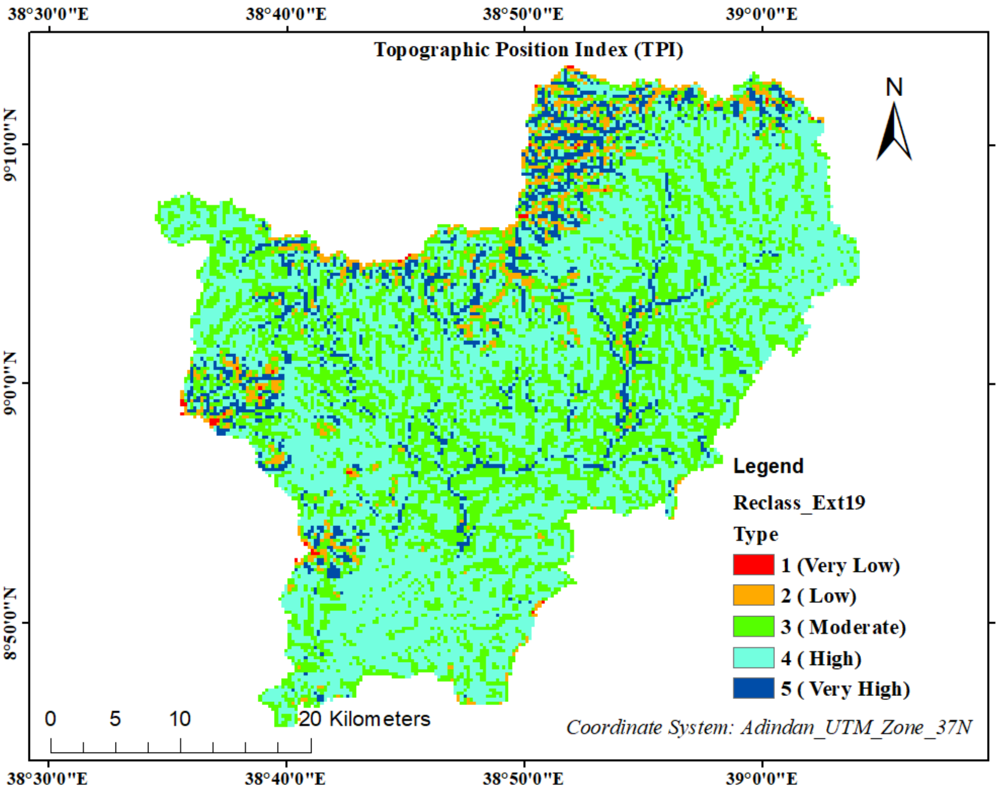


*Figure 36**:** Reclassified Topographic Position Index (TPI) of Akaki Catchment*

4.2.9 Reclassified Topographic Wetness Index (TWI): High TWI values are typically found in areas with low slopes and large upstream contributing areas, such as valleys, wetlands, and depressions. These areas are more likely to accumulate water because they receive runoff from higher elevations. Therefore high Topographic Wetness Index (TWI) value indicates an area that is likely to have a high potential for groundwater recharge. The Developed Akaki Catchment TWI value shown in Figure 24 ranges from 3.88 to 21.16. As mentioned earlier, given that the topographic wetness index (TWI) directly reflects the propensity of surface water accumulation at individual pixels within the catchment area, higher weights were attributed to pixels with elevated TWI values, while lower weights were assigned to those with lower TWI values (Omid et al., 2019).Similar to the Topographic Position Index (TPI), there is no universally standardized classification method for the Topographic Wetness Index (TWI). However, various studies may define specific threshold values for TWI to delineate different hydrological regimes or landforms. For instance Perennially Wet Conditions (TWI values 10 – 12) indicating consistent saturation or near-saturation, Intermittent Wetness(TWI values 5 -10) indicating occasional or seasonal waterlogging, but not as consistently wet as perennially wet areas and Dry Upland Areas (TWI values< 5), indicating relatively dry conditions or well-drained upland areas. Hence using this general guideline and based on review of literature or studies that have utilized TWI in similar contexts (Bisrat et al.2020 and Yisak and Mikiyas (2022), the TWI of the study area is classified as per Table 32. Additionally the result of the TWI classification has been compared with other relevant spatial dataset, such as Land use Land cover thematic map of the study area (Very high TWI values corresponded to water bodies of the study area and Very Low TWI values corresponded to the most upland part of the catchment i.e. due to lower upstream contributing area).

Table 32: Topographic Wetness Index (TWI) Suitability Class for Groundwater Recharge Zone Identification

Factor	TWI (Index)	Description	Area(km2)	Area (%)	Rank	Suitability Classification
Topographic Wetness Index	3.88-6.46	Very Low TWI	398.7	27.3	1	Very Low
	6.47-7.88	Low TWI	590.1	40.3	2	Low
	7.89-9.71	Moderate TWI	313.1	21.4	3	Moderate
	9.72-12.49	High TWI	123.8	8.5	4	High
	12.5-21.16	Very High TWI	37.1	2.5	5	Very High

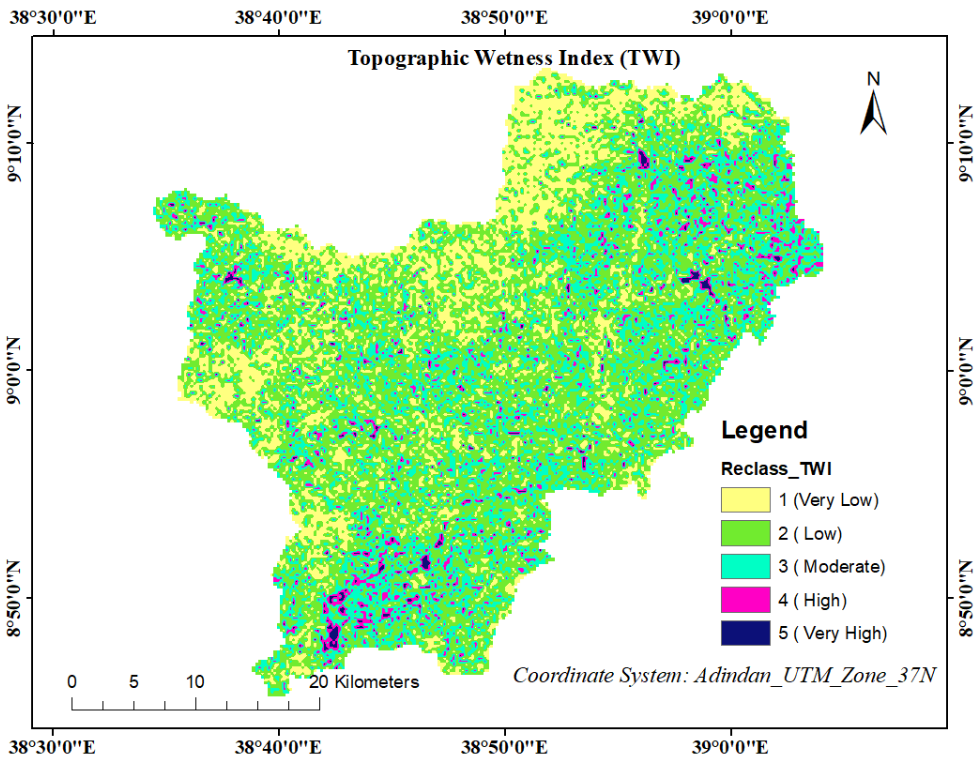


Figure 37: Reclassified Map of Topographic Wetness Index (TWI) ***for*** *Akaki Catchment*

4.3 Groundwater Recharge Zone Map

All thematic maps or layers were transformed into reclassified raster format and assigned normalized weights based on their influence on groundwater recharge potential. Likewise, each thematic layer's classes were assigned normalized ranks or weights As depicted in Figure 38, the overall potential groundwater recharge zones within the Akaki catchment were developed and categorized by integrating the index values derived from nine thematic factors (Rainfall, Land Use Land Cover (LULC), Soil Texture, Lithology Lineament Density, Slope, Drainage Density Topographic Position Index (TPI),and Topographic Wetness Index (TWI)) A weighted linear combination/weighted overlay (WOA) method were used in Arcgis spatial analyst tool to delineate the recharge zones.

GWRPZ = {[21.98%*(RFr)] +[19.46 %* (LuLcr)] + [17.71%* (Str)] +[13.29%* (Lir)] +[9.47%* (Ldr)] + [6.75 %* (Slr)] +[5.13 %*(Tpr)]+ [3.52 %* (Ddr)] + [2.43%*(Twi)]}……………. (21)

Where, GWRPZ = Groundwater recharge potential zone, whereas the coefficients = weight of each thematic map and r_i = reclassified rank of each pixel of the thematic map.

The integrated analysis of reclassified thematic layers revealed that the groundwater recharge potential zones within the study area are categorized into three main suitability classes: low, moderate, and high. These cover approximately 17.15%, 82.75%, and 0.10% of the total study area, respectively, as illustrated in Figure 38 and Table 33. The resulting groundwater recharge zone map indicates that a significant portion of the study area falls within the moderate groundwater recharge zone, encompassing 1192.69 km² of the total area. High and low groundwater recharge zones, covering 1.38 km² and 247.25 km² of the total study area, are also present in the catchment. Notably, no areas were classified as very high or very low recharge suitability zones within the study area. It's important to note that due to the limited range of values (3 in the case of soil texture and 5 classes in others), the output map of the weighted overlay analysis was constrained to only three classes: 2, 3, and 4, representing low, moderate, and high suitability classes.

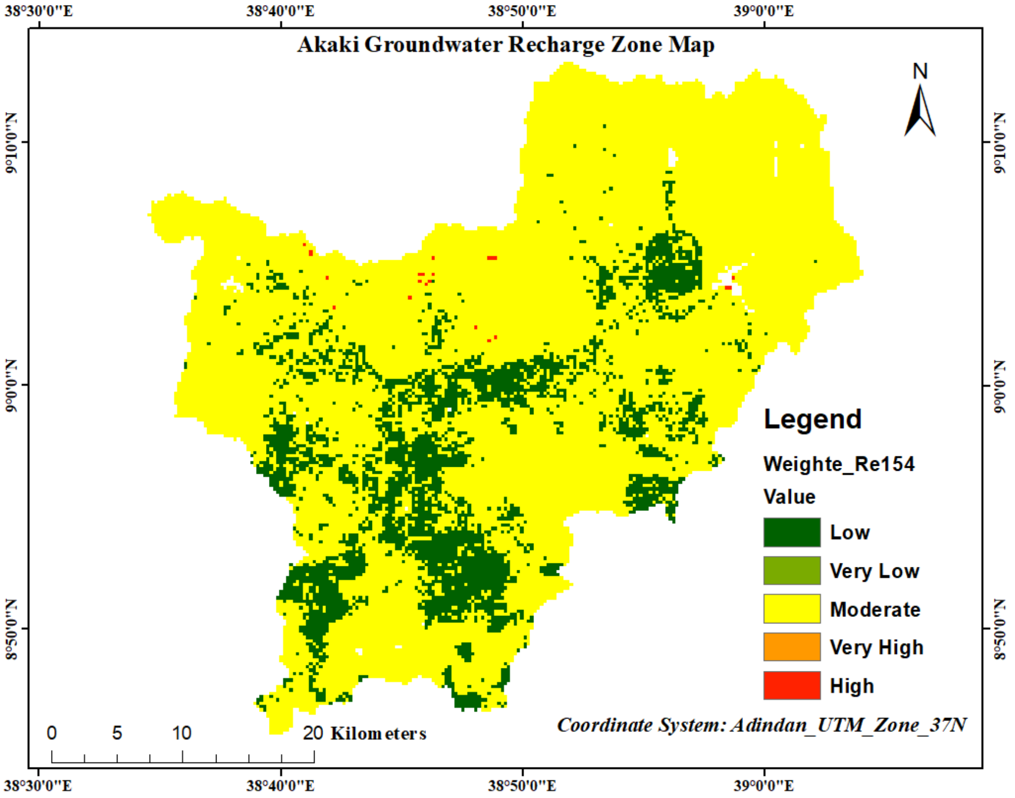


Figure 38: Map depicting zones of groundwater recharge potential

Table 33: Groundwater recharge zone indexes and areas

No.	**recharge index value**	**Classes of Recharge Zone**	**Area in km^2**	**Area in %**
1	-	Very Low	-	-
2	2	Low	247.25	17.15
3	3	Moderate	1,192.69	82.75
4	4	High	1.38	0.10
5	-	Very High	-	-

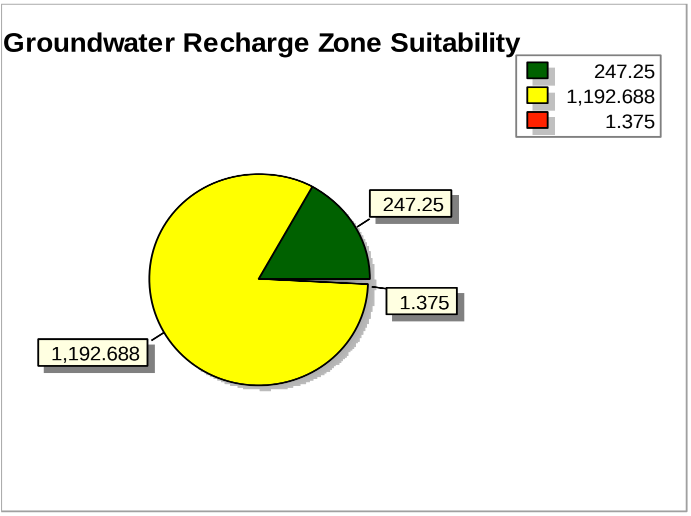


Table 34: Relative weights of thematic layers with their corresponding rank and scores

Thematic Layer/Parameter	Feature Class	Rank	Weight	Final Weight/Corresponding Score
Rainfall (mm)	961.82-999	1	21.98	21.98
	999-1046	2		43.96
	1046-1100	3		65.94
	1100-1195	4		87.92
	1195-1305.87	5		109.9
Land Use Land Cover	(Urban/ Built Up)	1	19.46	19.46
	(Bare/Sparse Vegetation)	2		38.92
	(Crop Land/Cultivated Land and Grass Land)	3		58.38
	(Shrub or herbaceous cover, flooded and Forest)	4		77.84
	(Water Bodies)	5		97.3
Soil texture	Clay	1	17.71	17.71
	Clay Loam	2		35.42
	Silty Clay Loam	3		53.13
Lithology	Qel	1	13.29	13.29
	Nwt/Nwt(a)/Qtp/Tetr/Tv2/Tv3/Twtr+Nwt(a)	2		26.58
	Eaa/Npp/Nwp/Qb/Qs/Tcb+Ttb/Tpx+Nwp+Tdig/Tv1	3		39.87
	Qus/Tev	4		53.16
	Lake/Qts	5		66.45

Lineament Density (Km/km²)	0 - 0.46	1	9.74	9.74
	0.46 - 1.21	2		19.48
	1.21 - 1.78	3		29.22
	1.78 - 2.51	4		38.96
	2.51 - 3.95	5		48.7
Slope (Degree)	0° - 2°	5	6.75	33.75
	2° - 5°	4		27
	5° - 8°	3		20.25
	8° - 17°	2		13.5
	17° - 44°	1		6.75
Topographic Position Index	75.53-114.91	1	5.13	5.13
	25.53-75.52	2		10.26
	1.75-25.52	3		15.39
	-16.29-1.74	4		20.52
	-94.21--16.3	5		25.65
Drainage Density(km/km^2)	0.07 - 0.09	5	3.52	17.6
	0.09 - 0.5	4		14.08
	0.5 - 1	3		10.56
	1 - 1.43	2		7.04
	1.43 - 2.08	1		3.52
Topographic Wetness Index	3.88-6.46	1	2.43	2.43
	6.47-7.88	2		4.86
	7.89-9.71	3		7.29
	9.72-12.49	4		9.72
	12.5-21.16	5		12.15

4.4 Validation of Groundwater Recharge Zone Map

For validation, over two hundred (approximately 230) water inventory points were gathered from the Addis Ababa Water and Sewerage Authority (AAWSA), covering various well fields including Akaki Phase-4(Koye), Akaki Phase 2, Akaki Phase 3A, Akaki Phase 3B, Legedadi Phase-1 Works, Legedadi Phase- 2 South Ayat North Fanta (SANF) and Addis Ababa Pocket., as detailed in Appendix Table (8).The Receiver Operating Characteristic (ROC) curve and its associated Area Under the Curve (AUC) were utilized as performance indicators to validate the groundwater recharge potential map created from thematic maps. Figure 39 shows the ROC curve of the groundwater recharge potential map obtained using MCDA technique.

In ROC Analysis, True Positive Rate (Sensitivity) represents the proportion of actual positive cases (recharge zones, in this case) that are correctly identified as positive by the model. In the context of validating a groundwater recharge zone index map, the true positive rate represents the sensitivity of the model in correctly identifying areas where wells are located within the predicted recharge zones. False positive rates represents the proportion of actual negative cases (i.e.non/low-recharge zones) that are incorrectly classified as positive by the model. In the context of validating a groundwater recharge zone index map, the false positive rate represents the rate of false alarms, or areas incorrectly identified as recharge zones where wells are not located. The area under the ROC curve (AUC) is a measure of how well a parameter can distinguish between two diagnostic groups.

The correlation between AUC and prediction accuracy can be encapsulated as follows (Yesilnacar and Topal, 2005; Naghibi et al., 2015): Poor (0.5–0.6); average (0.6–0.7); good (0.7–0.8); very good (0.8–0.9); and excellent (0.9–1). For this study using the Add Tool Box of ArcGIS, the ROC curve was constructed using the ARCSDM Tools. Accordingly, the calculate ROC curves and AUC Values of the ROC tool was used to construct the ROC and AUC using the Borehole well point validation data as true positives input and the Generated Recharge Map as classification Model input. The validation of result revealed that AHP has a very good prediction of AUC=**0.756**. Therefore, the results of groundwater recharge potential maps obtained using the AHP method has been considered as a **Good** prediction as per the above classification.

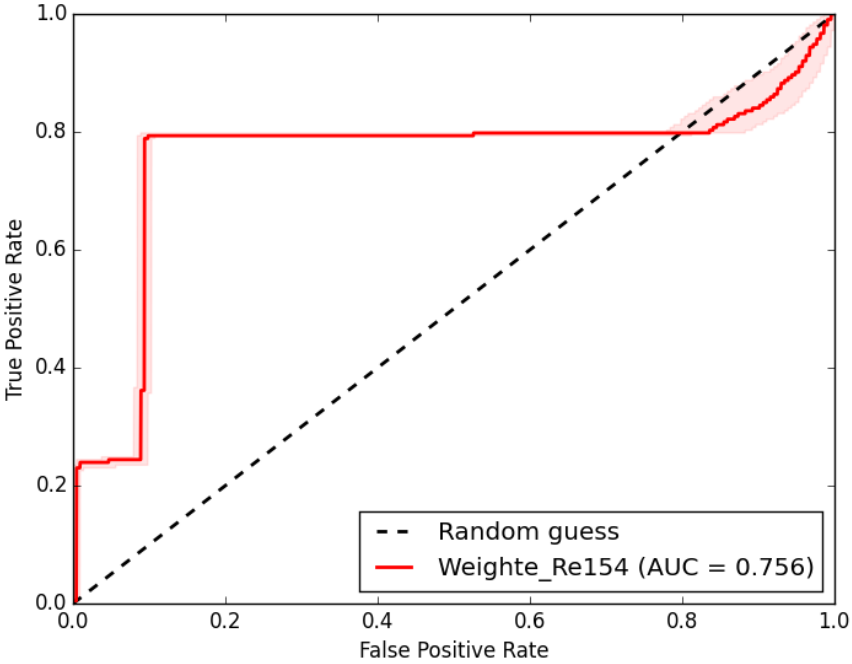


Figure 39: Receiver Operating Characteristic (ROC) curve for validation of predicted map.

Other than the quantitative validation, the potential groundwater recharge zone map underwent additional validation through the location of the 230 bore wells. As viewed on the validation map, out of the 230 bore well 201 well location falls over the moderate and 29 over low ground water recharge potential (Figure 40).

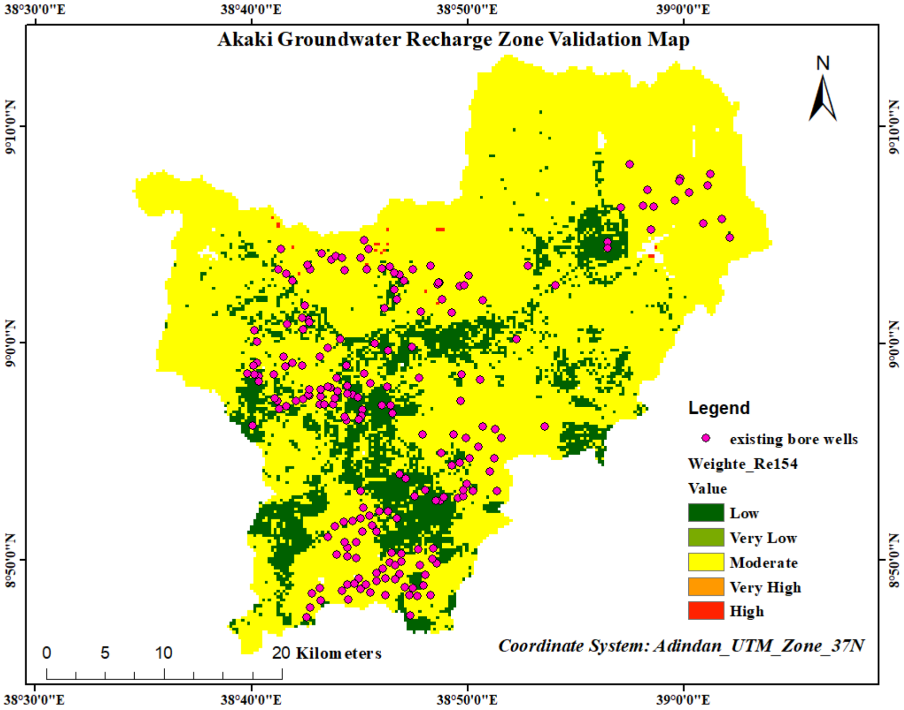


Figure 40: Validation map of Groundwater Recharge potential zone map

4.5 Sensitivity analysis

In Multi-Criteria Decision Analysis (MCDA), sensitivity analysis encompasses a range of methods aimed at assessing the uncertainty level in the output of the model and the significance of input parameters such as weights and criteria values. The key sources of uncertainty in Geographic Information System (GIS)-based MCDA lie in these variables—criterion values and weights. Conducting sensitivity analysis leads to the establishment of a more dependable decision-making rule for site suitability selection and serves to illustrate how altering criterion weights impacts the spatial distribution of suitability mapping. Accordingly, Sensitivity analysis was conducted in this study to evaluate how each factor impacts the groundwater recharge potential zone within the study area. This analysis utilized the Analytic Hierarchy Process (AHP) and involved systematically removing individual thematic layers. By removing one thematic layer at a time, it is possible to identify the critical layers that significantly affect the output map, specifically the groundwater recharge potential. Initially, a single criterion was removed, followed by updating the pairwise comparison matrix of the remaining criteria to redistribute their weights accordingly (Appendix table 9). Subsequently, the Weighted Linear Combination (WLC) method was applied to derive new overall values for all alternatives. Several combinations of weights were computed, and the resulting suitability maps were compared to a base map. The smaller the disparities between the base map and the maps generated with varying weights, the greater the robustness assumed for the assigned weights.

Table 35: New weights assigned by removing one criterion at a time

Factors	Rainfall	Land Use Land Cover	Soil Texture	Lithology	Lineament Density	Slope	Topographic Position Index	Drainage Density	Topographic Wetness Index
Rainfall	0	26	24	25	24	25	24	24	24
Land Use Land Cover	27	0	23	21	20	21	20	21	21
Soil Texture	24	24	0	20	19	18	18	18	18
Lithology	17	17	18	0	15	14	13	13	13
Lineament Density	12	13	13	12	0	10	10	10	9
Slope	8	8	9	8	8	0	7	7	6
Topographic Position Index	6	6	7	6	6	5	0	5	5
Drainage Density	4	4	4	4	4	4	4	0	3
Topographic Wetness Index	3	3	3	3	3	3	3	3	0

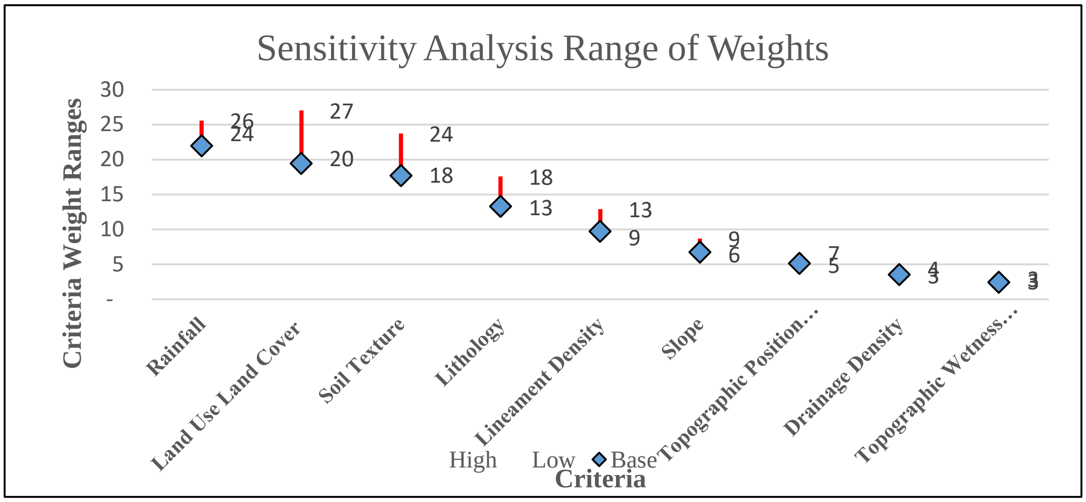
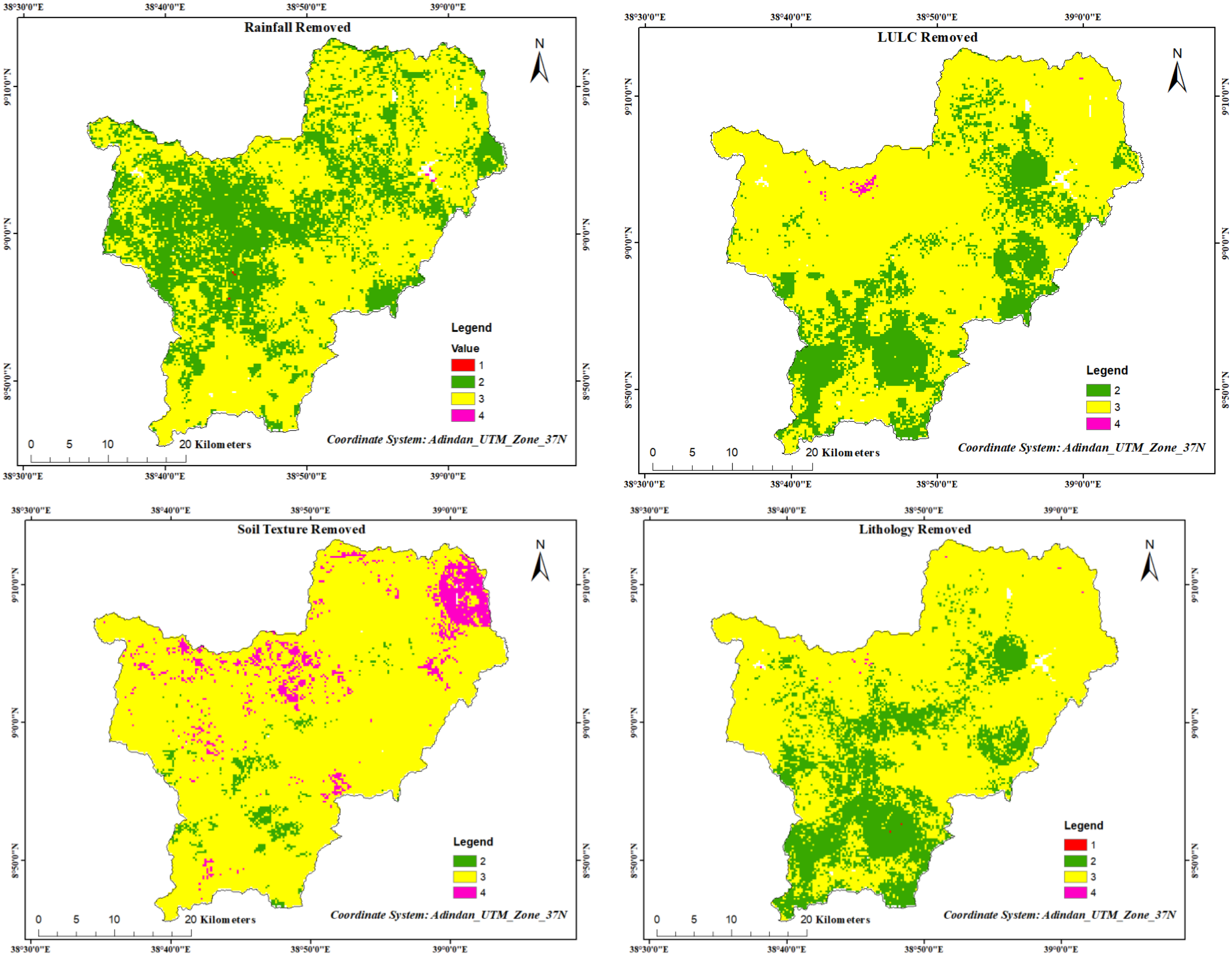
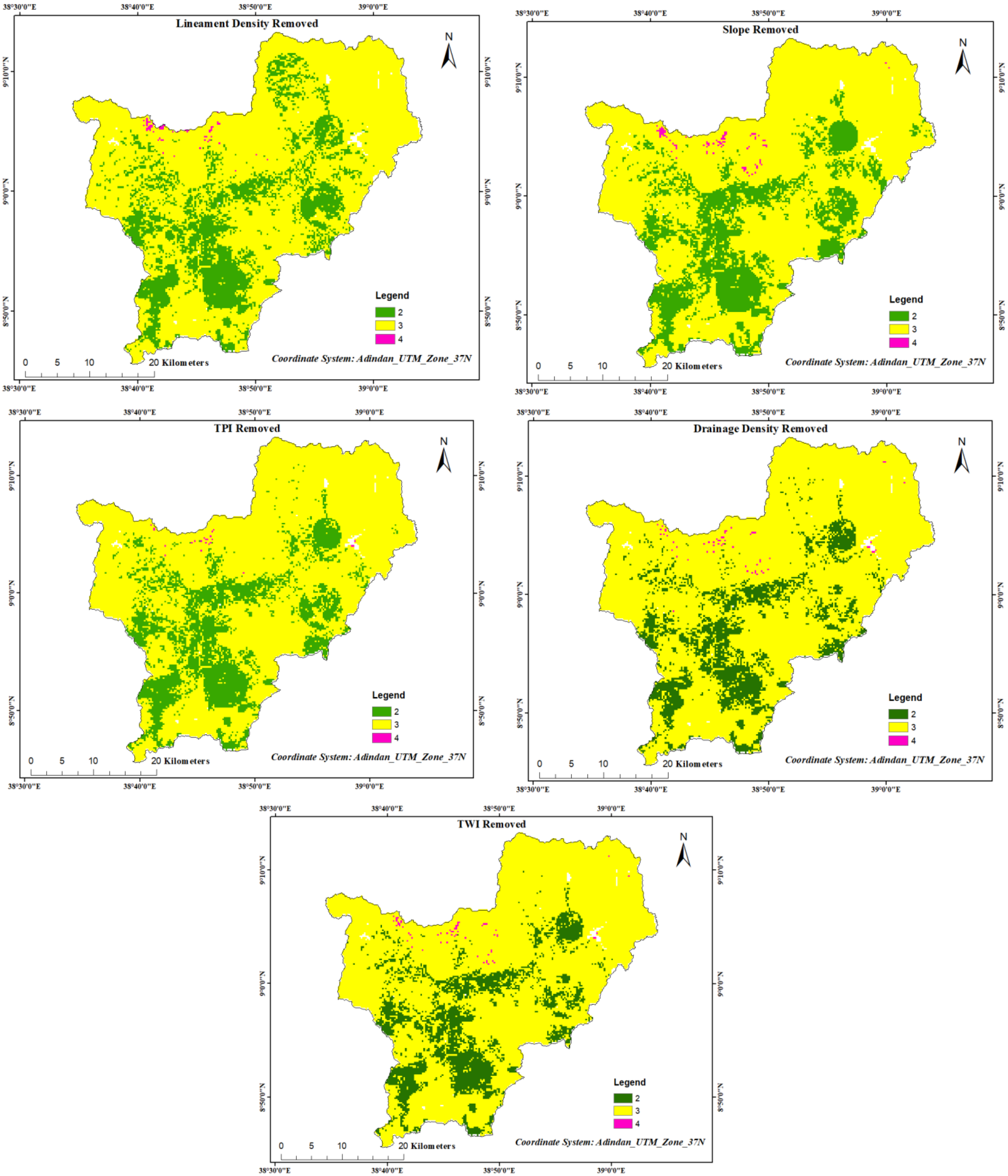


Figure 41: Range of weights of criteria used in the sensitivity analysis





Figures 42: Maps showing variability of spatial distribution of potential zones for each omitted map

Table 36: New Areas based on Distributed Criteria Weights

Factor/Suitability	Very Low Suitability	Low Suitability	Moderate Suitability	High Suitability
Rainfall	*0.19*	*530.44*	*910.25*	*0.44*
Land Use Land Cover		334.31	1,103.81	3.19
Soil Texture		*42.13*	*1,299.81*	*104.25*
Lithology	*0.13*	*369.94*	*1,072.38*	*1.06*
Lineament Density		333.94	1,106.88	3.88
Slope		337.25	1,098.00	6.06
Topographic Position Index		318.44	1,121.44	1.44
Drainage Density		234.44	1,203.13	3.75
Topographic Wetness Index		250.69	1,186.63	4.00

Accordingly, rainfall, soil texture and lithology criteria were found to be the most influential factors since the most significant shifts between suitability classes occurred following the removal of these factors, otherwise the sensitivity analysis yielded consistent outcomes for the site suitability maps across various weighting schemes listed in table 35. In the rainfall and lithology scenario, the removal of these criterion resulted in shifts of both low and moderate suitability classes as indicated in figure 42 and areal changes table 36 above. The second most pronounced shift occurred when the soil texture criterion is eliminated, leading to significant lowering of low suitability area and increment of moderate and high suitability area as indicated in figure 42 above.

4.6. Preliminary Identification of Suitable Artificial Groundwater Recharge Mechanisms

Since artificial recharge structures vary greatly depending on the site (Central Groundwater Board, 2007; Chowdhury et al., 2010), thorough scientific assessments are essential to determine the suitability of an area for their implementation (Russo et al., 2014; Raicy and Elango, 2017).

After identifying the suitability indexes of groundwater recharge, the subsequent step involves selecting the suitable techniques for replenishing the aquifer. The initial phase of this process entails synthesizing all pertinent groundwater data.

According to (Central Groundwater Board, 2007) the following detailed studies are necessary before implementation of artificial groundwater recharge schemes.

1. **Hydro meteorological Studies**: Analysis of rainfall amount, duration, daily and hourly rainfall intensity, and rainfall variability.
2. **2 Hydrological Studies:** Source water availability, infiltration characteristics of major soil types and various land use categories.

3. Hydrogeological Studies: detailed characteristics of regional hydrogeology and aquifer Characteristics, behavior of ground water levels, Ground water potential, and Ground water flow pattern and hydraulic connection between ground water and surface water bodies.

4 Hydro chemical Studies: Quality aspects of source water for artificial recharge, Spatial and temporal variations in groundwater quality.

In this study an attempt has been made to create a map illustrating the types of artificial recharge structures and highlighting the optimal sites for their placement. The proposed structure locations are preliminary, requiring further evaluations before final decisions can be made. Accordingly, sample locations and methods have been located on the map (Figure 43&44) based on evaluation of the specific recharge method against Topographic Slope (**Slope Map**), Stream Order (**Drainage Density map**), Soil Type(**Soil Texture Map**), Aquifer Type and **Rainfall Map**/Distributions (Appendix Table 10). The Manual on Artificial Recharge of Groundwater Prepared by Central Groundwater Board of India (CGWB 2007) was used as a general guideline to recommend the structures .Accordingly, as per appendix Table 10. Bench Terracing and Contour Trenches, Check Dams and Recharge Shafts are recommended as per the indicated locations on Figure 43 and Gravity Head Recharge Wells (Figure 44) are recommended as per the evaluations on the mentioned appendix.

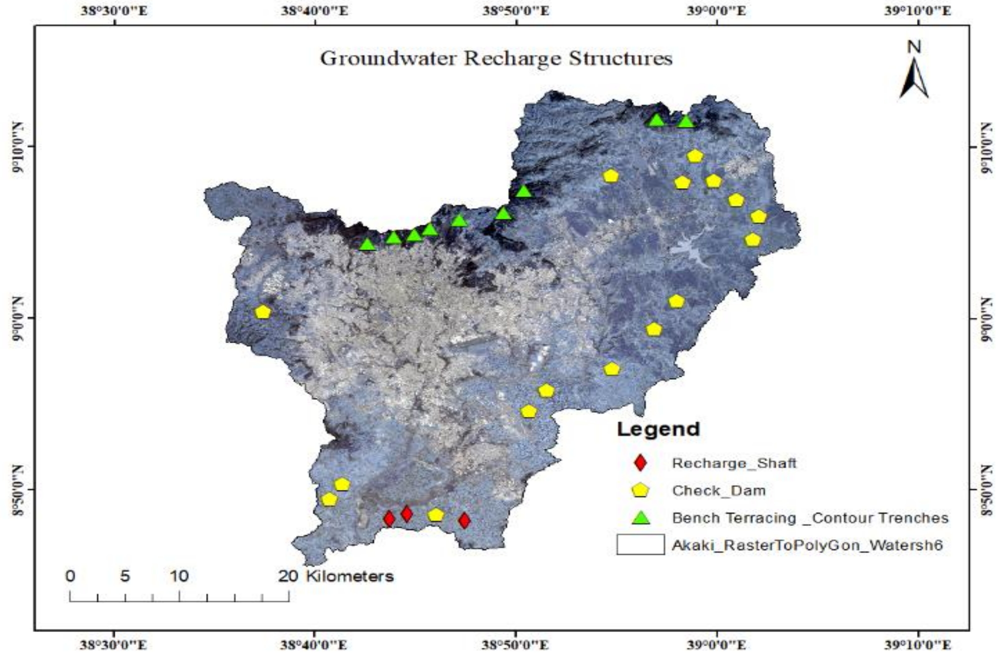


Figure 43 Recommended Artificial Recharge Structures and Sample Locations

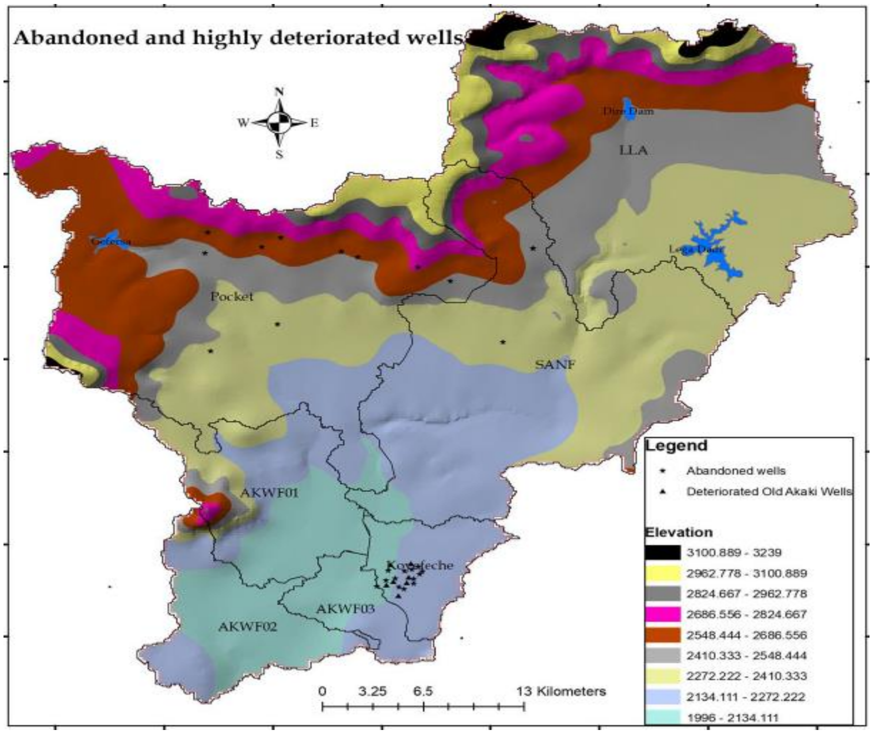
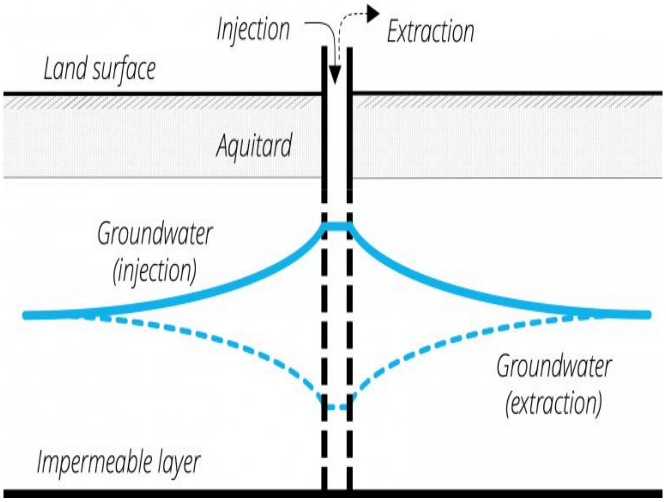


Figure 44: Location of Abandoned and yield deteriorated wells to be used for Gravity Head Recharge (Adopted from Debebe M, 2020)

4.7 Managed Aquifer Recharge (MAR) Method Selection through INOWAS Platform

To streamline the potential Managed Aquifer Recharge (MAR) options for the study area, the online INOWAS platform (INOWAS, 2021) was also employed. INOWAS has a comprehensive database of previously published MAR suitability studies. Decision-makers have the flexibility to apply various filters to locate desired information, such as literature on specific MAR techniques, global locations where a particular MAR method is practiced, and the suitability of MAR methods based on specific conditions. By specifying attributes of the study area, such as soil type, land use, MAR objectives, and the typical scale of the study, INOWAS offers recommendations for appropriate MAR methods derived from its MAR studies database (Sallwey et al., 2019).Accordingly, the MAR techniques recommended by the platform were Aquifer storage and recovery (ASR) and Aquifer storage, transfer, and recovery (ASTR) after specifying the general characteristic of the area such as having ephemeral, perennial, floods /runoff/rainwater as sources of water ,highly clayey soil, Land use such as Agricultural, Stream bed and barren lands, Residential, industrial and designated use for restoration of groundwater and agricultural uses and for large scale schemes.



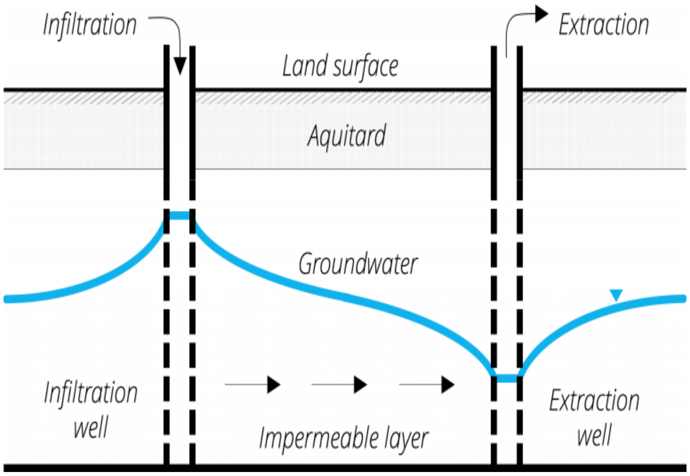


Figure 45: Aquifer Storage and Recovery

Figure 46: Aquifer Storage, Transfer and Recovery

4.8 Discussions

4.8.1 Identified factors influencing recharge of groundwater

In the present study, factors influencing groundwater recharge zones were identified and selected based on past studies considering three criteria's 1) factor usage, 2) significance of factor and 3) accessibility of the data. Accordingly nine factors were identified and selected as these factors had high contribution in the determination of groundwater recharge potential of the catchment. The relative weights of the thematic layers are determined using a Pairwise Comparison Matrix (PCM) method, informed by a literature review and consultations with experts. Criteria are weighted according to their recharging potential through pairwise assessments, and the values of various factors are normalized to establish a unified scale, ensuring positive correlation among all thematic layers.

Table 37*:* Summary of Factors weight

Factors	***Weight***
Rainfall	21.98
Land Use Land Cover	19.46
Soil texture	17.71
Lithology	13.29
Lineament Density	9.74
Slope	6.75
Topographic Position Index	5.13
Total	3.52

The primary determinants influencing the aquifer's recharge potential were rainfall, land use/land cover, and soil texture, collectively accounting for approximately 60% of the total weighting. The interaction among factors influencing groundwater recharge potential is complex, with rainfall patterns, lithological characteristics, topographic features, and land use practices interplaying to determine the effectiveness of recharge. For example, in a region with high rainfall, gentle slopes, permeable lithology, and vegetated land cover, groundwater recharge potential may be high due to favorable conditions for infiltration and minimal runoff. Conversely, in areas with steep slopes, impermeable lithology, and intense land use changes, recharge potential may be lower due to rapid runoff and limited infiltration opportunities.

For this study the maps were reclassified into five classes (four in the case of soil texture) based on recharging potentiality. Ultimately, a weighted index map of the study area was generated within the GIS framework, integrating nine thematic layers utilizing the Weighted Overlay Analysis (WOA) method.

Table 38: Reclassified ranges of thematic maps

Factors	Suitability class				
	1	2	3	4	5
R.F	961.82-999	999-1046	1046-1100	1100-1195	1195-1305.87
LULC	(Urban/ Built Up)	(Bare/Sparse Vegetation)	(Crop Land/Cultivated Land and Grass Land)	(Shrub or herbaceous cover, flooded and Forest)	(Water Bodies)
ST	Clay	Clay Loam	Silty Clay Loam		
LI	Qel	Nwt/Nwt(a)/Qtp/Tetr/Tv2/Tv3/Twtr+Nwt(a)	Eaa/Npp/Nwp/Qb/Qs/Tcb+Ttb/Tpx+Nwp+Tdig/Tv1	Qus/Tev	Lake/Qts
L.D	0 - 0.46	0.46 - 1.21	1.21 - 1.78	1.78 - 2.51	2.51 - 3.95
SL	17° - 44°	8° - 17°	5° - 8°	2° - 5°	0° - 2°
TPI	75.53-114.91	25.53-75.52	1.75-25.52	-16.29-1.74	-94.21--16.3
D.D	1.43 - 2.08	1 - 1.43	0.5 - 1	0.09 - 0.5	0.07 - 0.09
TWI	3.88-6.46	6.47-7.88	7.89-9.71	9.72-12.49	12.5-21.16

4.8.2 Summary of key characteristics of recharge zones

The weighted index map of the study area, created through the integration of nine thematic layers using the Weighted Overlay Analysis (WOA) technique in the GIS environment, reveals that the catchment area is divided into three PARZ zones: high, moderate, and low. The distinguishing characteristics of these recharge potential zones are outlined as follows:

Table 39: Recharge Potential Zones and Key Characteristics

No	Recharge Potential	Key Characteristics
1	**High Recharge Zone**	Is localized to small portion of northern part of the catchment (1.38 km2). Due to insignificant coverage key characteristics are not distinct.
2	**Moderate Recharge Zone**	Are distributed in most western, central, north eastern south eastern, eastern and southern part of the study area and cover most part of the study area (82.75%). The area is characterized by Very low to Very High Precipitation per annum, flat to steep slope, very low to very high drainage density, cultivated/agricultural, grass land/forest and urban areas, clay and clay loam dominated soil texture. Quaternary Basalt(Qb), Basalt of Addis Ababa (Eaa), basalts, Pyroclastic rocks such as: welded tuff, ash, ignimbrite with interlayers of rhyolitic flow(Tpx) welded tuff, ash, ignimbrite with interlayers of rhyolitic flow(Tpx) having moderate recharge potential, Alluvium (Qus), and Entoto Volcanics such as trachyte lava flow with pyroclastic rocks interlayer with sediments (Tev) are among the major lithological units found in the area.
3	**Low Recharge Zone**	Are found along the southern, central, western and north eastern portion of the study area and sparsely distributed on the eastern and western parts. The areas are characterized by Low to Very Low Rainfall distribution, very low to high lineament density, undulating to steep slope, very high to moderate drainage density, cropland/ cultivated and urban and heavy clay soil. The lithological formations of the area is characterized by Pyroclastic Flows (Welded to Partially Welded) (Npp),Alluvium (Qus) ,Wechecha Trachytes Nwt (a),Pyroclastics and pumice fall deposits (Qtp) , Pyroclastic Flows Welded (Nwp) ,Addis Ababa Basalts (Eaa),Pyroclastic rocks such as welded tuff, ash, ignimbrite are present

According to a study by Bearbeitet von and Seifu Kebede, 2012 the majority of groundwater wells and springs at the foot of the Entoto Mountain have higher tritium content than the majority of springs emerging within the mountain and concluded that this testifies that the Entoto Mountain is not feeding these wells and springs at its foot rather the infiltration at Entoto follows deeper flow paths and is not detectable in shallower aquifers at the foot of the mountain. Thus according to the study main recharge source for the aquifers at furthest distance (Akaki) from Entoto seems the central sector of the slope (foot of Entoto Mountain) or local vertical recharge based on ispotope contents.

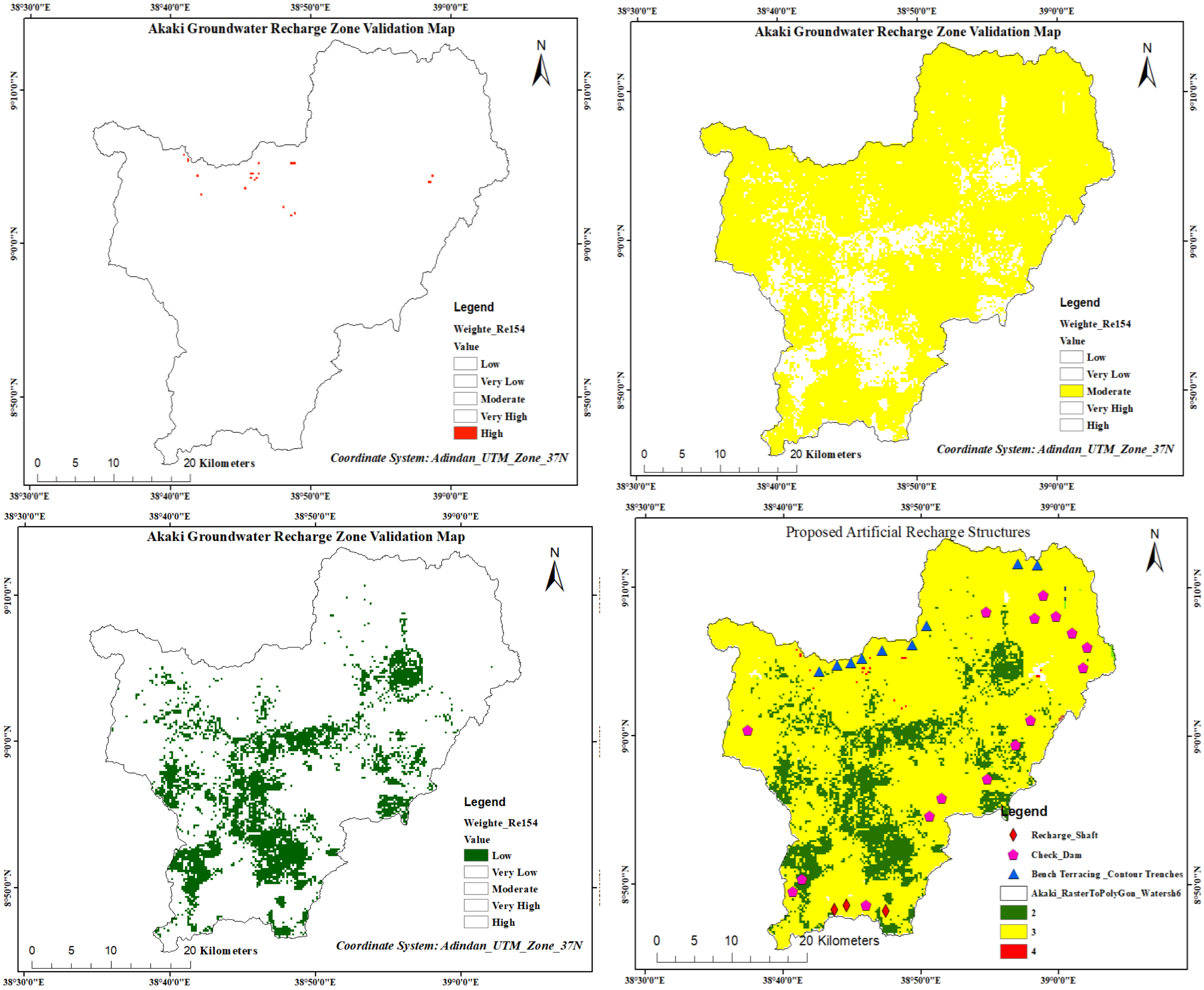


Figure 47: High, Moderate and Low Recharge Potential Zones and Proposed ARS

4.8.3 GIS, AHP and R.S Utilisation for Artificial Recharge Implementation in Study Area

The identification of potential AGRZs is essential for implementing AGR techniques in the study area. From the study's standpoint, GIS, RS, and AHP methods have proven to be effective in preparing, analyzing, and integrating thematic layers of surface and subsurface features to map groundwater recharge sites. In this research, GIS technology was employed for the preparation of thematic layers, spatial integration/ overlay into a unified layer, and analysis of each factor affecting groundwater recharge. It possesses the capability to classify the study area into various groundwater recharge potentials. The validation of identified groundwater recharge potential zones was conducted using existing borehole data within the GIS environment.

Bench Terraces and Contour Trench Artificial Recharge Structures were found to be suitable for the main recharge areas of Entoto Ridge (North and North Eastern part) having 8% Slopes. Check Dams were found to be Suitable for Pervious, gentle Slopes ($<10^{o}$) and on 2nd and 3rd order streams. Gravity head recharge wells were another subsurface recharge methods proposed to be used at abandoned and yield deteriorated wells in the Catchment such as koyefeche wells and pocket areas. Recharge Shafts are also suitable to Akaki well field semi confined aquifer thickness having deeper groundwater depth.

5. CONCLUSIONS AND RECOMMENDATIONS

5.1 Conclusion

In this study, the combined use of GIS, RS, and MCDA was employed to delineate potential groundwater recharge zones in the Akaki catchment, Ethiopia and in order to use the identified sites for application of artificial groundwater recharge. The study has demonstrated that GIS and RS can be crucial for viable groundwater assessments.

- A spatial model was developed to delineate groundwater recharge potential zones using nine thematic layers: Rainfall, Land Use Land Cover, Soil Texture, Lithology, Lineament Density, Slope, Topographic Position Index (TPI), Drainage Density, and Topographic Wetness Index (TWI). GIS and AHP methodologies were utilized, assigning weights to each thematic layer based on their relative contribution to groundwater recharge while ensuring the consistency of these assignments.
- Based on the calculated weights, the primary factors influencing aquifer recharge potential were rainfall, land use land cover, and soil texture, accounting for approximately 60% of the total weight.
- weighted overlay analysis (WOA) of Arcgis was used to integrate the nine factors/ layers after making the necessary conversion of vector data to raster, projecting all thematic maps to the same projected coordinate system, reclassifying and resampling all layers to the same cell size (250mx250m resolution).
- Accordingly, the generated map is classified in to 3 indexes of potential zones, high (0.10%, which is 1.38 km2), moderate (82.75%, which is 1,192.69 km2), and low (17.15% which is 247.25 km2) of the total area. Additionally, the groundwater recharge potential distribution was assessed and the generated map were validated using borehole inventory data. The validation result obtained shows agreement between the generated groundwater recharge potential zone map and inventory borehole yield and was found to be 76%, which is in good agreement.
- In this study recommendations were also given on the appropriate artificial recharge mechanisms (as per the evaluations on the appendix table 10) and a map showing the types and best sites for the selected artificial recharge structures was prepared. However, the

locations of the proposed structures were of a preliminary nature and further detailed evaluations need to be taken for final decisions.

- Given the suitability of this technique for “sloping lands with surface gradients up to 8%” and the potential for increased infiltration and groundwater recharge, implementation of bench terraces can be prioritized in high and moderate recharge zones of the entoto ridge (North and North Eastern Parts of the catchment).Contour Trenches can also Complement bench terracing to further enhance rainwater harvesting.
- For Moderate Recharge Zones (most western, north eastern, central, south eastern, eastern and southern parts) check dams across small streams can be constructed in areas with gentle slopes to retain surface water and facilitate groundwater recharge. These structures are feasible and effective in both hard rock and alluvial formations.
- For Low Recharge Zones (southern, central, western and north eastern portion of the study area) utilizing existing dug wells and tube/bore wells as recharge wells (Gravity Head Recharge Wells) particularly in abandoned or yield-deteriorated wells. This approach provides a cost-effective mechanism for artificial recharge in areas with desaturated aquifers due to over-exploitation of groundwater resources.
- Implementing recharge shafts in areas where aquifers are located deep below the ground surface and overlain by poorly permeable strata can also augment recharge into phreatic aquifers with deeper groundwater depths.

In conclusion, integrating GIS and RS techniques has proven to be highly efficient, useful, and both time- and cost-effective. This study has successfully demonstrated the application of remote sensing and GIS technology for mapping groundwater recharge potential zones and identifying suitable sites for artificial recharge. This comprehensive approach offers a valuable platform for decision support, aiding planning authorities and stakeholders in implementing water resource management plans.

5.2 Recommendations

Based on the study's findings and the insights gained, the following recommendations and future works are outlined below:

- Future research could focus on refining and improving the methodologies for delineating potential Artificial Groundwater Recharge Zones (AGRZs). The research has the potential to be extended by using other MCDA and soft computational analysis (SCA) methods such as Multi Influencing factor, Frequency Ratio, Fuzzy Logic, ANN and Boolean Logical Operators to give weights to the map layers and can be cross validated.
- It is recommended to use satellite images with higher spatial resolution in future studies i.e. for preparation of thematic layers of factors influencing groundwater recharge. Future studies could explore the use of emerging RS technologies to gather more detailed and precise information about the study area.
- Due to difficulty in mapping landform of the area, geomorphological layer was not considered in this study despite its criticality and other important factors such as elevation, amount of available source water etc... can be added in future studies.
- For optimizing the design and placement of the proposed Artificial Groundwater Recharge (AGR) structures, it is necessary to conduct a detailed hydrological modeling (to estimate the potential increase in groundwater recharge and subsequent availability) and field investigation /in situ studies to determine the most suitable locations and configurations for these structures within the study area. These studies would consider factors such as recharge rates, infiltration capacities, aquifer characteristics, groundwater levels and storage capacities. Source water quality study must also be conducted before implementation of the schemes.
- After implementation of the schemes, it is necessary to assess the effectiveness and long-term performance of AGR structures in enhancing groundwater recharge by monitoring groundwater levels, environmental impact, water quality, and recharge rates over time to evaluate the impact of AGR interventions on groundwater replenishment and sustainability.
- The generated map can be a valuable tool for ground water resource management and can serve as a guide for governmental/non-governmental organizations, water policy decision-makers, engineers, planners, and water managers in selecting suitable locations for groundwater management practices. while the results might aid in planning projected artificial recharge structures, the suitability maps should not be the primary basis for an explicit decision on MAR placement and operational strategies (due to the need for detailed investigations) but rather a guidance tool to focus on the sites for further investigation.

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Appendices

Appendix Table 1: Filled and Averaged Monthly Rainfall Data

Addis Ababa Bole (Latitude: 477874.22, Longitude992766.61, Elevation: 2354)

Year	Jan	Feb	Mar	Apr	May	Jun	Jul	Aug	Sep	Oct	Nov	Dec	Annual
1990	3.2	161.1	60.4	144.5	25.2	48.3	194.2	293.6	143	46.1	2.1	0	**1121.7**
1991	0.2	29.6	134.1	15	7.7	107.5	279.4	287.9	123.1	4.4	2.1	0	**991**
1992	14.5	28	35	58.6	55	82.2	254.8	223.3	157	64.4	2.2	0.4	**975.4**
1993	11.7	52.1	11.6	168.3	91.5	157.2	209.5	291.7	190.1	24.1	0	0	**1207.8**
1994	0	0	52.9	70	29	112.4	242.3	199.3	99.4	0.5	11	0	**816.8**
1995	0	81.3	73.1	133.3	95.9	77.4	165.5	256.9	97	0	0	29.3	**1009.7**
1996	20.5	15.8	134.4	96	124.6	290.2	346.3	312.7	211.4	0.2	0.4	0	**1552.5**
1997	29.1	0	22.1	66.8	44.8	128	257	160.7	94.7	58.6	15.3	0	**877.1**
1998	66.6	40	43.8	99.8	197.7	111.6	270.7	236.8	173.4	139.4	0	0	**1379.8**
1999	4.4	0	35	17.8	30.5	104.6	294	270.5	62.8	127.1	0	0	**946.7**
2000	0	0	17.6	87.8	95.2	102.1	192.9	221.9	157.5	19.6	7.5	0	**902.1**
2001	0	10.3	174.3	14.8	116.7	166	289.4	207.3	113.3	10.6	0	0	**1102.7**
2002	30.6	25.9	79.4	36.6	49.6	115.5	213.9	233.6	72.6	0.5	0	32.8	**891**
2003	4.8	34.2	48.9	111.5	18	111	204.3	238.4	130.2	4.6	0	33.3	**939.2**
2004	26.1	11.7	32.4	142.8	7	114.5	240.6	230.1	122.1	50	0.6	0	**977.9**
2005	55.4	14.1	41.8	116.2	164.6	159.1	174.3	248	77.6	25.8	7.2	0	**1084.1**
2006	2	36.6	107.8	93.9	37.8	115.1	313.2	331.1	132.5	35.9	0	0	**1205.9**
2007	9.9	21.3	61.1	86.8	134	157.6	191.3	305.4	130.9	37.2	0.1	0	**1135.6**
2008	0	0	0	34	75.3	73.1	295.1	259.1	192.7	22.2	53.1	0	**1004.6**
2009	40.9	0	12.4	46.1	52	77.5	238.2	269.5	86.1	42.4	2	79.9	**947**
2010	0.4	115.2	75.6	159.5	94.7	107.2	320.2	138.8	105	0	13.8	15.7	**1146.1**
2011	3.4	13.6	27.9	48.2	86	148	183.1	296.5	141.3	0	11.9	0	**959.9**
2012	0	0	34.5	75.1	58.5	72.8	228.8	281.6	176.9	1.2	0	0.1	**929.5**
2013	0	0	63.5	114.4	78.5	101.4	157.6	270.2	126.7	45.3	3.2	0	**960.8**
2014	0	41.7	29.7	33.7	62.1	41.8	179.7	253.6	95.1	34.8	0	0	**772.2**
2015	0	0	21.3	35.6	193.6	155.7	163	203	112.3	0	1.3	1.8	**887.8**
2016	54.6	12.4	67.7	137.5	124.1	104.4	162.9	226.6	132	17.6	3.4	0	**1043.2**
2017	0	13.6	56	26.6	103.5	44.1	217	241.7	260.5	5.3	0	0	**968.3**
2018	0	30.8	21.7	145.7	87.1	198.1	259	352.8	53.5	51.5	5.2	0	**1205.4**
2019	0	0	51.9	109	72.4	125.1	417	352.3	230.7	10.2	35.2	0	**1403.8**
2020	3.2	3.5	79.5	97.7	104.6	186.4	354.2	363.2	403.7	27.4	0	1.8	**1625.2**
2021	0	31.3	0	159.9	78.6	1259	235.6	258.2	163.4	29	0.8	0	**1082.6**
Average	***11.9***	***25.8***	***53.4***	***87.0***	***81.1***	***119.4***	***242.0***	***259.9***	***142.8***	***29.2***	***5.6***	***6.1***	**1064.2**

A.A Observatory (Latitude: 472248.08, Longitude 996952.4, Elevation: 2386)

Year	**Jan**	**Feb**	**Mar**	**Apr**	**May**	**Jun**	**Jul**	**Aug**	**Sep**	**Oct**	**Nov**	**Dec**	**Annual**
1990	0.8	155.9	59.2	106.4	20	88.8	218.7	268.6	184	16.2	6	0	**1124.6**
1991	0	74.5	106.6	34.7	58.0	198.5	248.9	262.6	126.4	3.4	0	50	**1163.6**
1992	20.2	33.7	20.2	41	52	109.1	248.5	294.7	209.4	69.7	0	2.9	**1101.4**
1993	10.8	67.2	16.1	157.9	97.2	208.3	274	426.5	243.3	62.1	0	4.5	**1567.9**
1994	0	0	82.4	82.3	63.3	123.4	308.9	225	142	0.5	14.7	0	**1042.5**
1995	0	69	41.5	174.4	68.2	102.9	190.2	314.9	136.1	0	0	49.1	**1146.3**
1996	28.1	5.2	106.8	128.2	122	258.5	266.4	338.7	294.2	0.2	0.2	0.1	**1548.6**
1997	39.2	0	24.5	51.3	38.5	104	272.6	194.3	113.8	62.4	50.3	1.5	**952.4**
1998	55.2	20.5	49	48.5	154.2	124.4	285.4	260	213.6	126.9	0	0	**1337.7**
1999	2.9	0.3	28.8	16.3	23.8	119.6	279.5	305.3	88.4	75.4	0	0	**940.3**
2000	0	0	17.6	49.9	110	144.5	244.8	306.2	250.6	46.4	21.1	0	**1191.1**
2001	0	12.2	210.8	25	168	216.2	428	246.4	131.7	13.7	0	0	**1452**
2002	14.7	21	90.2	56.3	63.1	172.5	256.9	215.9	108.8	0.2	0	16.5	**1016.1**
2003	10.5	53.3	62.6	99.3	20.2	151.8	291.8	233.3	193.3	0.8	1.5	54.9	**1173.3**
2004	24.8	20.3	49.5	139.9	30.1	141.9	238.5	272.6	164	76.9	0	0	**1158.5**
2005	45.9	51.6	83.2	160.9	133.7	179.8	246	315.2	162.5	29.7	4.4	0	**1412.9**
2006	0.7	11.2	140.4	78.9	74.6	150.1	356.3	243.6	239.1	54	0.3	8	**1357.2**
2007	51.3	19.1	59.8	73.8	120.1	171.3	261.8	381.2	147.6	24.8	0	0	**1310.8**
2008	0	13	0	49.4	94.3	88.9	277	360.9	256.7	88.2	79.4	22.9	**1330.7**
2009	21.3	2.7	28.4	80.6	58.9	82.6	349.9	388.3	112.7	45.8	4.4	65	**1240.6**
2010	2.6	79.8	55.5	97.8	74.4	271.1	313.9	205.8	237.8	1.8	25.7	15	**1381.2**
2011	14.1	13.1	44.3	22.8	66.1	182	180.9	340.8	146	0	42.3	0	**1052.4**
2012	0	0	15.8	76.1	50.2	69.4	324.2	298	215.5	2.3	0	9.8	**1061.3**
2013	4.4	0	52.1	92.3	85	153.2	227.6	353.2	196.3	58.4	22.3	0	**1244.8**
2014	1.7	47.4	61.5	26.2	93.6	66.7	219.9	262.4	264.7	35	1.7	0	**1080.8**
2015	0	0	27.5	16.9	110.0	214.9	217	309.9	148.9	0	7.7	0.1	**1052.9**
2016	59.8	12.1	47.9	136.8	132.7	187.3	182.8	299.9	141.8	15.5	3.6	1.9	**1222.1**
2017	0	20.7	36.6	33.7	164.2	64.5	290.4	329.8	386	10.2	0	0	**1336.1**
2018	0	32.1	19	61.8	71.8	187.96	331.6	284.1	49.9	48.8	15.1	0	**1102.2**
2019	0	9.2	36.7	174.8	117.8	159.2	339.4	205	222.1	50.2	20.1	11	**1345.5**
2020	0	1.4	66.6	133.8	92.9	159.7	337.7	324.8	242.7	51.3	0	2.5	**1413.4**
2021	0	41.8	5.2	124.8	84.2	131	277.2	205.2	211	30.7	0	0	**1111.1**
Average	***12.8***	***27.8***	***54.6***	***82.9***	***84.8***	***149.5***	***274.6***	***289.8***	***186.9***	***34.4***	***10.0***	***9.9***	**1217.9**

Akaki (Latitude: 476690.05, Longitude 980707.55, Elevation: 2057)

Year	Jan	Feb	Mar	Apr	May	Jun	Jul	Aug	Sep	Oct	Nov	Dec	Annual
1990	7.7	120.6	48.4	159.1	37.3	78.9	280.7	222.9	107.3	5.8	1.2	0	1069.9
1991	0	37.6	62.4	11.6	45.6	90.4	263.7	308.5	113.3	4.4	0	56.5	994
1992	33.5	24.2	30.5	15.5	25.6	100.4	218.4	276	86.7	43.3	0.2	0	854.3
1993	1.2	53.9	5.6	118.4	54.6	116.5	218	251.5	118.3	20.5	0	0	958.5
1994	0	0	62.7	72.2	20.2	131.2	219.3	181	94.5	0	11	0	792.1
1995	0	25.4	62.7	102.1	20.9	95.7	279	242.3	79.5	0	0	4.8	912.4
1996	15.3	0.3	79.7	38.8	90.5	240.1	292.5	234.1	119	1.9	0	0	1112.2
1997	27.6	0	29.5	102.7	25.2	57	203.6	203.4	82.5	114.9	10.3	0	856.7
1998	32.7	30.2	19.6	69.3	159.9	116.9	207.8	280	118.5	36.9	0	0	1071.8
1999	1.3	1.8	91.8	12.1	45.4	92.8	282.6	300.7	61.7	65	0	0	955.2
2000	0	0	29.1	93	64.9	100.1	188.9	210	124.1	17.2	23.4	3.8	854.5
2001	0	20.7	121.2	23.6	118	142.6	257.5	145	64.9	2.2	0	0	895.7
2002	31.1	10.5	87.8	53.9	76.6	108	167.1	166.3	52.3	0	0	17.7	771.3
2003	19.6	24.8	23.9	114	1.4	125.4	325.1	307.4	113.4	0	0	40.8	1095.8
2004	15.6	15.8	61.4	154.5	15.4	95.2	150.3	189.1	80.9	4.8	3.4	0.7	787.1
2005	28.8	7.3	47.9	112.2	140.7	139.9	218.7	231.4	152.7	9.1	15.2	0	1103.9
2006	2.6	44.2	56.3	79.7	22	84.3	276.4	262.6	148.1	38	0	3.2	1017.4
2007	34.2	24.7	25.6	96.8	64.6	132.7	254.2	221.8	148.5	14.3	1.3	0	1018.7
2008	0	0	0.6	34.2	62.4	140.2	253.5	252.3	197.1	7.2	64.8	0	1012.3
2009	60.2	0	10	118.7	47.7	63.5	235.3	322.4	71.3	32.8	4	16.8	982.7
2010	0	63.8	126.2	170	95.2	164.8	334.4	169.8	154.1	5.2	14.8	7.8	1306.1
2011	0	2.5	45.2	20.7	128.7	60	204.3	304	194.5	0	4.7	0.0	964.6
2012	0	0	59.6	61	26.1	80.6	228	243.9	122.9	0	0	0	822.1
2013	0	0	77	89.1	73.4	111.5	179.6	242.4	142.5	20.6	0	0.2	936.3
2014	0	39.4	76	13.9	66.3	52.6	176.8	281.6	115.3	52.3	0	0	874.2
2015	0	0	13.7	2.3	96.5	158	187.8	247.5	70	0	14.5	0	790.3
2016	0	46	39.3	184.5	134.2	105.7	232.4	165.7	119.1	16.2	9.3	0	1052.4
2017	0	36.5	46.1	22.5	70.3	65.7	213.9	124.4	177.2	0	0	0	756.6
2018	0	19.8	13.2	84.5	47.5	165.7	238.3	274.1	47.3	13.2	6.5	0	910.1
2019	0	32.7	4.2	36.4	79.5	137.7	238.8	220.3	243.8	2.6	21.3	11.2	1028.5
2020	0	0	76.7	75.2	45.6	122.6	314.9	313.6	105.6	3.8	0	1.3	1059.3
2021	0	32.1	0	115.5	120	77.4	223.3	184.8	92	310.4	2.7	0	1158.2
Average	*9.7*	*22.3*	*47.9*	*76.8*	*66.3*	*111.1*	*236.4*	*236.9*	*116.2*	*26.3*	*6.5*	*5.2*	961.7

Intoto (Latitude: 469780.52, Longitude 1004113.64, Elevation: 2903)

Year	Jan	Feb	Mar	Apr	May	Jun	Jul	Aug	Sep	Oct	Nov	Dec	Annual
1990	0	156.6	42.8	117.9	17.6	100.5	324.5	499.7	180.8	20.9	1.5	0	**1462.8**
1991	12.8	64.9	156.2	37.5	39	171.2	258.5	395.2	146.7	1.4	0	44.2	**1327.6**
1992	52.7	31.5	14.6	42.7	84.6	131.6	247.8	387	188.4	42.4	0.7	8.1	**1232.1**
1993	15.3	44.6	5.7	147.5	49	123.3	266.1	407.6	183.2	28.7	0	0	**1271**
1994	0	0	62.2	56	91	154.8	336.3	307.2	142.5	0.3	24.4	0	**1174.7**
1995	0	96.3	29.7	186.1	83.7	98	297	222.1	133.7	5	0.2	22.7	**1174.5**
1996	31.1	12.2	121.6	78.3	95.2	242.7	387.2	493.9	184.7	1.2	0.6	0	**1648.7**
1997	21.2	0	18.6	77.3	27.4	77.2	256.3	240.8	89.3	88.3	90	0.2	**986.6**
1998	25.3	25.3	45.2	47	149.5	149.2	369	376.3	204.8	44.5	0	0	**1436.1**
1999	15.8	6.3	34.9	25.4	37	127.7	283.1	280.3	105	58	0.2	0	**973.7**
2000	0	0	5.2	108	91.4	110.7	303.8	359.1	132.8	17.2	33.5	1.7	**1163.4**
2001	20.6	5.5	147.5	29.8	141.7	164.3	285.6	321.4	92.5	52.4	0	1.8	**1263.1**
2002	17.9	50.4	88.8	67.4	49.2	138.7	293.1	262.9	92.1	10.7	0	28	**1099.2**
2003	5.2	47.7	57.1	117.3	13.9	188	370.8	248.9	141.1	0	6.3	25.6	**1221.9**
2004	28.8	31.3	46.7	124.6	13.8	166	271.9	334.7	124.8	49.7	1.1	1.6	**1195**
2005	8.3	11.4	42.8	98.6	143.9	106.4	241.8	339.3	134.4	19.6	8.2	0	**1154.7**
2006	0.9	19.1	93.8	66.5	79.1	131.5	371.1	311.5	128.7	36.1	0.6	16.5	**1255.4**
2007	38.6	16.2	36.4	52.1	106.4	246.7	272.1	322.6	87	16.4	0	0	**1194.5**
2008	0	9.3	1.5	74.8	45.3	142.5	399.3	359.5	190.6	50.1	95.1	0.5	**1368.5**
2009	10.9	3.3	15.9	40.1	28.2	122.7	304.7	326.3	154.2	91.3	7.4	68.4	**1173.4**
2010	9.5	73.4	79.4	71.2	107.9	235.2	388.8	288.6	173.2	1.8	0	11.9	**1440.9**
2011	0	0	50.3	51.7	96.2	143.2	271.1	366	113.6	0	43.5	12.3	**1147.9**
2012	0	0	19.5	79.5	77.1	133.2	363	366.3	242.7	4.2	0.3	7.8	**1293.6**
2013	12.2	0	59.8	128.8	82.1	164.6	364.3	462.2	198.1	64.3	10.7	0.2	**1547.3**
2014	0	16.1	41.8	30.7	80.6	81.7	323.6	282.7	131.6	25.5	14	0.4	**1028.7**
2015	0	4.6	0	6.6	119.8	158.1	364.3	322.3	86.3	14.1	29.6	0.1	**1105.8**
2016	19.4	11.9	65.1	104	163	177.4	300.8	301.3	113.6	14.9	2.7	0.3	**1274.4**
2017	0	12.8	34	42.4	168.5	79	468.3	367.6	332.8	49.2	1	0	**1555.6**
2018	0	22.4	26.1	28.7	122.1	448.9	453.1	379.2	66.7	30	32.3	0	**1609.5**
2019	0	5.6	32.2	47.2	168.8	291.9	449.4	438.3	279.3	10.6	10.2	9.1	**1742.6**
2020	0.4	0	71.2	146.1	174.6	204.6	455.9	453.3	273.7	12	0.1	5.8	**1797.7**
2021	0	60.6	15.3	105.2	112.5	122.4	394.8	388.7	244.4	20.8	0	3.9493	**1468.6**
Average	***10.8***	***26.2***	***48.8***	***76.2***	***89.4***	***160.4***	***335.5***	***350.4***	***159.2***	***27.5***	***12.9***	***8.5***	**1305.9**

Sendafa (Latitude: 502362.15, Longitude 1011675.48, Elevation: 2558)

Year	Jan	Feb	Mar	Apr	May	Jun	Jul	Aug	Sep	Oct	Nov	Dec	Annual
1990	21.5	190.4	35.7	148.4	38.2	87.8	282.7	469.9	141.8	3.8	2.4	0	**1422.6**
1991	15.9	20.5	118.1	0.5	34.5	72.7	216.8	9.4	134.5	11.9	0	5.6	**640.4**
1992	10.7	46.5	1	67.7	67.5	69.6	253.2	357.9	151.6	55.5	0	0	**1081.2**
1993	4.3	105.2	0	106.3	59.6	184.6	457.2	353.2	153.8	13.7	0	0	**1437.9**
1994	0	0	0	64.1	11	130.7	337.7	184.1	122	0	6.4	0	**856.0**
1995	0	11.4	106.2	116.7	42.4	22.5	230.8	388.8	206.3	0	0	0	**1125.1**
1996	69.4	5.6	99.3	124.2	76.6	187.2	339.2	338.6	121.4	0	0	0	**1361.5**
1997	44.5	0	29.4	60	44.8	149.7	303.8	251.1	84.7	72	34.6	0	**1074.6**
1998	28.9	23.3	5.8	27	38.2	68.8	359.1	289.7	152	98.9	0	0	**1091.7**
1999	0	1.2	56.3	11.8	25.4	144.7	441.6	365.2	111.0	79.6	0	0	**1236.8**
2000	0	0	35.5	44	87.9	166	352.2	373.4	113.9	5	10	0	**1187.9**
2001	0	35.3	154.1	9.2	134.9	149.5	335.5	276.8	27.4	9.8	0	0	**1132.5**
2002	21.2	3.4	67.2	20.6	60.9	144.4	246.8	289.1	85.4	0	0	27.4	**966.4**
2003	75.5	0	29.7	122.9	1.7	120.6	304.4	373.4	122.4	0	0	19.7	**1170.3**
2004	15.2	7.1	2.2	118.9	0	69.8	315	319	30.6	0	0	0	**877.8**
2005	24.5	22.3	12.3	136.1	150.2	57.7	381.3	282.9	73.3	34.6	0	0	**1175.2**
2006	0	54.7	84.5	77.2	31.1	126.2	455.8	398.7	127.9	0	0	0	**1356.1**
2007	38	8.8	8.2	92.9	24.2	162	288.8	343.4	114.1	0	0	0.5	**1080.9**
2008	0	0	0	0	0	87.9	290.3	306.2	175.3	24.7	63.7	0.5	**948.6**
2009	0	0	3.6	12	30.2	61.3	311.7	372	113.3	53.0	0	18.2	**975.4**
2010	0	12.5	18	205.3	76.4	106.7	316.2	295.8	65.6	1.5	0	0.7	**1098.7**
2011	0	0	30.6	71.5	136.7	86.8	216.8	328.6	51.9	7.9	0	0	**930.8**
2012	0	0	35.3	87.3	221.7	437.3	390.8	339.3	187.3	17.5	1.8	4.1	**1722.3**
2013	7.3	3.4	0	44.7	45.3	274.7	374.6	449	27.5	0	0	5.9	**1232.4**
2014	3.9	11.3	42.4	0	73.8	79.1	211.5	731.3	139	6.4	0	0	**1298.7**
2015	0	0	18.8	0	101.1	231.1	378.3	345.0	103.9	20.8	12.1	0.5	**1211.6**
2016	8.7	0	42.8	220.2	44.7	138.3	315.4	313.4	118.0	61.0	1.5	0.4	**1264.4**
2017	3.9	16.2	37.9	51.9	107.4	111.9	350.8	329.2	267.0	137.5	2.0	0.7	**1416.3**
2018	3.9	59.5	23.3	68.1	156.1	278.3	360.5	338.4	115.8	58.2	4.1	0.5	**1466.7**
2019	3.9	5.9	26.1	126.5	118.5	195.3	385.2	465.6	500.5	63.3	174.8	21.7	**2087.3**
2020	2.3	4.5	67.7	190	152.9	202.8	474.2	387.5	288.1	132.1	0	0	**1902.1**
2021	7.3	139.6	16.3	161.1	177.2	320.1	662.4	436.2	259.9	66.3	0	0.5	**2246.9**
Average	***12.8***	***24.6***	***37.8***	***80.8***	***74.1***	***147.7***	***341.9***	***346.9***	***140.2***	***32.3***	***9.8***	***3.3***	**1252.4**

Appendix Table 2: Average monthly maximum temperature (°C) for the study area

Stations (Periods)	Jan	Feb	Mar	Apr	May	Jun	Jul	Aug	Sep	Oct	Nov	Dec
A.A Bole (1990-2021)	24.05	25.09	25.61	25.08	25.30	23.76	21.37	21.12	22.06	23.37	23.40	23.32
A.A Observatory (1990-2021)	24.37	25.54	25.90	25.29	25.36	23.69	21.29	20.94	22.07	23.40	23.65	23.64
Akaki (1990-2021)	20.84	21.62	22.00	21.90	21.77	20.68	18.93	18.53	19.71	20.41	20.40	20.24
Intoto(1990-2013)	14.18	15.03	14.95	14.48	14.73	13.49	11.77	11.67	12.24	13.22	13.62	13.73
Average	**20.86**	**21.82**	**22.11**	**21.69**	**21.79**	**20.40**	**18.34**	**18.06**	**19.02**	**20.10**	**20.27**	**20.23**

Appendix Table 3: Average monthly minimum temperature (°C)for the study area

Stations (Periods)	Jan	Feb	Mar	Apr	May	Jun	Jul	Aug	Sep	Oct	Nov	Dec
A.A Bole (1990-2021)	7.76	8.21	10.55	10.59	11.23	10.65	11.19	11.02	10.37	8.99	7.26	6.94
A.A Observatory (1990-2021)	8.75	9.11	11.33	11.71	12.20	10.96	11.16	11.36	10.70	10.13	8.39	7.93
Akaki (1997-2021)	10.82	10.82	12.58	13.14	13.57	13.03	13.34	13.15	12.68	11.87	10.96	9.98
Average	**9.11**	**9.38**	**11.49**	**11.81**	**12.33**	**11.55**	**11.90**	**11.84**	**11.25**	**10.33**	**8.87**	**8.28**

Appendix Table 4A: Average monthly sunshine hour (hr) for the study area

Stations (Periods)	Jan	Feb	Mar	Apr	May	Jun	Jul	Aug	Sep	Oct	Nov	Dec
A.A Bole (2006-2021)	9.40	8.98	8.22	6.87	7.41	5.68	3.58	3.85	5.29	8.54	9.17	9.39
A.A Observatory (2006-2021)	8.90	8.87	8.06	6.64	6.42	4.69	2.54	2.80	4.35	7.76	8.44	8.75
Average	**9.15**	**8.93**	**8.14**	**6.75**	**6.92**	**5.19**	**3.06**	**3.32**	**4.82**	**8.15**	**8.81**	**9.07**

Appendix Table 5: Average monthly wind speed (m/s) for the study area

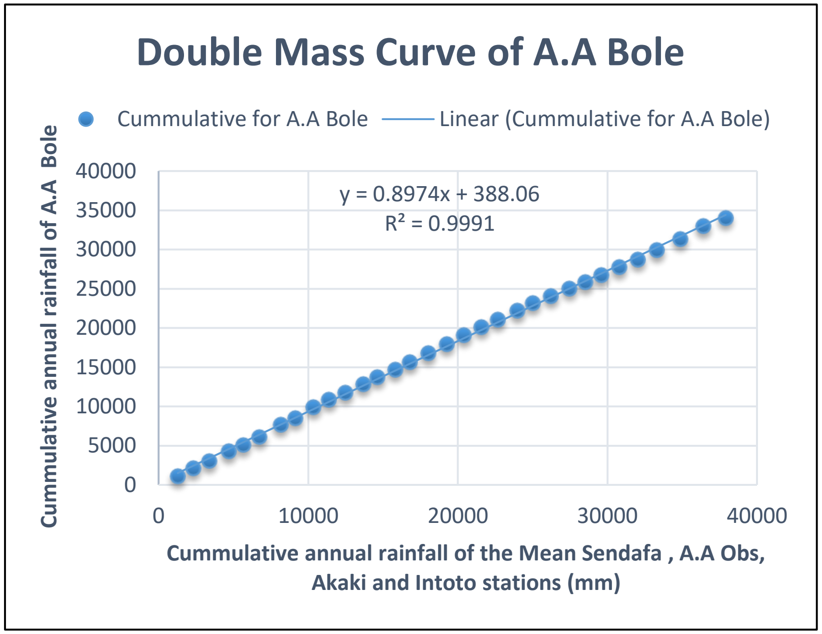
Stations (Periods)	Jan	Feb	Mar	Apr	May	Jun	Jul	Aug	Sep	Oct	Nov	Dec
A.A Bole (2017-2021)	2.18	2.37	2.40	2.25	2.12	1.76	1.59	1.60	1.58	2.33	2.42	2.28
A.A Observatory (1990-2005/2013-2021)	0.64	0.68	0.69	0.65	0.60	0.43	0.37	0.33	0.41	0.64	0.67	0.62
Average	**1.41**	**1.52**	**1.55**	**1.45**	**1.36**	**1.09**	**0.98**	**0.97**	**0.99**	**1.49**	**1.54**	**1.45**

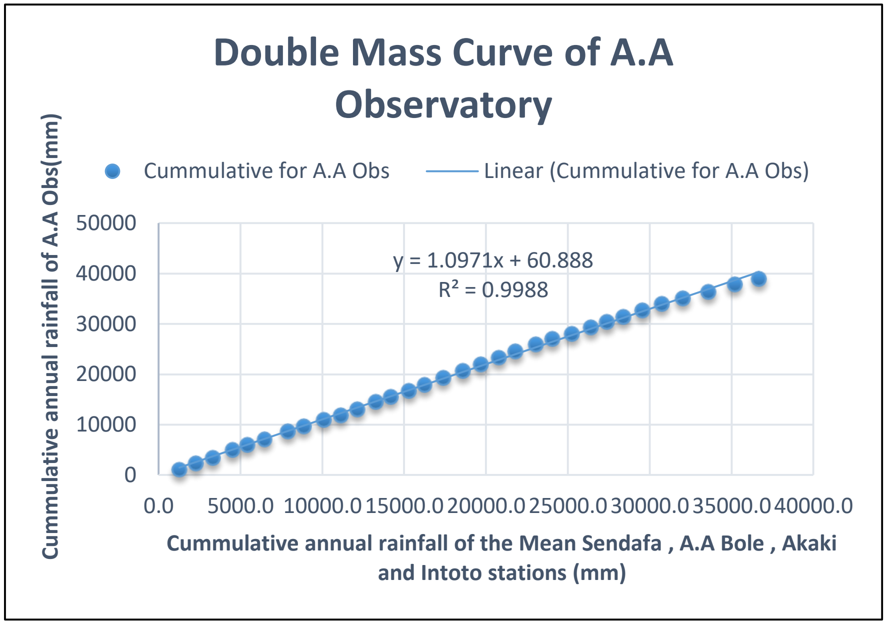
Appendix Table 6: Relative Humidity (%) /Averaged

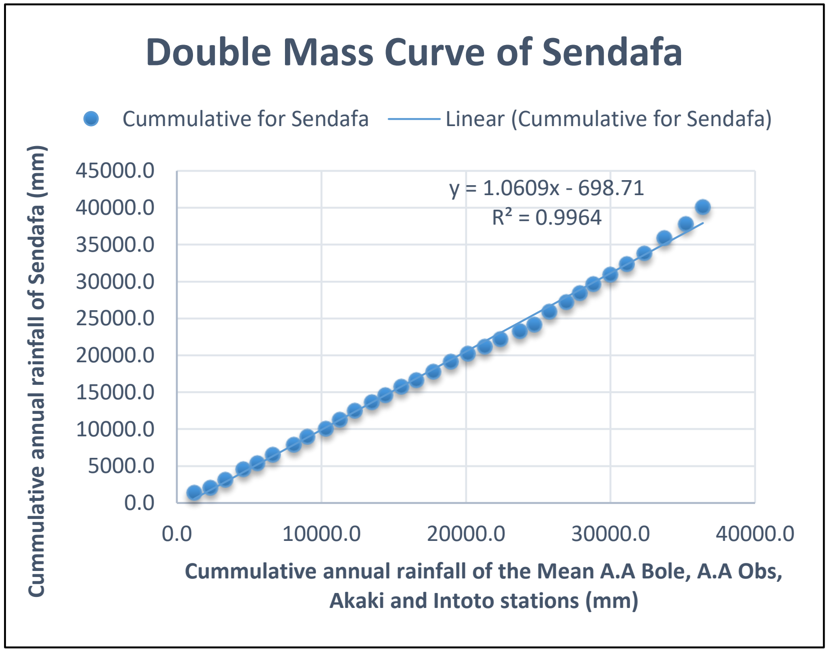
Stations (Periods)	Jan	Feb	Mar	Apr	May	Jun	Jul	Aug	Sep	Oct	Nov	Dec
A.A Bole (1998-2021)	67.33	56.05	64.45	66.21	69.03	82.65	96.85	100.67	87.40	67.17	64.99	67.61
A.A Observatory (1990-2007/2012-2021)	46.61	40.55	46.65	48.27	50.25	57.48	65.43	72.15	63.73	49.76	45.24	46.15
Average	**56.97**	**48.30**	**55.55**	**57.24**	**59.64**	**70.07**	**81.14**	**86.41**	**75.56**	**58.47**	**55.11**	**56.88**

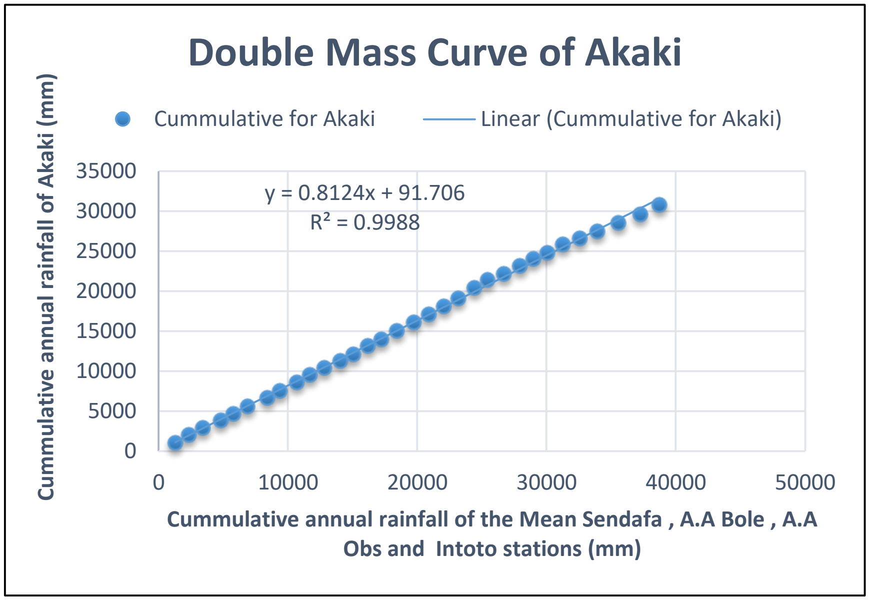
Appendix Table 7: Maximum Relative Humidity (%) /Averaged

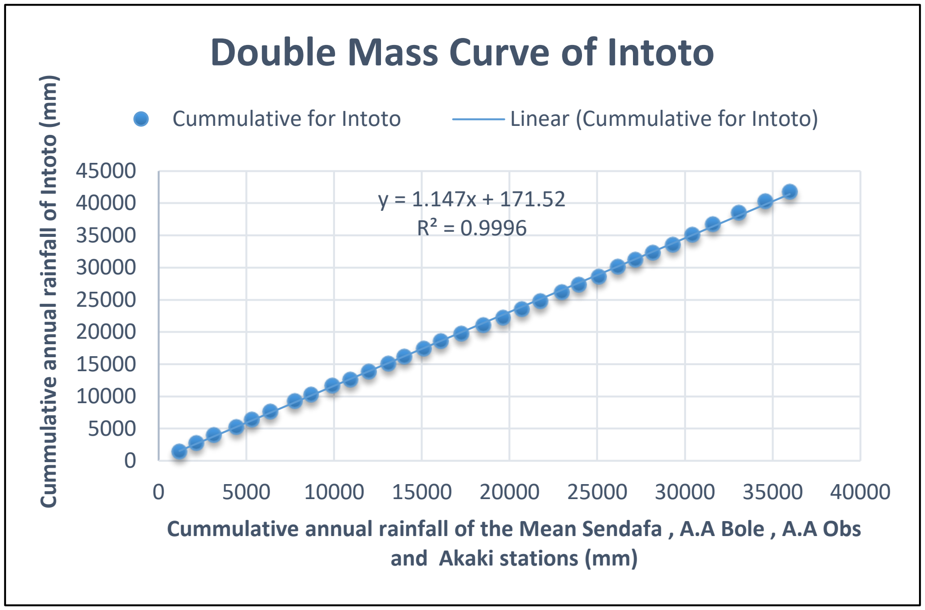
Stations (Periods)	Jan	Feb	Mar	Apr	May	Jun	Jul	Aug	Sep	Oct	Nov	Dec
A.A Bole (1998-2021)	87.90	76.98	87.51	88.03	90.66	102.55	113.85	117.48	106.03	89.82	87.29	91.85
A.A Observatory (1990-2007/2012-2021)	59.38	52.19	58.47	58.92	61.17	68.23	75.35	82.48	73.45	58.31	54.06	57.32
Average	**73.64**	**64.59**	**72.99**	**73.48**	**75.92**	**85.39**	**94.60**	**99.98**	**89.74**	**74.07**	**70.67**	**74.58**

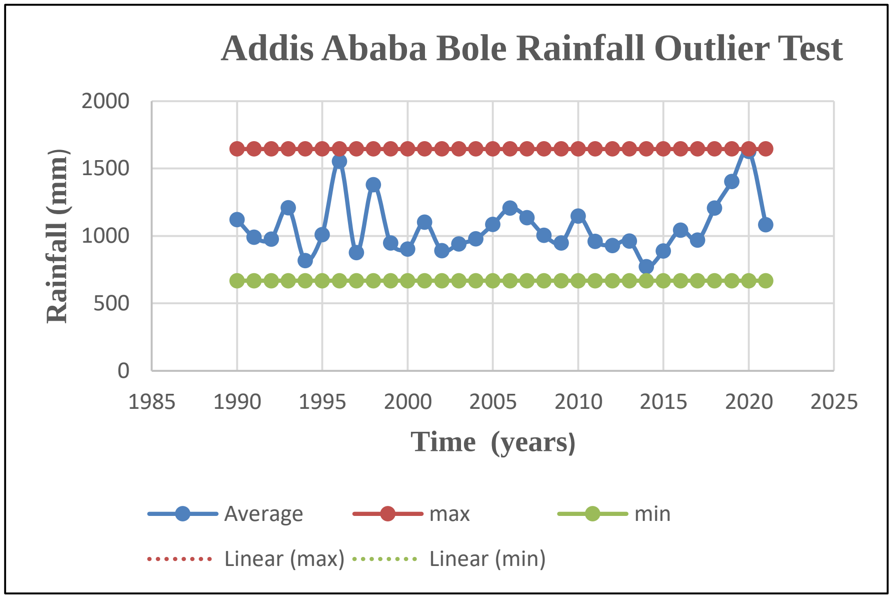

Double Mass Curve of A.A Bole
Cummulative for A.A Bole
Linear (Cummulative for A.A Bole)
y = 0.8974x + 388.06
R² = 0.9991
Cummulative annual rainfall of A.A Bole
40000
35000
30000
25000
20000
15000
10000
5000
0
0
10000
20000
30000
40000
Cummulative annual rainfall of the Mean Sendafa , A.A Obs, Akaki and Intoto stations (mm)

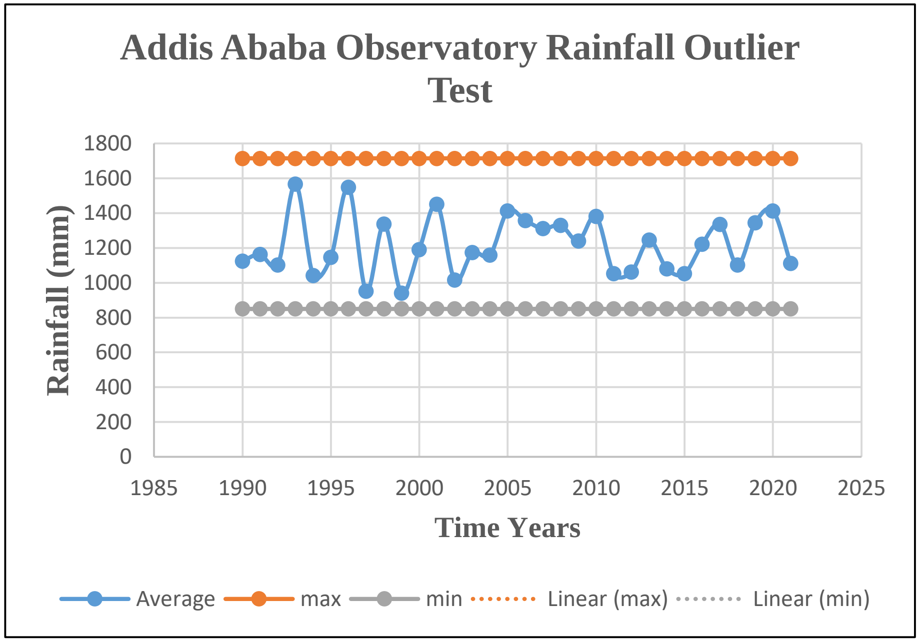

Double Mass Curve of A.A Observatory
Cummulative for A.A Obs
Linear (Cummulative for A.A Obs)
y = 1.0971x + 60.888
R² = 0.9988
Cummulative annual rainfall of A.A Obs(mm)
50000
40000
30000
20000
10000
0
0.0
5000.0
10000.0
15000.0
20000.0
25000.0
30000.0
35000.0
40000.0
Cummulative annual rainfall of the Mean Sendafa , A.A Bole , Akaki and Intoto stations (mm)

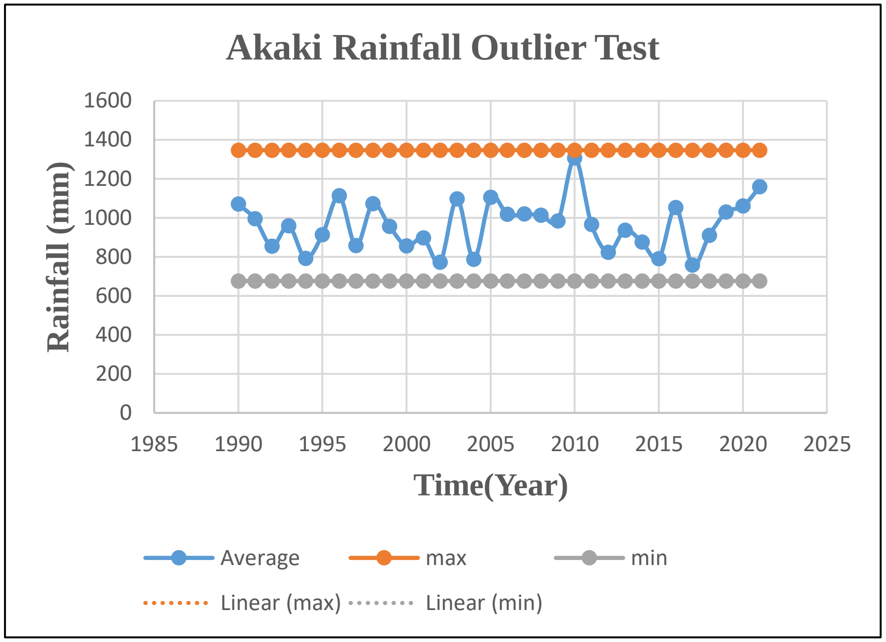

Double Mass Curve of Sendafa
Cummulative for Sendafa
Linear (Cummulative for Sendafa)
y = 1.0609x - 698.71
R² = 0.9964
Cummulative annual rainfall of Sendafa (mm)
45000.0
40000.0
35000.0
30000.0
25000.0
20000.0
15000.0
10000.0
5000.0
0.0
0.0
10000.0
20000.0
30000.0
40000.0
Cummulative annual rainfall of the Mean A.A Bole, A.A Obs, Akaki and Intoto stations (mm)

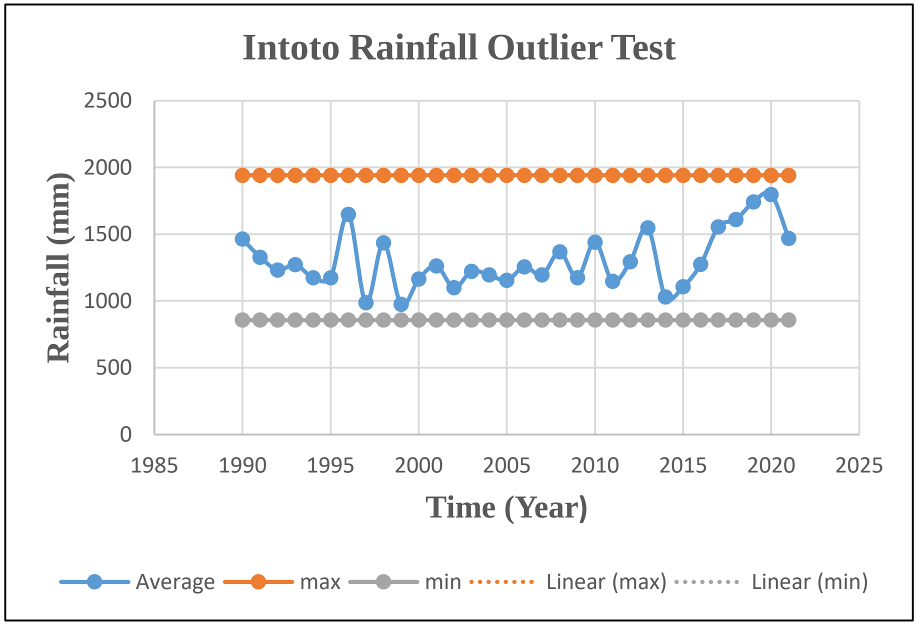

Double Mass Curve of Akaki
Cummulative for Akaki
Linear (Cummulative for Akaki)
y = 0.8124x + 91.706
R² = 0.9988
Cummulative annual rainfall of Akaki (mm)
35000
30000
25000
20000
15000
10000
5000
0
0
10000
20000
30000
40000
50000
Cummulative annual rainfall of the Mean Sendafa , A.A Bole , A.A Obs and Intoto stations (mm)

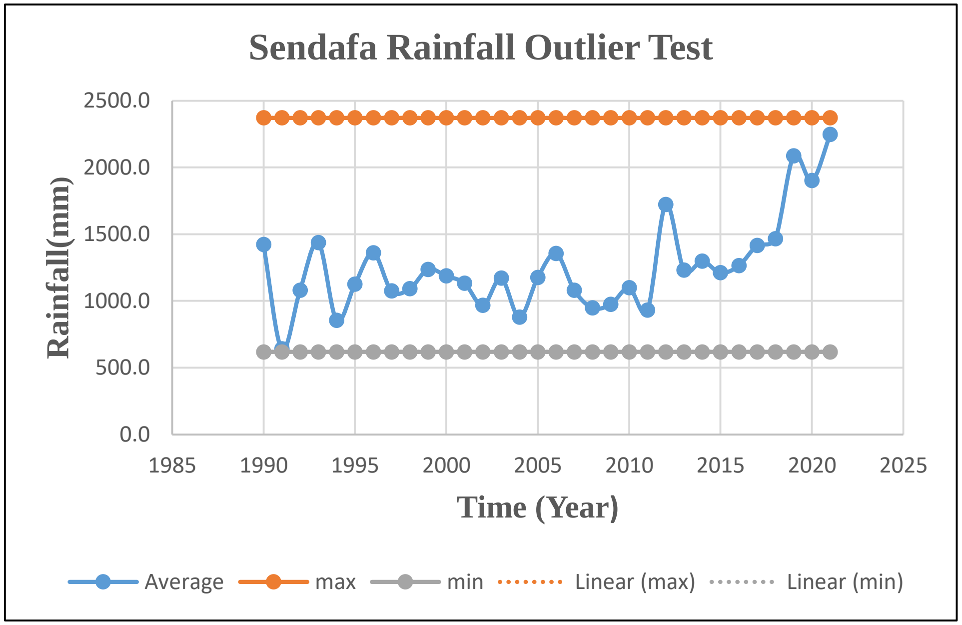

Double Mass Curve of Intoto
Cummulative for Intoto
Linear (Cummulative for Intoto)
y = 1.147x + 171.52
R² = 0.9996
Cummulative annual rainfall of Intoto (mm)
45000
40000
35000
30000
25000
20000
15000
10000
5000
0
0
5000
10000
15000
20000
25000
30000
35000
40000
Cummulative annual rainfall of the Mean Sendafa , A.A Bole , A.A Obs and Akaki stations (mm)

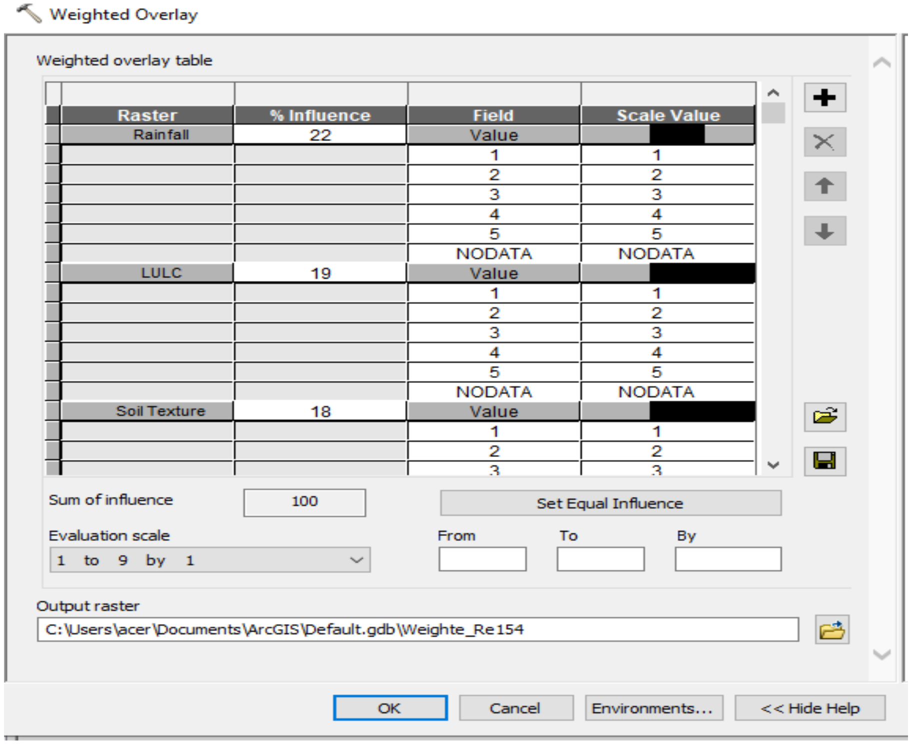

Addis Ababa Bole Rainfall Outlier Test
Rainfall (mm)
2000
1500
1000
500
0
1985
1990
1995
2000
2005
2010
2015
2020
2025
Time (years)
Average
max
min
Linear (max)
Linear (min)


Addis Ababa Observatory Rainfall Outlier Test
Rainfall (mm)
1800
1600
1400
1200
1000
800
600
400
200
0
1985
1990
1995
2000
2005
2010
2015
2020
2025
Time Years
Average
max
min
Linear (max)
Linear (min)


Akaki Rainfall Outlier Test
Rainfall (mm)
1600
1400
1200
1000
800
600
400
200
0
1985
1990
1995
2000
2005
2010
2015
2020
2025
Time(Year)
Average
max
min
Linear (max)
Linear (min)






Weighted Overlay

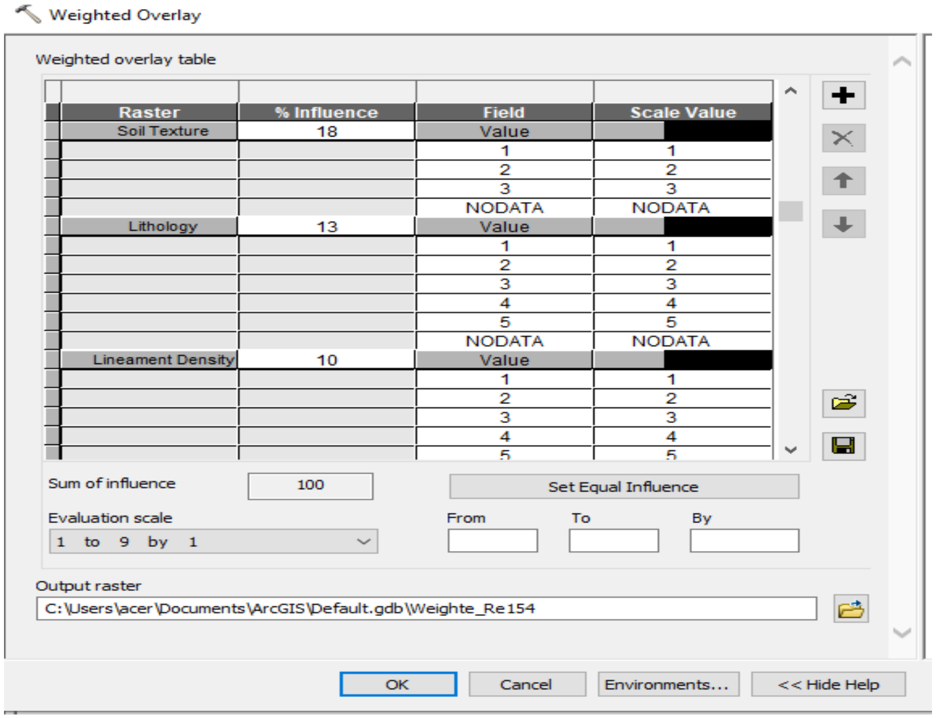
Weighted overlay table

Raster	% Influence	Field	Scale Value
Rainfall	22	Value	
		1	1
		2	2
		3	3
		4	4
		5	5
		NODATA	NODATA
LULC	19	Value	
		1	1
		2	2
		3	3
		4	4
		5	5
		NODATA	NODATA
Soil Texture	18	Value	
		1	1
		2	2
		3	3

Sum of influence: 100

Evaluation scale: 1 to 9 by 1

Output raster: C:\Users\acer\Documents\ArcGIS\Default.gdb\Weighte_Re154


Weighted Overlay

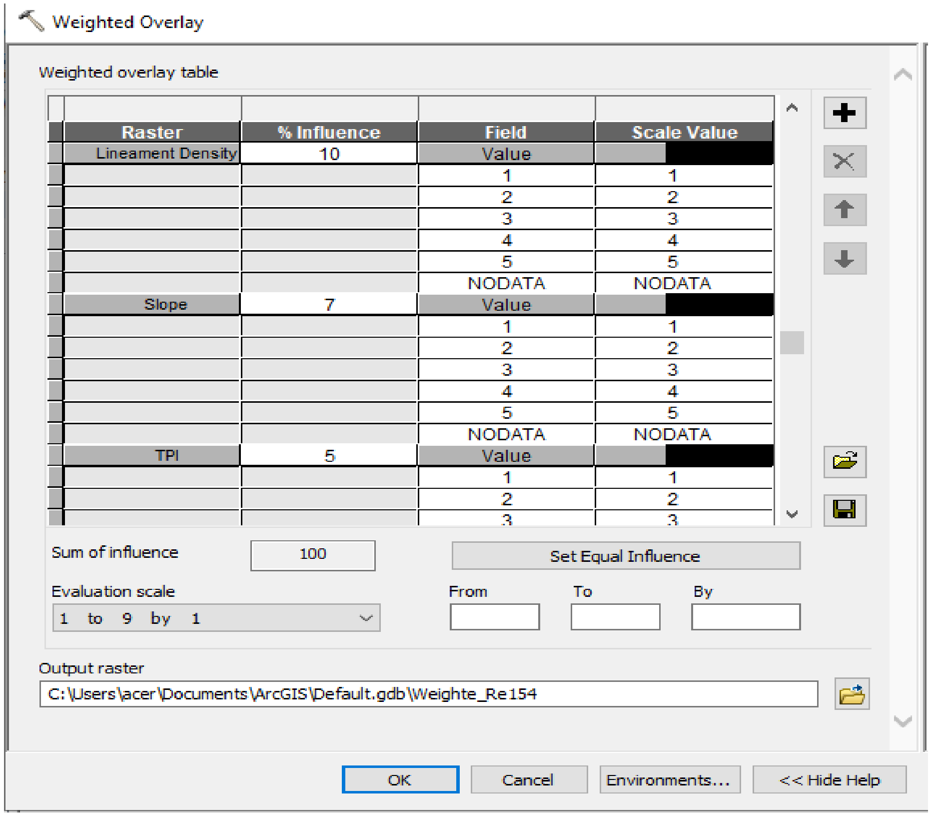
Weighted overlay table

Raster	% Influence	Field	Scale Value
Soil Texture	18	Value	
		1	1
		2	2
		3	3
		NODATA	NODATA
Lithology	13	Value	
		1	1
		2	2
		3	3
		4	4
		5	5
		NODATA	NODATA
Lineament Density	10	Value	
		1	1
		2	2
		3	3
		4	4
		5	5

Sum of influence: 100

Evaluation scale: 1 to 9 by 1

Output raster: C:\Users\acer\Documents\ArcGIS\Default.gdb\Weighte_Re154



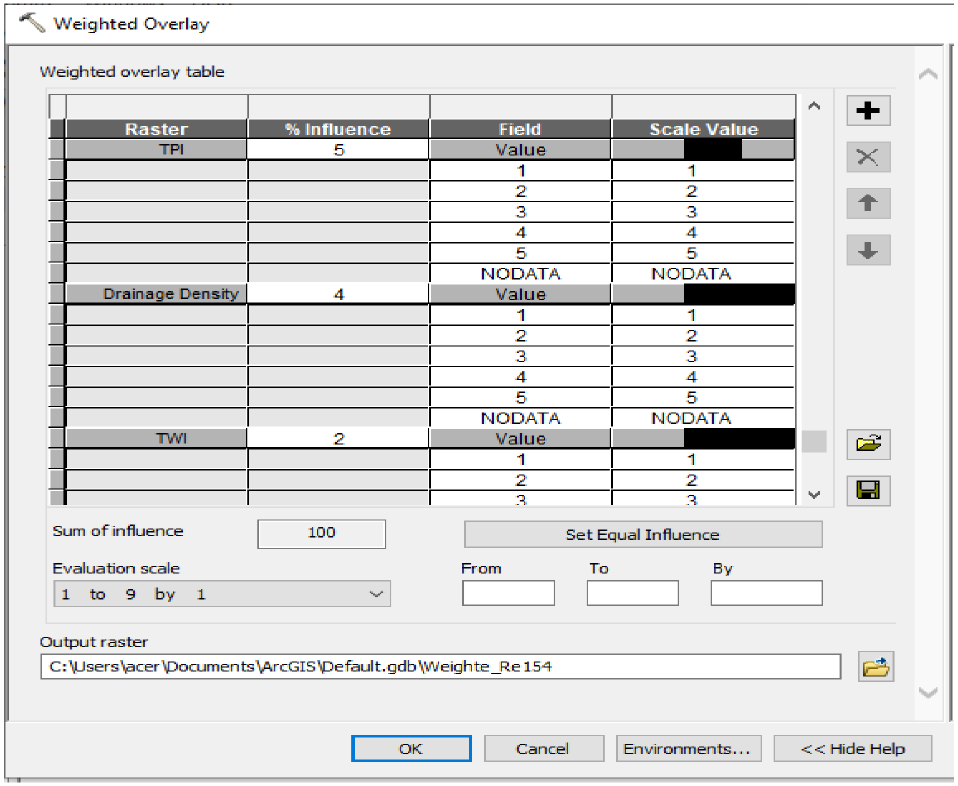
Raster	% Influence	Field	Scale Value
Lineament Density	10	Value	
		1	1
		2	2
		3	3
		4	4
		5	5
		NODATA	NODATA
Slope	7	Value	
		1	1
		2	2
		3	3
		4	4
		5	5
		NODATA	NODATA
TPI	5	Value	
		1	1
		2	2
		3	3

Sum of influence 100

Evaluation scale 1 to 9 by 1

From To By

Output raster
C:\Users\acer\Documents\ArcGIS\Default.gdb\Weighte_Re154



Raster	% Influence	Field	Scale Value
TPI	5	Value	
		1	1
		2	2
		3	3
		4	4
		5	5
		NODATA	NODATA
Drainage Density	4	Value	
		1	1
		2	2
		3	3
		4	4
		5	5
		NODATA	NODATA
TWI	2	Value	
		1	1
		2	2
		3	3

Sum of influence 100

Evaluation scale 1 to 9 by 1

From To By

Output raster
C:\Users\acer\Documents\ArcGIS\Default.gdb\Weighte_Re154

Appendix Table 8: Borehole Well Data

1. Summary of Akaki Phase-4 Koyefeche data

<u>Bhs Well data</u>

No	Site name	Design Well data													
		Date of drilling	Locality	Destination	X-UTM	Y-UTM	Elevation	Depth	Casing(Ø)	SWL	DWL	DD	Pump. p(m)	Discharge,l/s	Recommended Working Hour
1	BH10R	March,2014	Akaki	CT5	479055	976033	2096	520	14&8	95.33	100.71	5.38	140m head	150	18
2	BH11R	March,2014	Akaki	CT5	478782	977309	2088	547	14&8	82.34	88.36	6.02	140m head	152	18
3	BH13R	March,2014	Akaki	CT5	478679	976462	2080	550	14&8	76.60	137.10	60.5	140m head	55.00	18
4	BH14R	March,2014	Akaki	CT5	478780	977307	2088	520	14&8	81.26	102.32	21.06	120	140.00	18
5	BH22R	March,2014	Akaki	CT5	477628	975889	2074	463	14&8	66.66	120.4	53.74	140m head	100	18
6	BH01R	March,2014	Akaki	CT5	478074	975053	2089	520	14&8	83.67	136.6	52.93	200	100	18
7	BH23R	March,2014	Akaki	CT5	477479	977222	2065	500	14&8	71.06	149.76	78.7	180	45	18
8	BH26R	March,2014	Akaki	CT5	478074	975053	2089	500	14&8	72.8	130.56	57.76	160	90	18

2. Summary of Akaki phase II water supply (AWF01) data

Bhs Well data

No	Site name	Design Well data													
		Date of drilling	Locality	Destination	X-UTM	Y-UTM	Elevation	Depth	Casing (Ø)	SWL	DWL	DD	Pump.p(m)	Disharge,l/s	Recommended Working Hour
1	SWA WF2	March,2010	Akaki	CT1	475697	979915	2055	448	12"&8"	9.5	98.8	89.3	120	55	18
2	SWA WF4B	March,2010	Akaki	CT1	472836	980785	2058	481	12"&8"	8	16.9	8.9	100	80	18
3	SWA WF5	March,2010	Akaki	CT1	472779	978788	2054	486	12"&8"	9.70	14.20	4.5	80	80.00	18
4	WF01-PW2	March,2010	Akaki	CT1	474204	980459	2069	250	12"&8"	21.20	106.10	84.9	130	50.00	18
5	WF01-PW3	March,2010	Akaki	CT1	474918	980486	2073	480	12"&8"	21.8	90.5	68.7	125	50	18
6	WF01-PW4	March,2010	Akaki	CT1	471185	979580	2061	500	12"&8"	37.38	132.8	95.42	180	100	18
7	WF01-PW5	March,2010	Akaki	CT1	470434	979201	2058	506	12"&8"	14.53	125.01	110.48	150	100	18
8	WF01-PW6	March,2010	Akaki	CT1	472630	979912	2058	533	12"&8"	8.4	92.9	84.5	120	80	18
9	WF01-PW8	March,2010	Akaki	CT1	473583	979260	2063	483.7	12"&8"	17.5	99.9	82.4	130	50	18
10	WF01-PW9	March,2010	Akaki	CT1	470470	979206	2049	514	12"&8"	19.22	149.74	130.52	180	70	18
11	WF01-PW11	March,2010	Akaki	CT1	472245	977865	2056	500	12"&8"	27.5	81.5	54	122	50	18

12	WF01-PW12	March,2010	Akaki	CT1	471476	977396	2049	480	12"&8"	34.1	39.7	5.6	100	80	18
13	WF01-PW13	March,2010	Akaki	CT1	472233	976508	2057	400	12"&8"	40.4	105.9	65.5	150	50	18
14	WF01-PW14	March,2010	Akaki	CT1	471521	976630	2050	552	12"&8"	39.7	42	2.3	100	100	18
15	WF01-PW15	March,2010	Akaki	CT1	473944	978722	2066	492	12"&8"	30.3	117.9	87.6	135	50	18
16	WF01-PW16	March,2010	Akaki	CT1	473386	980122	2062	549	12"&8"	11.4	143	131.6	125	30	18
17	WF01-PW17	March,2010	Akaki	CT1	472460	981553	2064	500	12"&8"	0	85.7	85.7	120	60	18
18	WF01-PW18	March,2010	Akaki	CT1	471918	979657	1969	272	12"&8"	9.32	13.01	3.69	55	120	18
19	WF01-PW19	March,2010	Akaki	CT1	470557	976837	1972	501	12"&8"	54.43	109.18	54.75	155	65	18
20	WF01-PW20	March,2010	Akaki	CT1	471298	977837	1978	504	12"&8"	26.7	127.02	100.32	157	35	18

3. Summary of Akaki phase IIIA water supply (AWF02) data

Bhs Well data

No		Design Well data													
	Site name	Date of drilling	Locality	Destination	X-UTM	Y-UTM	Elevation	Depth	Casing(Ø)	SWL	DWL	DD	Pump.p(m)	Disharge,l/s	Recommended Working Hour
1	WF02-PW5	March, 2014	Akaki	CT3	476795	971654	2090	498.6	12"&8	80.1	82.39	2.29	130	>50	18
2	WF02-PW6	March, 2014	Akaki	CT3	471351	970556	2067	500	12"&8	73.84	109.34	35.5	120	30	18
3	WF02-PW7R	March, 2014	Akaki	CT3	471576	972958	2057	550	12"&8	53.72	147.71	93.99	230	75.00	18
4	WF02-PW8	March, 2014	Akaki	CT3	469163	973946	2063	502	12"&8	45.74	103.30	57.56	120	50.00	18
5	WF02-PW9	March, 2014	Akaki	CT3	473955	974576	2064	505	12"&8	50.73	71.56	20.83	120	80	18
6	WF02-PW10	March, 2014	Akaki	CT3	469239	972866	2071	500	12"&8	84.75	108.64	23.89	150	40	18
7	WF02-PW11	March, 2014	Akaki	CT3	469738	971752	2075	341	12"&8	83.40	105	21.6	130	70	18
8	WF02-PW12	March, 2014	Akaki	CT3	470153	970500	2048	520	12"&8	61.2	94.8	33.6	150	50	18
9	WF02-PW13	March, 2014	Akaki	CT3	469197	970946	2059	342	12"&8	64.81	71.04	6.23	110	70	18
10	WF02-PW14	March, 2014	Akaki	CT3	468453	973497	2062	500	12"&8	53.4	83.44	30.04	120	70	18
11	WF02-PW15	March, 2014	Akaki	CT3	469835	978303	2064	540	12"&8	52.73	132.09	79.36	150	100	18

12	WF02-PW16	March, 2014	Akaki	CT3	468849	970179	2064	493	12"&8	55.05	81.41	26.36			18
13	WF02-PW17	March, 2014	Akaki	CT3	468336	972312	2061	480	12"&8	61.62	89.11	27.49			18
14	WF02-PW18	March, 2014	Akaki	CT3	468006	971498	2066	496	12"&8	57.8	102.05	44.25			18
15	WF02-PW19	March, 2014	Akaki	CT3	472860	971308	2067	550	12"&8	82.7	174.6	91.9	200	26	18
16	WF02-PW20	March, 2014	Akaki	CT3	471027	973709	2056	379	12"&8	44	58.2	14.2	100	100	18
17	SL-PW-12	March, 2014	Akaki	CT3	475507	974697	2046	320	12"&8	49.45	55.95	6.5	72	112	18

4. Summary of Akaki phase IIIB water supply (AWF03) data

Bhs Well data

No		Design Well data													
	Site name	Date of drilling	Locality	Destination	X-UTM	Y-UTM	Elevation	Depth	Casing(Ø)	SWL	DWL	DD	Pump Setting Depth(m)	Discharge,l/s	Recommended Working Hour
1	SL-PW-01	2014	Akaki	CT2	472446	974756	2089	468	14" & 8"	40.6	72.3	31.7	112	100	18
2	SL-PW-03	2014	Akaki	CT2	475276	976930	2052	582	14" & 8"	54.32	128.99	74.67	140	70	18
3	SL-PW04	2014	Akaki	CT2	476037	976861	2068	595	14" & 8"	55.18	91.25	36.07	110	88.00	18
4	SL-PW-05	2014	Akaki	CT2	475058	976100	2062	502	14" & 8"	48.79	68.99	20.2	100	91.00	18
5	SL-PW-06	2014	Akaki	CT2	475528	975870	2059	600	14" & 8"	52.02	86.4	34.38	101	86	18
6	SL-PW-07	2014	Akaki	CT2	476098	976183	2076	550	14" & 8"	53.52	131.03	77.51	150	46	18

7	SL-PW-08	2014	Akaki	CT2	474528	975585	2057	569	14" & 8"	49.06	73.5	24.44	110	95	18
8	SL-PW-09	2014	Akaki	CT2	473954	975244	2068	600	14" & 8"	64.54	78.72	14.18	94	70	18
9	SL-PW-10	2014	Akaki	CT2	473954	975244	2053	591	14" & 8"	49.28	133.39	84.11	150	50	18
10	SL-PW-11	2014	Akaki	CT2	471453	974241	2048	335	14" & 8"	50.04	63.35	13.31	72	112	18
11	SL-PW-13	2014	Akaki	CT2	472078	974359	2050	319	14" & 8"	51.65	57.57	5.92	84	100	18
12	SL-PW-14	2014	Akaki	CT2	472640	973882	2072	518.5	14" & 8"	70.25	98.33	28.08	122	80	18
13	SL-PW-15	2014	Akaki	CT2	473428	973584	2078	623	14" & 8"	70.55	134.5	63.95	150	30	18
14	SL-PW-16	2014	Akaki	CT2	474702	974792	2069	59.5	14" & 8"	69.98	97	27.02	120	98	18
15	SL-PW-17	2014	Akaki	CT2	474733	973382	2072	501	14" & 8"	78.54	124.67	46.13	150	30	18
16	SL-PW-18	2014	Akaki	CT2	477023	973986	2090	503	14" & 8"	84.85	114.61	29.76	150	66.17	18
17	SL-PW-19	2014	Akaki	CT2	476375	974046	2091	568	14" & 8"	90.5	147.06	56.56	165	25	18
18	SL-PW-21	2014	Akaki	CT2	477959	974168	2103	501	14" & 8"	98.47	108.3	9.83	135	90	18
19	SL-PW-22	2014	Akaki	CT2	475507	974679	2070	51.5	14" & 8"	76.65	120.13	43.48	120	98	18
20	SL-PW-24	2014	Akaki	CT2	475941	975137	2063	551	14" & 8"	65	71.67	6.67	81	102	18
21	SL-PW-25	2014	Akaki	CT2	473071	974284	2060	552	14" & 8"	56.08	61.61	5.53	78	108	18
22	SL-PW-30	2014	Akaki	CT2	478528	973384	2113	518	14" & 8"	132.4	133.72	1.32	150	46	18
23	SL-PW-32	2014	Akaki	CT2	476725	973381	2111	170	14" & 8"	110	149.74	39.74	167	46	18
24	SL-PW-33	2014	Akaki	CT2	477415	973284	2112	453	14" & 8"	116.38	139.69	23.31	81	102	18

5. Summary of LLA-phase I water supply data

No	Bhs name	Design Well Data									
		X-UTM	Y-UTM	Elevation	Depth	Casing(Ø)	SWL	DWL	DD	Pump.p(m)	Disharge,l/s
1	LLA3	496269	1004908	2444	598	14&8	0	14.31	14.31	100	50
2	LLA-PW1	497270	1004423	2472	504	14&8	12.86	27.82	14.96	100	80
3	LLA-PW4	494679	1006306	2492	504	14&8	19.8	26.38	6.58	100	90
4	LLA-PW5	496594	1006485	2486	550	14&8	14.24	86.72	72.48	150	40
5	LLA-PW6	499750	1008782	2476	354	14&8	49.68	52.51	2.83	100	80
6	LLA-PW7	499253	1006931	2510	378	14&8	33.84	70.65	36.81	100	80
7	LLA4	498961	1005177	2460	181	14&8	0		0	90	100
8	LLA-PW3	500497	1007598	2474	372	14&8	29.4	32.79	3.39	100	100
9	LLA6	497470	1006388	2510	440	14&8	32.20	111.10	78.9	180	40.00
10	LTW-1	493552	1002852	2438	503	14&8	42.1	94.04	51.94	168-179	75

6. Summary of Addis Ababa pocket area water supply data

		Design Well Data								
No	Bhs name	X-UTM	Y-UTM	Depth	Casing(Ø)	SWL	DWL	DD	Pump.p(m)	Disharge,l/s
1	Ararat	480321	997370	180	10	10.52	29	18.48	112	43
2	Ayat Bashale	489127	999697	280	10	39	75	36	216-222	15
3	Bole Arabissa-1	0	0	152	10	4.95	54	49.05	98	6
4	Bole Arabissa-2	0	0	146	10	0	38.25	38.25	120	12
5	Kara Luke	482994	998429	203	10	44	47	3	125	34
6	Kotebe Dehninet-1	479316	999941	271	14&8	118.36	141.33	22.97	169	50
7	Kotebe Dehninet-2	479175	999755	250	12	107.3	153.9	46.6	160	15
8	Legetafo-1	486790	1001357	250	10	8	57	49	140	28
9	Legetafo-2	487881	997599	200	10	0	29	29	176-182	45
10	Salayish	480999	999648	228	8	12	24	12	90	22
11	Selam	481400	999700	200	8	5	42	37	135	20
12	Abo ferensay	475945	1000580	252	10	43	50	7	111-117	43
13	Addis Zemen Shero	473314	1002774	287.3	12	85.15	188.88	103.73	205	35.5
14	Afincho Ber			254	10	46	120	74	130	8
15	Ferensay - 1	475466	1000729	513	12&8	142.38	163.82	21.44	220	53
16	Ferensay - 2	475466	1000729	500	12&8	153.25	169.78	16.53	195	37.5
17	Ferensay - old	475068	1001254	260	10	106	108	2	152-164	18
18	Gurara	477067	1001053	500	12&8	81.98	118.09	36.11	146	53
19	Hamle-19 (New)	474402	1001122	505	12&8	136.57	151.51	14.94	195	53
20	Hibiret Ferie School	475436	999350	242	10	29.02	143.25	114.23	200	15
21	I/Embassy	476287	1000116	409	12	95.3	124.53	29.23	221	57
22	K/tsebha	475706	998531	456	12&8	39.6	182.45	142.85	230	8

23	Meketeya	472608	1002066	312	12	58.85	110.03	51.18	203.4	8
24	Ras syum	475068	1001254	260	10	106	108	2	152-164	18
25	Yeka Park	477715	997474	216	8	19	39	20	150	15
26	Hana kotobe bh	481763	1000506	327	12	31.76	63.72	31.96	167	55
27	Bole Arabsa 3	485830	995120	510	14&8	73.13	176.37	103.24	240	20
28	Ferensay Danse	478543	1001375	422	12&8	90	110.4	20.4	174	33.6
29	N/Palace	474636	997762	552	14&8	31.2	160.9	129.7	195	10
30	Chefe kuskem	472900	1003550	101.7	8	1.85	24.6	22.75	90	4
31	Asko 1/97	465621	1001028	473.5	12&8	35.42	72.9	37.48	110.5	60
32	Abadir			228	10	63.8	82.65	18.85	128	48
33	Mikiland-1	465998	1000153	193	8	0	12	12		17
34	Mikiland-2	466336	1000658	420	12&8	96.8	99.57	2.77	190	53
35	Mikiland-3	466601	1000250	133	8		19	19		20
36	Mikiland-4	466841	1000105	392	12&8	73.9	126.39	52.49	210	18
37	Sanisuzi-New	465819	1002753	332	12&8	84.62	179.3	94.68	186	55.5
38	Shegole-1	469150	1001150	240	10	0	105	105	144-150	15
39	Shegole-2	469275	1002378	502	14&8	22.32	128.77	106.45	185	25
40	Gihon Berekina	468352	1001079	500	12&8	68.2	166.1	97.9	237.5	13
41	Franchisko	479255	999962	228	12&8	74	77.07	3.07	172	50
42	Lukanda	467870	998015	346	12&8	80	113.47	33.47	201	25-30
43	holland embassy	468152	996813	519	14&8	76.4	125.54	49.14	170	30
44	keraniyo-4	468380	996211	270	10					40
45	keraniyo-2	467660	996912	270	10	12			100	45
46	keraniyo-3	468268	996584	252	10	5	22	17	100	45
47	keraniyo-1/97	463595	995915	150	8	66			150	6
48	deginet-1	463973	991974	405	12&8	45.25	83.1	37.85	195	54.1
49	deginet-2	463590	992116	420	12&8	80.1	144.77	64.67	195	50.6
50	repi roll	463850	993100	150	8	84.71	-	-	-	11.3
51	yeshi debele	466403	996384	430	12&8	59.1	237.3	178.2	240	10
52	alem bank	463835	994912	416	14&8	120.05	203.39	83.34	238	7.73
53	ayer tena-new	466050	993650	201	10	71	82	11	-	20
54	ayer tena-old	466050	993650	136	6	71	77.55	6.55	96	10

55	Tsion-2	470158	1001882	505.8	14&8	61.65	172.28	110.63	212	32
56	Tsion-1	470503	1002189	410	14&8	99.15	209.7	110.55	225	30
57	aweliya	468110	1001429	406	12&8	126	202	76	228	43
58	success	466842	993128	250	10	38	95	57	170	5
59	augusta	468505	995156	250	10	0	167.15	167.15	13.3	
60	EgzihaberAb-OLD	471026	1002023	222	10	23	128	105	148	23
61	EgzihaberAb new	479550	998479	550	14&8	114.35	176.85	62.5	243	8.5
62	repi-33	463985	991540	185	8	25	40	15		20
63	Mekdela school	469860	994357	500	12&8	64.85	88.65	21.7	213	30
64	Ewket lehibret	469196	993623	327	10&6	62.2	168.1	105.9	204-216	8
65	Alemgena BH	466200	988800	100	6		38		62	5
66	Mekanisa-2/97 BH	466308	989421	184	8	2.6	56.12	53.52	152	15
67	Site-19 BH	468261	990357	196	10	7	113	106	130	17
68	Site-01 BH	463453	987806	184	10	1	14	13	123-135	47
69	Site-16 BH	467135	989840	213	10	3	97	94	130	25
70	Site-18	469191	989547	230	8	3	106	103	134	8
71	Site-20	470277	989578	230	10	13	89	76	130-140	15
72	Site-21	469245	990260	240	10	1.8	50	48.2	132-138	30
73	Site-23	465741	989188	135	10	3	36	33	100	20
74	Site-24	468512	989680	230	10	0	14	14	120-130	60
75	Site-26	469458	990594	181	8	0	25	25	159-171	15
76	Site-27	468196	990422	180	8	5	19	14	162-168	18
77	Site-28	467723	990028	161	8	2.65	8	5.35	111	20
78	Site-29	470790	990330	240	10	0	45	45	120-126	40
79	Gofa-codominium	471925	990400	352	12&8	21.8	51.14	29.34	92.5	58.1
80	Kosta-sefer	472792	989152	500	12&8	7.5	119.94	112.44	201	50
81	Lafto-Hana	471400	988250	84	8	9	-		75	21.3
82	Site-25	471500	990500	200	8	12	20	8	130	17
83	Mekanisa-1/98(old)	470453	990127	140	10	22	25.36	3.36	86	50
84	Mekanisa-2/96	470070	991000	170	8	10	66	56	154	10
85	Mekanisa-1/97	471125	989636	-	10	11	-		103	26
86	Mekanisa--1/96	469500	989600	150	8	4	39	35	121	3

87	Repi-31	465591	989872	257	10	7	66	59	135	30
88	Repi-32	465295	990132	200	8	10	32	22	120	20
89	Jemo-michael	469231	990882	552	14&8	25	100.34	75.34	183	30
90	Yohanes-menafsha	477566	991862	344	12&8	28.86	122.7	94.73	202	9.3
91	Gofa-military camp	471454	991141	309	10	38.58	55.1	16.52	157	31.4
92	Fitawerari	472882	992205	312	10&6	90	114.93	24.93	156	16
93	Lafto-Bridge	472364	990174	300	10	26.23	27.11	2.85	150	31
94	Ginbot-20	472716	988618	328	10	38.52	48.12	9.6	160	30
95	Mekanisa(arki-fabi)	470610	991840	463	12&8	8.06	54.3	46.24	180	40
96	Lafto -industry sefer	471236	988500	340	10&6	42.2	143.2	101	194	15
97	Saris Addis sefer	475182	989526	474	12&8	7.9	69.32	61.42	153	75
98	Kotari Mango BH	470682	987316	357	14&8	0	141.22	141.22	179	50
99	Nifas silk BH	473446	991371	507	14&8	93.2	137.98	44.78	180	72
100	Bole Lemi-7	481151	992112	200	8	22	48	26	168-174	15
101	Site -2	482784	991683	205	8	14	16	2	186-192	13
102	Kality Gebrael	475300	984900	93	8	0	25.93	25.93	38	13.5
103	Kality Gebrael -2	474716	985017	394	12&8	0	15.85	15.85	96	69
104	Kilinto	478130	982300	260	10	6	165	159	242-248	15
105	Fanta-1	480847	981623	260	10	18	52	34	155	32
106	Fanta-2	481322	981799	240	10	29	63	34	208	25
107	Akaki-1	477252	982872	260	10	0	52	52	120	25
108	Akaki-2	476692	982390	306	10	0	113	113	220	7
109	Salo Giorgis	472585	982237	517	12&8	71.23	193.82	122.59	268	12
110	serti	476415	983274	500	12&8	39.92	140.26	100.34	160	31.23
111	Yosef	474858	991049	460	14&8	41.7	93.89	52.19	186	81.1
112	Genet Condominium	475908	983603	476	12&8	15.41	28.13	12.72	100 or 124	71
113	Bole high school	476933	994457	500	14&8	62.8	145.2	82.4	165	37.5
114	EP-1	479340	981400	108.7	12"& 6"	0.73	13.51	12.78		26.5
115	EP-2	481600	982850	150	12"& 6"	33.48	39	5.52		11.1
116	F-1	479000	981400	120	10"	9	16	7		-
117	F-3	479700	981700	116	10"	10	-			40.88
118	F-7	481337	982304	135	10"	20	32.35	12.35		40

119	Bulbula Medhanialem	475334	988807	500	14"&8"	1.65	170	168.35	191	15-20
120	Bira Sefer	467754	995964	500	12"& 8"	46	121.9	75.9	196	6
121	Salo Gora	472669	982829	550	12"& 8"	0	171.86	171.86	208-219	20
122	Zenebe Woreq	467635	992857	378	12"& 8"	37	86.85	49.85	170	30
123	Ayer Tena School	466206	992781	420	12"& 8"&6	68.52	124.5	55.98	223	39.5
124	Bereket Condominium	462983	992212	404	12"& 8"	118.73	161.1	42.37	232	23
125	Kara Kore	465246	992155	407	12"& 8"&6	43.8	87.03	43.23	232	20
126	Sodo Sefer	463496	992901	412	12"& 8"	153.03	182.59	29.56	246	27
127	16-Condominium	473820	994780	298	10"& 6"	111.2	212.4	101.2	235	8
128	Hana Lafto	472456	988272	301	10"& 8"	14.23	52.72	38.49	125	30
129	Sarbet	470899	995149	300	10"& 8"	54.85	71.09	16.24	137	15
130	Batu Condominium	469842	991054	310	8"& 6"	11	56.9	45.9	182-217	20
131	Jemo Mestawot Factory	468254	990885	305	10"& 6"	31.4	67	35.6	160-165.8	28
132	Saris Bulbula Tena School	474393	989479	302	10"& 6"	38.2	52.86	14.66	155	30
133	OR10-LTW2	493563	1003393	582	14"&8"	37.92	178.65	140.73	187.13-204.68,210-228	18
134	Ersha Sebel	473155	1001045	362	12"& 8"	50	167.01	117.01	213	3
135	Sheger Menafesha	471284	1000999	412	12"& 8"	21	162.9	141.9	200	3
136	Tesfa School	471384	992886	297	10"& 6"	31.6	169.81	138.21	228-234	5
137	Geja School	47439	989479	302	10"& 6"	99.6	178.3	78.7	200	10
138	Bole Arabssa Woreda-9	481740	994597	253	Abandoned because high Fluoride content (> 6 mg/lit)					
139	Dandi Boru Condominium Well	474907	994171	236	10"& 6"	103.5	143.5	40	211 m to 215	10
140	Hana Kotari	470662	990671	428	14"&8"	3.7	61.46	57.76	160	67

7. Summary of SANF water supply data

		Design Well Data									
No	Bhs name	X-UTM	Y-UTM	Elevation	Depth	Casing(Ø)	SWL	DWL	DD	Pump.p(m)	Disharge,l/s
1	SANF-TW-01	477891	987018	2215	411	14&8	8.91	80.08	71.17	98	35
2	SANF-TW-02	484001	987465	2245	442	14&8	0.35	41.52	41.17	94	50
3	SANF-TW-03	481012	984597	2192	440	14&8	29.8	75.5	45.7	110	50
4	SANF-PW-01	483963	985000	2220	528	14&8	16.65	137.84	121.19	195	35
5	SANF-PW-02	481887	984954	2206	420	14&8	38.85	133.73	94.88	150	38
6	SANF-PW-03	482141	982240	2277	523	14&8	32.2	136.15	103.95	185	40
7	SANF-PW-04	477224	981760		519	14&8	5.95	132.17	126.22	185	30
8	SANF-PW-05	479454	985457	2185	512	14&8	18.63	78.38	59.75	135	60
9	SANF-PW-06	499681	1008600	2511	530	14&8	4.85	90.65	85.8	130	86
10	SANF-PW-07	480482	986991	2204	546.5	14&8	14.2	115.22	101.02	154	90
11	SANF-PW-08	482636	985971	2225	542	14&8	30.48	172.43	141.95	216 to 228	32
12	SANF-PW-09	481550	986735	2199	491.5	14&8	35.36	115.72	80.36	138	78
13	SANF-PW-11	482948	987663	2220	440	14&8	20.6	146.34	125.74	180	50
14	SANF-PW-12	483560	983856	2240	542	14&8	68	130.51	62.51	176	30
15	SANF-PW-14	481129	989896	2236	458.5	14&8	1	123.32	122.32	154	70
16	SANF-PW-15	480370	984380	2180	546	14&8	40	147.32	107.32	196 to 208	40
17	SANF-PW-16	484553	986685	2240	546.2	14&8	7.1	130.7	123.6	154	80
18	SANF-PW-17	488270	987666	2224	333.9	14&8	6.55	141.98	135.43	172	58
19	SANF-PW-18	485313	984138	2270	550	14&8	59.6	179.25	119.65	200	23
20	SANF-PW-19	485707	983543	2222	482.4	14&8	37.48	197.81	160.33	214	20
21	SANF-PW-21	484142	982196	2206	549.5	14&8	13.23	138.38	125.15	160	45

8. Summary of LLA-phase II water supply data

No	Bhs name	Design Well Data									
		X-UTM	Y-UTM	Elevation	Depth	Casing(Ø)	SWL	DWL	DD	Pump.p(m)	Disharge,l/s
1	LLA-07	508854	1001610	2520	254	14"&8"	52.2	64.4	12.2	145-150	113
2	LLA -PW15	503284	1005378	2509	323	14"&8"	54.8	63.62	8.82	147-152	110
3	LLA-PW8	496944	1007787	2527	551	14"&8"	57.64	149.56	91.92	195-200	50
4	LLA-08	503937	1003756	2499	501	14"&8"	52.69	62.9	10.21	152-158	110
5	LLA-09	502084	1008222	2508	514	14"&8"	57.4	86.06	28.66	175-178	95
6	LLA -PW17	501684	1004947	2497	371	14"&8"	73	95.94	22.94	185-187	95
7	LLA -PW14	502267	1009162	2515	378	14"&8"	62.65	77.32	14.67	165-168	100
8	LLA-11	508321	1013326	2540	550	12"&6"	85.1	154.3	69.2	180-190	6
9	LLA -PW12	495420	1009986	2515	510	14"&8"	59.1	145.3	86.2	202-205	30

*Appendix Table 9: Sensitivity Analysis (**Table 1 Pairwise comparison matrix excluding Rainfall (**Consistency ratio is 0.06 < 0.1))*

Factors	Land Use Land Cover	Soil Texture	Lithology	Lineament Density	Slope	Topographic Position Index	Drainage Density	Topographic Wetness Index	Criteria weight (%)
LULC	1	2	3	4	3	4	3	4	**27.00**
ST	1	1	2	3	4	5	6	7	**23.72**
Li	1/3	1/2	1	2	3	4	5	6	**16.53**
LD	1/4	1/3	1/2	1	2	3	4	7	**12.14**
Sl	1/3	1/4	1/3	1/2	1	1	3	4	**7.60**
TPI	1/4	1/5	1/4	1/3	1	1	2	3	**5.94**
D.D	1/3	1/6	1/5	1/4	1/3	1	1	2	**4.21**
TWI	1/4	1/7	1/6	1/7	1/4	1/3	1/2	1	**2.85**
Sum	**3.25**	**4.59**	**7.45**	**11.23**	**14.58**	**18.83**	**24.50**	**34.00**	**100.00**

Table 2 Pairwise comparison matrix excluding Land use Land Cover (Consistency ratio is 0.05 < 0.1,)

Factors	Rainfall	Soil Texture	Lithology	Lineament Density	Slope	Topographic Position Index	Drainage Density	Topographic Wetness Index	Criteria weight (%)
R.F	**1**	**3**	**2**	**3**	**2**	**3**	**4**	**5**	**25.56**
ST	**1/3**	**1**	**2**	**3**	**4**	**5**	**6**	**7**	**23.61**
Li	**1/2**	**1/2**	**1**	**2**	**3**	**4**	**5**	**6**	**17.47**
LD	**1/3**	**1/3**	**1/2**	**1**	**2**	**3**	**4**	**7**	**12.55**
Sl	1/2	1/4	1/3	1/2	1	1	3	4	**8.15**
TPI	1/3	1/5	1/4	1/3	1	1	2	3	**6.22**
D.D	1/4	1/6	1/5	1/4	1/3	1	1	2	**3.83**
TWI	1/5	1/7	1/6	1/7	1/4	1/3	1/2	1	**2.61**
Sum	**3.45**	**5.59**	**6.45**	**10.23**	**13.58**	**17.83**	**25.50**	**35.00**	**100.00**

Table 3 Pairwise comparison matrix excluding Soil Texture (Consistency ratio is 0.07 < 0.1)

Factors	Rainfall	Land Use Land Cover	Lithology	Lineament Density	Slope	Topographic Position Index	Drainage Density	Topographic Wetness Index	Criteria weight (%)
R.F	1	2	2	3	2	3	4	5	23.81
LULC	1/2	1	3	4	3	4	3	4	23.03
Li	1/2	1/3	1	2	3	4	5	6	17.58
LD	1/3	1/4	1/2	1	2	3	4	7	12.93
Sl	1/2	1/3	1/3	1/2	1	1	3	4	8.69
TPI	1/3	1/4	1/4	1/3	1	1	2	3	6.62
D.D	1/4	1/3	1/5	1/4	1/3	1	1	2	4.39
TWI	1/5	1/4	1/6	1/7	1/4	1/3	1/2	1	2.95
Sum	3.62	4.75	7.45	11.23	12.58	16.83	22.50	32.00	100.00

Table 4 Pairwise comparison matrix excluding Lithology (Consistency ratio is 0.08 < 0.1)

Factors	Rainfall	Land Use Land Cover	Soil Texture	Lineament Density	Slope	Topographic Position Index	Drainage Density	Topographic Wetness Index	Criteria weight (%)
R.F	1	2	3	3	2	3	4	5	**25.03**
LULC	1/2	1	2	4	3	4	3	4	**20.64**
ST	1/3	1	1	3	4	5	6	7	**20.34**
LD	1/3	1/4	1/3	1	2	3	4	7	**12.18**
Sl	1/2	1/3	1/4	1/2	1	1	3	4	**8.34**
TPI	1/3	1/4	1/5	1/3	1	1	2	3	**6.36**
D.D	1/4	1/3	1/6	1/4	1/3	1	1	2	**4.25**
TWI	1/5	1/4	1/7	1/7	1/4	1/3	1/2	1	**2.87**
Sum	**3.45**	**4.92**	**7.09**	**12.23**	**13.58**	**17.83**	**23.50**	[illegible]	**100.00**

Table 5 Pairwise comparison matrix excluding Lineament Density (Consistency ratio is 0.07 < 0.1)

Factors	Rainfall	Land Use Land Cover	Soil Texture	Lithology	Slope	Topographic Position Index	Drainage Density	Topographic Wetness Index	Criteria weight (%)
R.F	1	2	3	2	2	3	4	5	24.11
LULC	1/2	1	2	3	3	4	3	4	20.18
ST	1/3	1	1	2	4	5	6	7	19.46
Li	1/2	1/3	1/2	1	3	4	5	6	14.94
Sl	1/2	1/3	1/4	1/3	1	1	3	4	8.07
TPI	1/3	1/4	1/5	1/4	1	1	2	3	6.18
D.D	1/4	1/3	1/6	1/5	1/3	1	1	2	4.17
TWI	1/5	1/4	1/7	1/6	1/4	1/3	1/2	1	2.88
Sum	**3.62**	**5.00**	**7.26**	**8.95**	**14.58**	**18.83**	**24.50**	**32.00**	**100.00**

Table 6 Pairwise comparison matrix excluding Slope (Consistency ratio is 0.08 < 0.1)

Factors	Rainfall	Land Use Land Cover	Soil Texture	Lithology	Lineament Density	Topographic Position Index	Drainage Density	Topographic Wetness Index	Criteria weight (%)
R.F	1	2	3	2	3	3	4	5	24.84
LULC	1/2	1	2	3	4	4	3	4	20.81
ST	1/3	1	1	2	3	5	6	7	18.10
Li	1/2	1/3	1/2	1	2	4	5	6	13.70
LD	1/3	1/4	1/3	1/2	1	3	4	7	10.27
TPI	1/3	1/4	1/5	1/4	1/3	1	2	3	5.48
D.D	1/4	1/3	1/6	1/5	1/4	1	1	2	4.04
TWI	1/5	1/4	1/7	1/6	1/7	1/3	1/2	1	2.76
Sum	**3.45**	**4.92**	**7.34**	**9.12**	**13.73**	**20.83**	**25.50**	**35.00**	**100.00**

Table 7 Pairwise comparison matrix excluding TPI (Consistency ratio is 0.08 < 0.1)

Factors	Rainfall	Land Use Land Cover	Soil Texture	Lithology	Lineament Density	Slope	Drainage Density	Topographic Wetness Index	Criteria weight (%)
R.F	1	2	3	2	3	2	4	5	**24.17**
LULC	1/2	1	2	3	4	3	3	4	**20.50**
ST	1/3	1	1	2	3	4	6	7	**17.98**
Li	1/2	1/3	1/2	1	2	3	5	6	**13.41**
LD	1/3	1/4	1/3	1/2	1	2	4	7	**9.84**
Sl	1/2	1/3	1/4	1/3	1/2	1	3	4	**7.49**
D.D	1/4	1/3	1/6	1/5	1/4	1/3	1	2	**3.91**
TWI	1/5	1/4	1/7	1/6	1/7	1/4	1/2	1	**2.70**
Sum	**3.62**	**5.00**	**7.39**	**9.20**	**13.89**	**15.58**	**26.50**	**36.00**	**100.00**

Table 8 Pairwise comparison matrix excluding Drainage Density (Consistency ratio is 0.08 < 0.1)

Factors	Rainfall	Land Use Land Cover	Soil Texture	Lithology	Lineament Density	Slope	Topographic Position Index	Topographic Wetness Index	Criteria weight (%)
R.F	1	2	3	2	3	2	3	5	**23.88**
LULC	1/2	1	2	3	4	3	4	4	**21.23**
ST	1/3	1	1	2	3	4	5	7	**17.84**
Li	1/2	1/3	1/2	1	2	3	4	6	**13.20**
LD	1/3	1/4	1/3	1/2	1	2	3	7	**9.55**
Sl	1/2	1/3	1/4	1/3	1/2	1	1	4	**6.56**
TPI	1/3	1/4	1/5	1/4	1/3	1	1	3	**5.10**
TWI	1/5	1/4	1/7	1/6	1/7	1/4	1/3	1	**2.63**
Sum	**3.70**	**4.92**	**7.43**	**9.25**	**13.98**	**16.25**	**21.33**	**37.00**	**100**

Table 9 Pairwise comparison matrix excluding TWI (Consistency ratio is 0.07 < 0.1)

Factors	Rainfall	Land Use Land Cover	Soil Texture	Lithology	Lineament Density	Slope	Topographic Position Index	Drainage Density	Criteria weight (%)
R.F	1	2	3	2	3	2	3	4	**23.78**
LULC	1/2	1	2	3	4	3	4	3	**21.07**
ST	1/3	1	1	2	3	4	5	6	**18.04**
Li	1/2	1/3	1/2	1	2	3	4	5	**13.31**
LD	1/3	1/4	1/3	1/2	1	2	3	4	**8.92**
Sl	1/2	1/3	1/4	1/3	1/2	1	1	3	**6.50**
TPI	1/3	1/4	1/5	1/4	1/3	1	1	2	**4.94**
D.D	1/4	1/3	1/6	1/5	1/4	1/3	1	1	**3.43**
Sum	**3.75**	**5.00**	**7.45**	**9.28**	**14.08**	**16.33**	**21.50**	**28.00**	**100.00**

Appendix Table 10. Evaluation of Suitability of Artificial Groundwater Recharge Structures for the Study Area based on Central Groundwater Board, 2007. Manual on Artificial Recharge of Groundwater. Government of India

S.No	**Artificial recharge structure (MAR Method)**	**Details**	**Suitability/Location**
A	**Direct Methods /Surface spreading Methods**		
A.1	"Flooding"	"This technique is ideal for lands adjoining rivers or irrigation canals in which water levels remain deep even after monsoons and where sufficient non-committed surface water supplies are available. The schematics of a typical flooding system are shown in (**Appendix Figure A)** to ensure proper contact time and water spread, embankments are provided on two sides to guide the unutilized surface water to a return canal to carry the excess water to the stream or canal."	Not Suitable since the catchment is dominated with Clayey soils having low permeability and are not suitable for flooding recharge as they restrict water infiltration and can lead to runoff or ponding. It also requires large flat permeable surface area, high potential for water pollution and evaporation
A.2	"Ditch and Furrows method"	"This method involves construction of shallow, flat-bottomed and closely spaced ditches or furrows to provide maximum water contact area for recharge from source stream or canal. The ditches should have adequate slope to maintain flow velocity and minimum deposition of sediments. The widths of the ditches are typically in the range of 0.30 to 1.80 m. A collecting channel to convey the excess water back to the source stream or canal should also be provided. A typical system is shown in **Appendix Fig B (**N.B they are adaptatable to irregular terrain and uneven surfaces)"	Despite its Suitability to Permeable soils with sufficient aquifer depth for effective infiltration, Areas in the catchment with moderate slopes are mostly clayey and Sufficient land is necessary for constructing the ditches and furrows without interfering with other land uses so not recommended in this study.
A.3	"Recharge Basin"	"Artificial recharge basins are commonly constructed parallel to **ephemeral or intermittent** stream channels and are either excavated or are enclosed by dykes and levees. They can also be constructed parallel to canals or surface water sources. In **alluvial** areas, multiple recharge basins can be constructed parallel to the streams" **(Appendix Fig C)**	Could be Suitable along the alluvial deposits of Akaki ephemeral streams of the catchment but location is dependent on availability of

			Permeable soils and sufficient aquifer depth for effective infiltration and Sufficient land is required for the basin without infringing on existing land uses
B	**Direct Methods /Runoff Conservation Structures**		
B.1	“**Bench Terracing**”	“Bench terracing involves leveling of sloping lands with surface gradients up to 8% percent and having adequate soil cover for bringing them under irrigation. It helps in soil conservation and holding runoff water on the terraced area for longer durations, leading to increased infiltration and ground water recharge”.	Suitable for the main recharge areas of Entoto Ridge having 8% Slopes i.e. North and North Western Intoto (Mt.wechecha).
B.2	“Contour Bunds”	“Contour bunding, which is a watershed management practice aimed at building up soil moisture storage involve construction of small embankments or bunds across the slope of the land. They derive their names from the construction of bunds along contours of equal land elevation. This technique is generally adopted in low rainfall areas (**normally less than 800 mm**) where gently sloping agricultural lands with very long slope lengths are available and the soils are permeable. They are not recommended for soils with poor internal drainage e.g. clayey soils. Contour bunding involves construction of narrow-based trapezoidal embankments (bunds) along contours to impound water behind them, which infiltrates into the soil and ultimately augment ground water recharge”.	Not Suitable since the study area receives rainfall >1000mm
B.3	“Contour Trenches”	“Contour trenches are rainwater harvesting structures, which can be constructed on hill slopes as well as on degraded and barren waste lands in both **high- and low**- rainfall areas. The trenches break the slope at intervals and reduce the velocity of surface runoff. The water retained in the trench will help in conserving the soil moisture and ground water recharge. In areas where soil cover is thin, depth of trenching is restricted and more trenches at closer intervals need to be constructed. In general, the horizontal interval may vary from 10 m in steep slopes to about 25 m in gentle slopes”	Suitable for the main recharge areas of Entoto Ridge North and North Western Intoto

B.4	“Gully Plugs and **Check Dam**s **“**	“Check dams are constructed across small streams having gentle slope and are feasible both in hard rock as well as alluvial formation. These structures (Gully Plugs and checks dams) are constructed across gullies, streams to check the flow of surface water in the stream channel and to retain water for longer durations in the pervious soil or rock surface. As compared to gully plugs, which are normally constructed across 1st order streams, check dams are constructed across **bigger streams** and in areas having **gentler slopes**. These may be temporary structures such as brush wood dams, loose / dry stone masonry check dams, Gabion check dams and woven wire dams constructed with locally available material or permanent structures constructed using stones, brick and cement. The site selected for check dam should have sufficient thickness of permeable soils or weathered material to facilitate recharge of stored water within a short span of time. The total catchment area of the stream should normally be between **40 and 100** ha. Local situations can, however, be a guiding factor in this regard. The rainfall in the catchment should be preferably less than **1000 mm / annum**. The rock strata exposed in the ponded area should be **adequately permeable** to cause ground water recharge”.	Suitable for Pervious, gentle Slopes (<10^{o}) and 2nd and 3rd order streams
B.5	“Earthen Dam Percolation Tanks/s (Homogenous, Zoned and Diaphragm, Earth Dams)”	“A percolation tank is an artificially created surface water body submerging a highly **permeable** land area so that the surface runoff is made to percolate and recharge the ground water storage. They differ from *check dams* in having larger reservoir areas. The hydrogeology of the area should be such that the litho-units occurring in the area of submergence of the tank should have **high permeability**. The soils in the catchment area of the tank should be **sandy** to avoid silting up of the tank bed. The availability of non-committed surplus monsoon runoff should be sufficient to ensure filling of the tank every year”.	Not recommended to apply due to difficulty in finding large uncultivated land (for the submergence area) and sandy area with high permeability having proximity to wells and cultivable land.

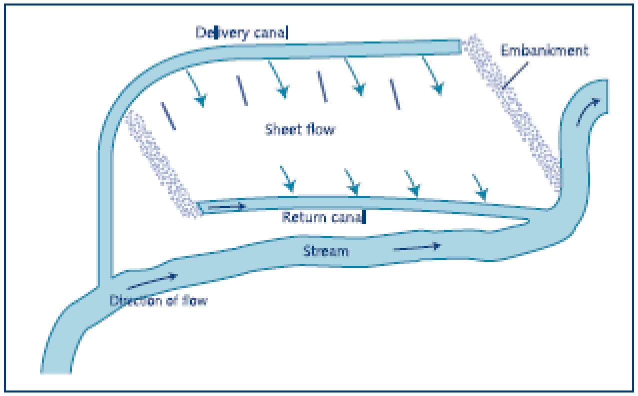
		“The percolation tank should be located downstream of runoff zone, preferably toward the edge of piedmont zone or in the upper part of the transition zone. These are the most prevalent structures in India as a measure to recharge the ground water reservoir both in alluvial as well as hard rock formation **Land slope between 3 and 5 percent** is ideal for construction of percolation tanks. There should be adequate area suitable for irrigation and sufficient number of ground water abstraction structures within the command of the percolation tank to fully utilize the additional recharge. The area benefited should have a productive **phreatic aquifer** with lateral continuity up to the percolation tank. The depth to water level in the area should remain more than 3 m below ground level during post monsoon period. Soils available in catchment area should be of **light sandy type** to avoid silting up of the tanks bed. Percolation tanks are to be normally constructed on **second or third** order streams, as the catchment area of such streams would be of optimum size. The location of tank and its submergence area should **be in non-cultivable** land and in natural depressions requiring lesser land acquisition. **There should be cultivable land downstream of the tank in its command with a number of wells to ensure maximum benefit by such efforts**. Detailed geological investigations may be carried out to study the nature and depth of formation at the bund (dam) site for deciding the appropriate depth of cut off trench (COT). This will help in reducing the visible seepage and also ensure safety and long life of the structure”.	
B.6	“Stream Channel Modification / Augmentation.”	“A natural drainage channel can be modified so as to increase infiltration by detaining stream flow and increasing the stream bed area in contact with water. The channel is so modified that the flow gets spread over a”	Not Suitable since most of The underlying geology should be composed of materials like sand

		“wider area, increasing contact with the Percolating river bed. The method includes (i) widening, levelling, scarifying or ditching the stream channel; (ii) L-shaped finger levees or hook levees constructed by bulldozer at the end of the high flow season; and (iii) low head check dams that allow flood flows to pass over safely. Stream channel modification methods are generally applied in **alluvial** areas. However, they can be effectively used also in hard-rock areas where thin river alluvium overlies a good phreatic aquifer or the rocks are extensively weathered or highly fractured in and around the stream channel offering scope for artificial recharge”	or gravel that readily allow water to infiltrate. Clayey or rocky streambeds wouldn't be suitable.
C	**Direct Methods/ Subsurface Techniques**		
C.1	“Injection Wells or Recharge Wells”	“Injection wells or recharge wells are structures similar to bore/tube wells but constructed for augmenting the ground water storage in deeper aquifers through supply of water either under gravity or under pressure. The aquifer to be replenished is generally one with considerable desaturation due to overexploitation of ground water. **. In alluvial areas**, injection wells recharging a single aquifer or multiple aquifers can be constructed in a manner similar to normal gravel packed pumping wells. However, in case of recharge wells, cement sealing of the upper section of the wells is done to prevent the injection pressure from causing leakage of water through the annular space of the borehole and the well assembly. For optimum benefits, it is advisable to have injection – cum – pumping wells to be used both for ground water recharge and extraction under favorable conditions. The recharge well should be designed to fully penetrate the aquifer to avoid additional head losses due to partial penetration”.	Detailed studies needed for the vertical and lateral extents of “the aquifers and its characteristics are necessary prerequisites for such schemes” (to identify the sand bearing aquifers) however not recommended in this study due to costy nature to apply to the deep seated aquifers.
C.2	“**Gravity Head Recharge Wells**”	“In addition to specially designed injection wells, existing dug wells and tube/bore wells may also be alternatively used as recharge wells, as and when source water becomes available. In areas where considerable de-saturation of aquifers have already taken place due to over-exploitation of ground water resources resulting in the drying up of dug wells and lowering of piezometric heads in bore/tube”	Suitable to use at Abandoned and yield deteriorated wells in the Catchment such as koyefeche wells and pocket areas.

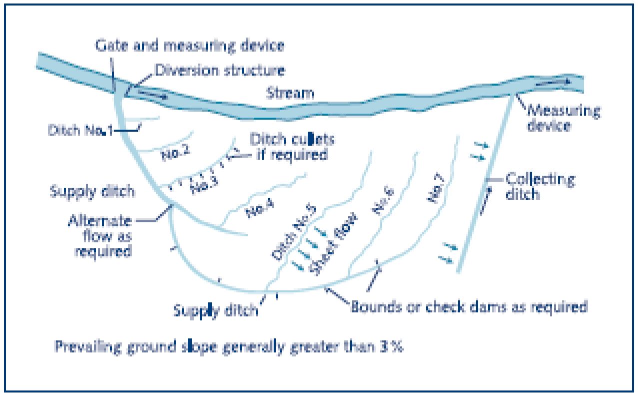
		“wells, **existing ground water abstraction** structures provide a cost-effective mechanism for artificial recharge of the phreatic or deeper aquifer zones as the case may be. In areas where **excess surface water** is available during rainy season and the phreatic aquifers remain unsaturated, surface water can be pumped into the dug wells for augmentation of ground water resources. Wells with higher yields before getting dried up due to the desaturation of aquifers should be selected for recharge as they prove to be more suitable for ground water recharge when compared to low yielding wells”.	
C.3	**“Recharge Pits”**	“Recharge pits are normally excavated pits of variable dimensions, which are Sufficiently deep to penetrate the low-permeability layers overlying the unconfined aquifers. They are similar to recharge basins in principle, with the only difference being that they are deeper and have restricted bottom area. In many such structures, most of the infiltration occurs laterally through the walls of the pit as in most layered sedimentary or alluvial material the lateral hydraulic conductivity is considerably higher than the vertical hydraulic conductivity. The permeability of the underlying strata should be ascertained through infiltration tests before taking up construction of recharge pits. The side slopes of recharge pits should be 2:1 as steep slopes reduce clogging and sedimentation on the walls of the pit. In hard rock areas, streambed sections crossing weathered or fractured rocks or sections along prominent lineaments or intersection of lineaments form ideal locations for recharge pits.”	Suitable but might be difficult to apply to the deep seated or confined aquifers of akaki well field.
C.4	“**Recharge Shafts**”	“In cases where an aquifer is located deep below the ground surface and overlain by poorly permeable strata, a shaft is used for artificial recharge. A recharge shaft is similar to a recharge pit but much smaller in cross	Suitable to Akaki well field semi confined aquifer thickness having deeper Groundwater depth.

		section (Appendix Figure I). Recharge Shafts are similar to recharge pits but are constructed to augment recharge into phreatic aquifers where water levels are much deeper and the aquifer zones are overlain by strata having low permeabilityA recharge shaft may be dug manually if the strata is non-caving. In good hard clays it is possible to dig deep shafts down to 25 to 30 m depth without lining The shaft should end in more permeable strata below the confining layer. Deeper shafts dug out in caving strata need lining or casing. It is not necessary to backfill lined shafts completely. A few metres thick gravel or coarse sand filter can be placed at the bottom. In case of clogging, the filter material can be removed by bailing and replaced with clean filter material. In lined shafts, the recharge water may be fed through a smaller conductor pipe reaching up to the filter pack.”	
D	**Indirect Methods**		
D.1	“Induced Recharge”	“Induced recharge involves pumping water from an aquifer, which is hydraulically connected with surface water to induce recharge to the ground water reservoir. Once hydraulic connection gets established by the interception of the cone of depression and the river recharge boundary, the surface water sources starts providing part of the pumping yield. For implementation of successful induced recharge schemes from stream channels, pumping wells should be selected at sites where water in the streams has sufficient velocity to prevent silt deposition.” .	Not Suitable due to High costs of construction and maintenance. High Potential for clogging or contamination of aquifers. .
D.2	“Aquifer Modification Techniques (Bore Blasting and Hydro-Fracturing)”	“These are used to change aquifer characteristics so it can store more water and transmit more water and after application of the techniques more recharge takes place under natural as well as artificial condition. Bore blasting method is used to increase the fracture porosity of an aquifer. Shallow bore wells are drilled in the area where fracture porosity of the aquifer is planned to increase. These bore wells are blasted with the help of explosives which creates fracture porosity in the aquifer. Hydro fracturing is used to improve the yield of a bore well. In this technique water is injected at a very high pressure widening the existing fracture of”	Not Suitable due to probable groundwater contamination , disruption of natural aquifer structure and High costs and technical challenge in accurately predicting the direction and extent of fractures created by blasting or fracturing

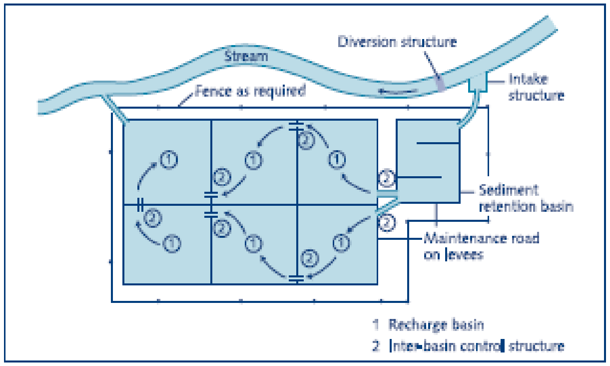
		“the rock. The high pressure injection of water also helps in removing of clogging, creates interconnection between the fractures, and extends the existing length of the old fractures. The high pressure injection also creates new fracture in the rock strata. As a result of these, the water storing and transmitting capacity of the strata increases”	
E	**Ground Water Conservation Techniques**		
E.1	“Sub-Surface Dykes / Ground Water Dams /”	“Ground water conservation techniques are intended to retain the ground water for Longer periods in the basin/watershed by arresting the sub-surface flow. A sub-surface dyke / ground water dam is a sub-surface barrier constructed across a stream channel for arresting/retarding the ground water flow and increase the ground water storage. At favorable locations, such dams can also be constructed not only across streams, but in large areas of the valley as well for conserving ground water. Valley shapes and gradients are important considerations for site identification. The limitations on depth of underground construction deem that the unconfined aquifer should be within a shallow to moderate depth (down to 10 m bgl) and has a well-defined impermeable base layer. Such situations occur in hard rock areas and shallow alluvial riverine deposits. The dyke is ideally constructed across narrow ground water valleys, generally not exceeding 150 to 200 m in width. On the basis of a thorough study of a water table contour map of the area, a narrow ground water valley section where the flow lines tend to converge from up-gradient direction, usually coinciding with a surface drainage line should be identified”.	Not Suitable due to Reduced downstream flow since Subsurface dams can impede the natural flow of groundwater, potentially impacting downstream ecosystems and communities reliant on that water Additionally high evaporation rate, Long-term maintenance needs and Finding suitable locations with an ideal combination of soil characteristics, aquifer depth, and surface water availability can be challenging.



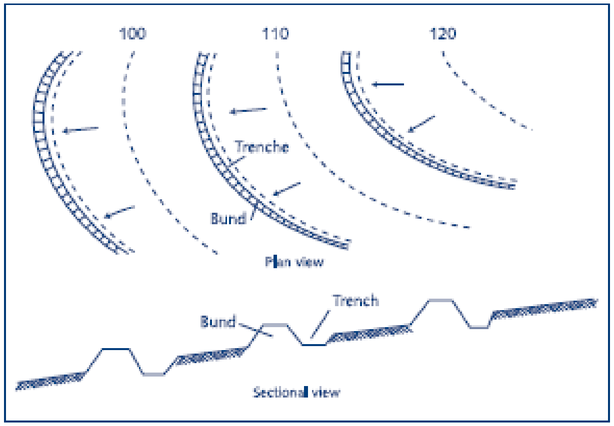
A) Flooding



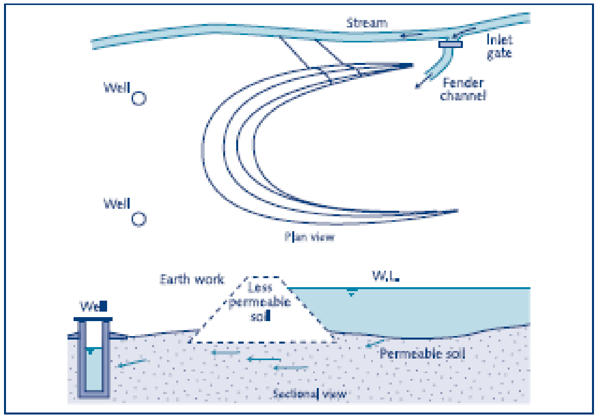
B) Ditch and Furrow method



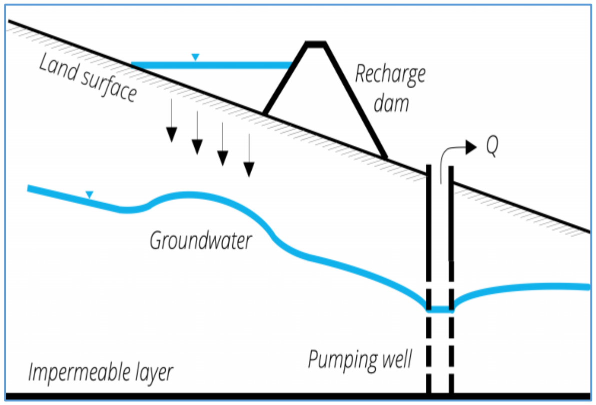
C)Recharge Basin



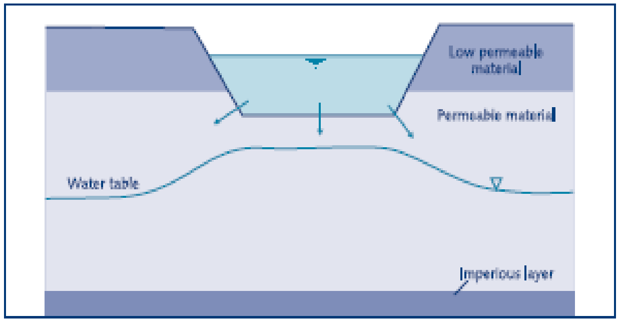
D) Contour Bunding



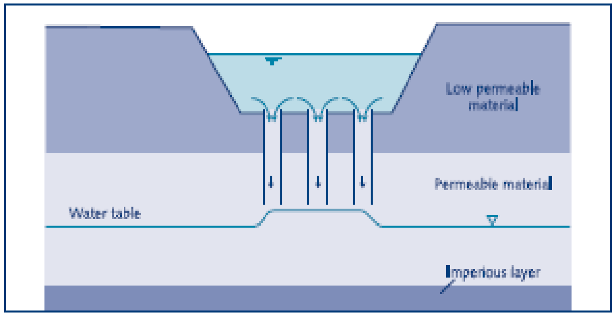
E) Percolation Tank



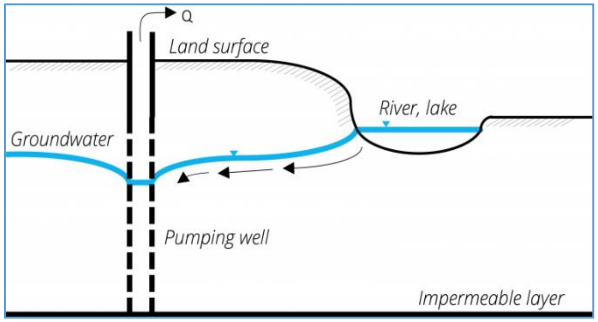
F) Check Dam



G) Recharge Pit



H) Recharge Shaft

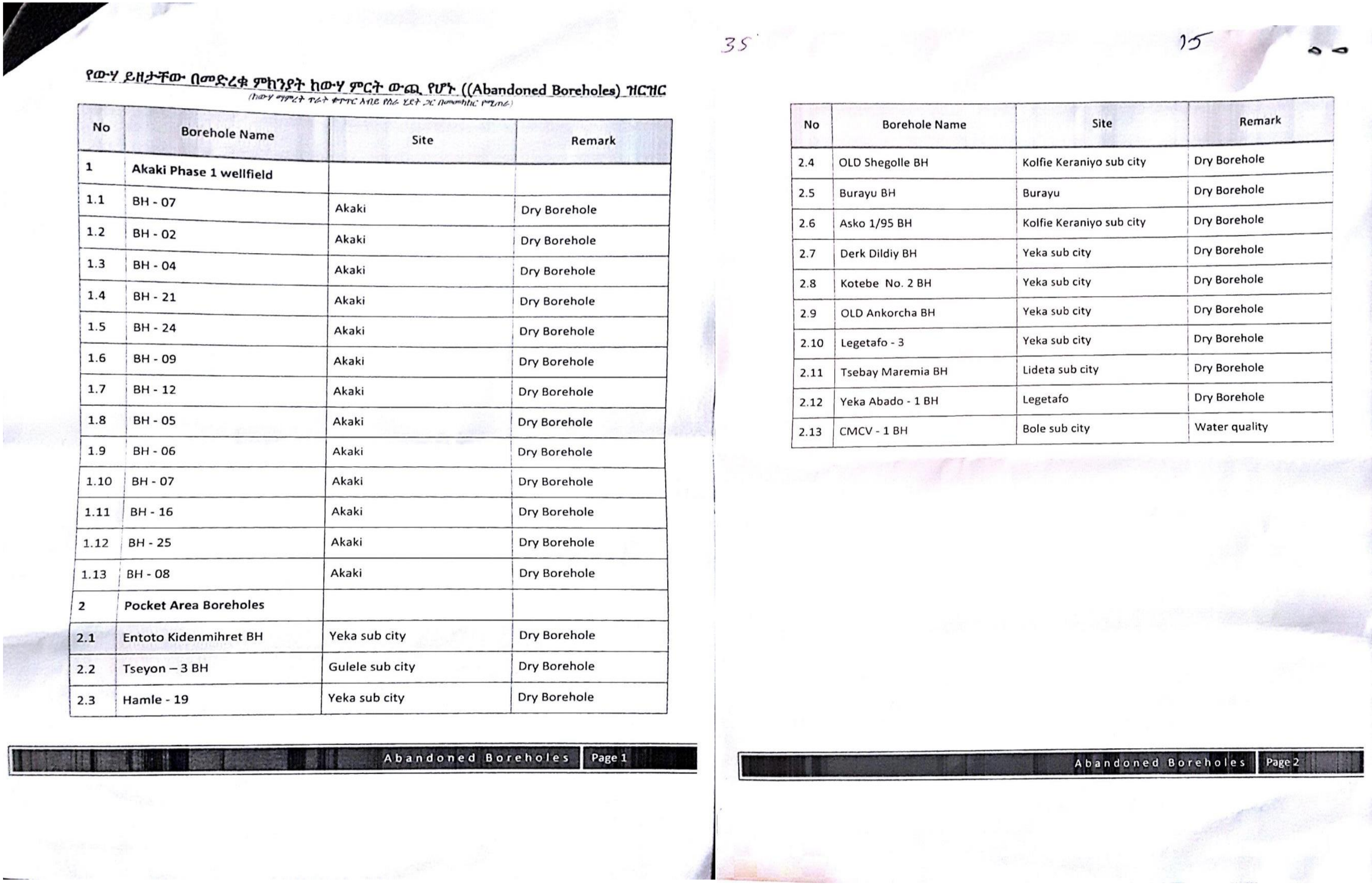


I) Induced Recharge

Appendix Table 11: General Description of the lithological Unit of the Study Area (Data taken from Geological Survey of Ethiopia)

S.No	Code and lithological description
1	**“Addis Ababa Basalts (Eaa)**: Exposure of this unit is found in the central parts of the study area. It is dark color fine-grained rock mainly composed of plagioclase, pyroxene and opaques. Generally, it is fresh, compact fine grained rock, but in places, it shows vesicular cavity. It shows intergranular and intersertal textures. “
2	**“Welded to Partially Welded Pyroclastic Flows (Npp**): Exposure of this unit is found in the western and south westerns parts of the watershed. It is light to dark-grey in fresh samples and reddish to yellow to pink in weathered ones.”
3	**“Welded Pyroclastic Flows (Nwp**): Exposure of this unit is found central east part of the map area. It is light to dark-grey in fresh samples and reddish to yellow to pink in weathered ones. It is fine grainend, densely welded rock with associated rhyolitic lava flows interleaved with ash and unwelded tuffs.”
4	**“Wechacha Trachytes (Nwt (a**): Exposure of trachytic lava flows and domes are found to the western and central portion of the map area. It is coarse-grained, light-grey, brown-grey to dark-grey but turns to pinkish yellow to reddish brown upon weathering. The products of this unit consist mainly of thick trachytic lava flows and lava domes with minor associated pyroclastic material “
5	**“Quaternary Basalt (Qb**): olivine phyric and vesicular basalt: Plateau basalts are exposed in the northern and northeastern parts of the map. In most cases it outcrops in boulder form and vesicles are filled by secondary minerals. It mainly forms ridges with the maximum thickness of about 50 m.”
6	**“Eluvial (Qel)**: Silt to Clay sized, light/dark gray to reddish brown and fertile”
7	**“Quaternary Superficial Sediments(Qs**): Mostly of eluvial soil This unit comprises mainly the eluvial soil and very small position of alluvial soil. The alluvial sediments texture varies from sand to silt in size. “
8	**“Pyroclastics and pumice fall deposits(Qtp):** It is light to dark-grey in fresh samples and reddish to yellow to pink in weathered ones. It is fine grainend, poorly welded rock containing vitrophyric fiamme and lithic fragments with associated rhyolitic lava flows interleaved with pumice, and unwelded tuffs. The fall deposits outcrop in the southern part of the study area.“
9	**“Scoria Fallouts (Qts)**: Exposure of this unit is found to the south and south eastern portions of the catchment area. It usually forms unevenly distributed cinder cones and sometimes broad-based gentle-sloping circular to elliptical hills.”
10	**“Alluvium (Qus**): Quaternary surficial deposits unit is found to South, southeast, east, central and western part of the catchment. It forms flat-lying topography and marshy areas. It consists of loose, brown to grey colour sand, silt and clay bearing clasts.”
11	**“Cheleka basalt (Tcb)**: the Cheleka basalt are Aphanitic and porphyritic basalts with minor pyroclastics. The basalts prominently dominated the north eastern parts of the study area covering 11.35% of the catchment area."
12	**“Sela Dingay-Debre birhan-Goro ignimbrite (Tdig):** are composed of ignimbrite, tuff, rhyolite, basalt, tuffaceous sediment, ash and agglomerate and are found in the eastern parts of the catchment.”
13	**“Trachytes (Tetr):** are porphyritic trachytic lava flow. Exposure of this unit is found on the entoto ridges i.e. northern part of the catchment.”
14	**“Entoto Volcanics (Tev**): are Trachyte lava flows with pyroclastic rocks interlayer with sediments and dominate the northern part of the catchment”
15	**“Pyroclastic rocks (Tpx**): are mainly welded tuff, ash, ignimbrite with interlayers of rhyolitic flow. This unit covers the North eastern and central parts of the study area. This unit forms hills on flat lying area. The thick pyroclastic tuff is overlain by the thin basalt layer. The pyroclastic tuff is white, very fine-grained (volcanic ash), light weight and very thinly bedded/laminated.”
16	**“Tarmaber megezeze basalt(Ttb**): this unit is exposed in the north eastern part of the study area and is formed from plagioclase phyric basalt and olivine-plagioclase phyric basalt with minor olivine phyric, pyroxene phyric, plagioclase-pyroxene-olivine phyric basalt and aphanetic basalt.“
17	**“Lower basalt (Tv1):** they are tertiary volcanic rock of phyric basalt (olivine-plagioclase and pyroxene-plagioclase) which is fractured and jointed.”

Appendix table 12: AAWSA Data of Abandoned Bore wells due to yield deterioration (Adopted from Debebe M,2020)



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የውሃ ይዘታቸው በመድረቁ ምክንያት ከውሃ ምርት ውጪ የሆኑ ((Abandoned Boreholes) ዝርዝር

(ከውሃ ማምረት ጥራት ቁጥጥር አብይ የስራ ሂደት ጋር በመመካከር የሚገበሬ)

No	Borehole Name	Site	Remark
1	**Akaki Phase 1 wellfield**		
1.1	BH - 07	Akaki	Dry Borehole
1.2	BH - 02	Akaki	Dry Borehole
1.3	BH - 04	Akaki	Dry Borehole
1.4	BH - 21	Akaki	Dry Borehole
1.5	BH - 24	Akaki	Dry Borehole
1.6	BH - 09	Akaki	Dry Borehole
1.7	BH - 12	Akaki	Dry Borehole
1.8	BH - 05	Akaki	Dry Borehole
1.9	BH - 06	Akaki	Dry Borehole
1.10	BH - 07	Akaki	Dry Borehole
1.11	BH - 16	Akaki	Dry Borehole
1.12	BH - 25	Akaki	Dry Borehole
1.13	BH - 08	Akaki	Dry Borehole
2	**Pocket Area Boreholes**		
2.1	Entoto Kidenmihret BH	Yeka sub city	Dry Borehole
2.2	Tseyon – 3 BH	Gulele sub city	Dry Borehole
2.3	Hamle - 19	Yeka sub city	Dry Borehole
2.4	OLD Shegolle BH	Kolfie Keraniyo sub city	Dry Borehole
2.5	Burayu BH	Burayu	Dry Borehole
2.6	Asko 1/95 BH	Kolfie Keraniyo sub city	Dry Borehole
2.7	Derk Dildiy BH	Yeka sub city	Dry Borehole
2.8	Kotebe No. 2 BH	Yeka sub city	Dry Borehole
2.9	OLD Ankorcha BH	Yeka sub city	Dry Borehole
2.10	Legetafo - 3	Yeka sub city	Dry Borehole
2.11	Tsebay Maremia BH	Lideta sub city	Dry Borehole
2.12	Yeka Abado - 1 BH	Legetafo	Dry Borehole
2.13	CMCV - 1 BH	Bole sub city	Water quality

Abandoned Boreholes Page 1

Abandoned Boreholes Page 2