ADDIS ABABA UNIVERSITY

COLLEGE OF NATURAL AND COMPUTATIONAL SCIENCES

SCHOOL OF EARTH SCIENCES

Managed Aquifer Recharge Suitability Mapping In The Akaki Catchment, central Ethiopia

A Thesis Submitted to the School of Graduate Studies of Addis Ababa University in Partial Fulfillment of the Requirments for the Degree of Masters of Sciences in Geological Science (Hydrogeology)

By

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Addis Ababa, Ethiopia

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This is to certify that the thesis prepared by Hebron Tadesse entitled: **Managed Aquifer Recharge Suitability Mapping In The Akaki Catchment, central Ethiopia** submitted in partial fulfillment of the requirements for the Degree of Master of Science in Hydrogeology complies with the regulations of the university and meets the accepted standard with respect to originality and quality.

Approval by Board of Examiners

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DECLARATION

I hereby declare that the dissertation entitled "Managed Aquifer Recharge Suitability Mapping In The Akaki Catchment, central Ethiopia" has been carried out by me under the supervision of Dr. Dessie Nedaw, School of Earth Sciences, Addis Ababa University, Addis Ababa during the year 2014-2015 E.C. as a part of Master of Science program in Hydrogeology. I further declare that this work has not been submitted to any other University or Institution for the award of any degree or diploma.

Name ______________________________________ Signature ______________________

Date ____________________________

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LIST OF ACRONYMS

MAR	Managed Aquifer Recharge
DEM	Digital Elevation Model
GIS	Geographic Information System
GIS-MCDA	Geographic Information System - Multicriteria Decision Analysis
MADM	Multiattribute Decision Making
MCDM	Multicriteria Decision Making
MODM	Multiobjective Decision Making
WLC	Weighted Linear Combination
IGRAC	International Groundwater Resources Assessment Centre
INOWAS	Innovative web-based Decision Support System for Water Sustainability
SAT	Soil Aquifer Treatment
ASR	Aquifer Storage and Recovery
ASTR	Aquifer Storage, Transfer and Recovery
SRTM	Shuttle Radar Topography Mission
SOTER	Soil Terrain Database
FAO	Food and Agriculture Organization
WLC	Weighted Linear Combination
AHP	Analytical Heirerachy Process
CAD	Computer-Aided Design
RS	Remote Sensing
GPS	Global Positioning System
PCM	Pair-wise Comparision Method
HSG	Hydrological Soil Group
ITCZ	Inter-Tropical Convergence Zone
CR	Consistency Ratio

Abstract

Groundwater resources in Akaki catchment are under increasing stress due to excessive use and a variety of anthropogenic influences such as population growth, urbanization, and pollution. The intense pumping has caused the water table level to drop quickly. For groundwater resources to be utilized in a sustainable manner, artificial recharge techniques and effective management methods are essential. Managed Aquifer Recharge is an artificial method for replenishing subsurface aquifers utilizing excess surface water, treated wastewater, and stormwater. It could be used as a method to increase freshwater availability and prepare for climate change. Creating a MAR suitability map may be one of the steps to be taken to reach sustainable groundwater management.

The present study used GIS multi-criteria decision analysis commonly known as GIS-MCDA method to identify suitable sites for implementing MAR. Utilizing a web-based application called INOWAS, the available MAR techniques are summarized based on the hydrogeologic parameter and the study area's objectives. To create the MAR suitability map, seven contributing factors were employed as criteria: drainage density, land use, slope, soil, geology, water level and rainfall. They were selected based on the objective and the available data. Three steps are performed in order to identify suitable sites for MAR: problem definition, suitability mapping, and sensitivity analysis. Among different criterions, step-wise function was used for standardization, pairwise comparison was used for criterion weighing as well as weighted overlay analysis was used as decision rules. The suitability map divided the study area into highly suitable, suitable, moderately suitable, low suitability, and unsuitable classes. The results show that 71.54% of the area is moderately suitable for implementing MAR. The suitable areas locate in the northern part of the catchment. The majority of areas are moderately suitable and are scattered throughout the watershed. The areas with low suitability are mainly in southern parts of the area. The first MAR suitability map for the Akaki watershed can be used as a guide and screening tool to target site-specific research for MAR implementation in highly suitable regions.

Keywords: Managed Aquifer Recharge (MAR), GIS, Suitability mapping, Multi-Criteria Decision Analysis, Akaki catchment

CHAPTER ONE

INTRODUCTION

1.1 Background

Groundwater is one of the most productive community resources, which underpins human health, economic improvement and biological differences. As a result of the combined effects of climate change and population increase, water supplies are currently under stress. On the one hand, climate change is increasing the natural variability of climate, which controls the distribution of water through precipitation, resulting in a decline in freshwater availability. Population expansion, on the other hand, raises the demand for water for food security and economic development. In this context, increasing water storage below the surface is a promising method for increasing freshwater availability and becoming more climate resilient (Dupont et al., 2018).

The Akaki watershed, which includes Addis Ababa, has historically relied on groundwater as a source of community water. In the Akaki watershed, numerous deep wells have been established with the aim of providing potable water to Addis Ababa population. However, several studies indicate that the quality and quantity of the groundwater supply of the catchments is deteriorating rapidly due to a variety of anthropogenic influences such as population growth, urbanization and pollution (Mekonnen, 2018). Accordingly, especially in the city of Addis Ababa and the Akaki River Basin in general, there are water supply problems due to the depletion of groundwater, although the water resources are very important as the capital of Ethiopia. The main developer of groundwater sources in Addis Ababa City and its suburbs is the Addis Ababa Water Supply & Sewerage Authority (AAWSA), however there are thousands of private groundwater developers (factories, service providers, etc.) on the other side. Except for a few industries, such as breweries and water bottling plants, which have significant groundwater abstraction rates, most people use very little groundwater for their own usage. In general, the extraction of groundwater in the city and its suburbs is chaotic (Wagena, 2011).

The overuse and scarcity of water resources, however, are becoming a serious issue. Artificial groundwater recharge is becoming a key factor to take into consideration for the area. Recharging aquifers with extra water during wet periods are one solution to the problem of deteriorating water tables. During the dry season, the extra storage might be put to good use on. Managed Aquifer Recharge (MAR) is a practice that is defined as "planned recharge of groundwater to aquifers for subsequent recovery or environmental advantages"(Dillon et al., 2018, 2020). Spreading methods, in-channel modifications, induced bank filtration, borehole recharge, and rainwater harvesting are all examples of MAR methodology(Bouwer, 2002). Groundwater management and MAR approaches can help ease the consequences of climate change, for example, by reducing evaporation, capturing run-off, limiting seawater intrusion, lowering pumping costs, reducing floods, and so forth (Escalante et al. 2019). MAR is becoming a popular technique for addressing water scarcity issues in the field of water resources planning and management. MAR has been used to recover groundwater levels, improve groundwater quality, store surface water in the subsurface, and protect against saline intrusion all over the world.

The first step towards MAR implementation is the selection of an appropriate site. Many factors need to be considered during the site selection process for MAR projects. Complex regional characteristics, heterogeneities in surface and/or subsurface characteristics, and variable groundwater qualities make site selection for MAR difficult. Because these parameters govern the groundwater recharge process, site suitability study for MAR is frequently based on intrinsic aspects including hydrogeology, topography, soil type, land use, and climate.(Sallwey et al., 2019) Even though all of these variables are important, their significance is determined by the MAR Objective and available data. Criteria such as availability, consumption and quality of water can be integrated into the detailed study of sites with specific goals (Valverde et al., 2016), e.g., agricultural use, domestic use, industrial use etc. Often, the unavailability of data is also a hurdle, as usually the data on the chemical quality of water is rarely available. In order to replenish deep or constrained aquifers, injection techniques are required. Subsurface geology and hydrogeology, therefore, play a larger effect than surface processes.

In contrast, spreading methods and in-channel alterations require an unconfined aquifer and are heavily sensitive on surface conditions. On the other hand, recently the integrated application of RS, GIS and MCDA techniques to select recharge zones/sites for artificial recharge has gained importance.

The major objective of this work is to identify the places in the catchment that demonstrate the best inherent qualities (environmental and physical parameters) for conducting future research on MAR, as opposed to first filtering out the sites that are unfavorable for MAR investigation. Other elements, like as existing infrastructure, water sources, and economy, are not taken into consideration because they are subject to change over time, unlike intrinsic factors, which are typically more or less stable. Nevertheless, socioeconomic aspects need to be examined before any particular MAR systems are put into practice. The conjunctive use of Multi-Criteria Decision Analysis (MCDA) and GIS commonly known as GIS-MCDA proved to be efficient for MAR site suitability mapping (Malczewski, 1999; Rahman et al., 2012).

1.2 Statement of the problem

The Akaki wellfield is Addis Ababa's largest wellfield and serves as a source of water for the city. For the past two decades, the city has been in constant quest to improve water supply sources as critical supply shortages have become a serious problem, particularly in the outskirts of topographically high locations. Due to rapid population growth and increasing water consumption, the city suffers from water shortages. Over the last decade, many well-fields have been drilled; Akaki, Legedadi-Legetafo-Ayat, South-Ayat-North-Fanta, and Addis Ababa pocket areas. In general, few places in the city have a constant supply of water throughout the day. People often queue at city water fountains to get their fill (Muleta & Abate, 2020). In the meantime, the Akaki catchment overuse and poor management of its groundwater resources have persisted. Due to increases in population, settlement size, deforestation, and land degradation, the issue became worse every year (Mekonnen, 2018). Groundwater is being overused as a result of the water stress brought on by the imbalance between water resources and water usage (Hailu, 2009).

Often groundwater abstractions are carried out without the basic understanding of the groundwater recharge, lateral and vertical extent of the aquifers, and the available groundwater reserve in the area (Ayenew et al., 2008). With this approach problems of different nature are occurring. Firstly, the intensive pumping of groundwater from the well field results in decline of groundwater level which potentially facilitates the flow of water from contaminated Akaki River to the shallow aquifer within the Akaki catchment. Secondly, in the Akaki well field itself, which captures water from the deep aquifer, significant drawdowns may lead to increased future installation and operational costs. Similar to other African cities, Addis Ababa faces significant challenges as a result of rapid urbanization. As a result, the city's need for water rises.

Therefore, it is necessary to carefully manage the groundwater resource that is currently accessible to maintain a balance between water supply and demand within the catchment region in order to encourage sustainable socioeconomic growth. It is necessary to put solutions into place to address the rising water demand. Consequently, regulated aquifer recharging is considered in this article as one potential remedy. Replenishing aquifers with additional water during the rainy season is one way to deal with the problem of falling water tables. Later, during the dry season, the improved storage could be used to prevent diminishing yields (Gale, 2005). Using MAR approaches, this project aims to address the study area water shortage. Two sub-objectives make up the current work in order to achieve this. The first is to delineate suitable sites for MAR implementation using GIS-MCDA and the second is to suggest suitable MAR techniques as a potential solution. The delineation of suitable MAR sites is performed using GIS-MCDA, whereas INOWAS, a web-based tool, is used to identify appropriate MAR techniques.

1.3 Objectives

1.3.1 General Objectives

The general objective of this research is to produce a Managed Aquifer Recharge suitability map in the case of the Akaki catchment using multi-criteria decision analysis (MCDA) through GIS platform.

1.3.2 Specific Objectives

1. Production of a map that serves as a screening tool and illustrates the study area's suitability for MAR.
2. Ranks the study area regarding its suitability for the application of MAR by suitability mapping
3. To suggest suitable MAR techniques

1.4 Significance of the research

Before MAR schemes can be developed, comprehensive planning is required to ensure their long-term sustainability. Since the site has an impact on the recharge process, operation strategy, and maintenance of the MAR system, selecting an appropriate recharge location is another critical step in the planning stage of a MAR project. Suitability maps for managed aquifer recharge (MAR) sites hold a strong potential for integration into sustainable groundwater management plans. MAR can be used in a wide range of environments because it integrates a variety of recharging techniques. Finding the appropriate techniques for a given site is one of the reasons for assessing the site suitability. These maps are increasingly being used and may fill a void in missing strategic MAR site planning. Their advantages for water management plans lie within the spatial display through maps, the quickness and simplicity of the analysis, the possibility to include projections of climate scenarios, population growth or land-use changes as well as the assessment of different MAR techniques and their location.

By combining multiple contributing elements, MAR suitability mapping provides a comprehensive perspective of a study area and divides it into zones of varying ranking depending on the suitability for applying MAR. Besides all of this the findings of this study will benefit the research community which will be interested in the field. In Ethiopia, MAR is still in its infancy. As a result, this study serves as a foundation and a jumping off point for future researchers, and it will help in rising the discipline as well as adding scientific knowledge and concepts to related fields.

CHAPTER TWO

LITERATURE REVIEW

2.1 Groundwater Hydrogeology

More than 98 percent of the freshwater that is available on Earth is made up of groundwater. Groundwater occurs in the subsurface, beneath the water table, where all pores in sediments and rocks are saturated. However, just because something is available doesn't mean it's easily accessible. More than half of the freshwater that is available is bound too tightly to subterranean sediments by molecular attraction to flow to wells. Groundwater is found at various depths in various hydrogeological basin geological units. Based on the size of their pores and other physical characteristics, all three types of rocks igneous, sedimentary, and metamorphic can hold ground water on a variety of scales. The porosity of rocks, which is related to the number of voids, determines how much ground water can be stored and how productive an aquifer is. In general, groundwater is the liquid that, when subjected to gravity, can travel through the spaces between rocks, sediments, and soils.(Landmeyer, 2012)

There are numerous categories for groundwater. This is due to a combination of several practical needs and the complicated and unpredictable natural factors that govern the development and dispersion of groundwater. Groundwater is categorized according to its source, the lithological structure and geological age of the rocks that contain water, various hydrodynamic characteristics and filtration parameters, temperature, chemical composition, and other factors. (Zektser I.S)

2.2 Depletion of Ground water

In several global aquifers, groundwater resources have been identified as being depleted, indicating that extraction rates have surpassed natural recharge rates in vitally significant global freshwater supplies. The depletion of groundwater has been attributed to groundwater pumping, frequently ignoring the direct and indirect effects of climate variability.

Excessive groundwater depletion affects major regions of North Africa, the Middle East, South and Central Asia, North China, North America, and Australia, and localized areas throughout the world.(Konikow & Kendy, 2005)

Groundwater depletion is the prolonged (multi-annual) withdrawal of groundwater from an aquifer in quantities exceeding average annual replenishment, leading to a persistent decline in groundwater levels and reduction of groundwater volumes. In case there is virtually no groundwater recharge occurring, non-renewable groundwater withdrawal leads to almost indefinite depletion and is also called groundwater mining.(Bierkens & Wada, 2019) An aquifer can be compared to a bank account, and ground water occurring in an aquifer is analogous to the money in the account. Hydrologists refer to this type of accounting as a water budget. Ground water can be recharged (deposited) by infiltration from precipitation, surface water, or applied irrigation water; it can be kept in storage (saved); and it can be discharged naturally to streams, springs, or seeps, or transpired by plants (withdrawn). In a ground-water system prior to development, the system is in long term equilibrium discharge is equal to recharge, and the volume of water in storage remains relatively constant. Ground-water levels fluctuate in time over a relatively small, natural range. Once pumping begins, however, this equilibrium is changed and groundwater levels decline. Just as a bank account must be balanced, withdrawals from an aquifer by pumping must be balanced by some combination of increased recharge, decreased discharge, and removal from storage (or depletion). An inventory of ground-water levels in wells reflects the volume of water stored (or occurring) in the aquifer, and is analogous to a financial statement.(U.S. Geological Survey, 2003)

2.2.1 Causes of Groundwater Depletion

1. **Groundwater depletion most commonly occurs because of the frequent pumping of water from the ground.** We pump the water more quickly than it can renew itself, leading to a dangerous shortage in the groundwater supply. As a growing world with a population that continues to rise, the more we pump water from the ground at a rapid rate, the more difficult it is for the groundwater to provide us with the amount of water that we need.(Konikow & Kendy, 2005)

2. **We continuously pump groundwater from aquifers and it does not have enough time to replenish itself**. Water flows freely through the saturated rocks known as aquifers. There are large and small aquifers, and they are the underground water reserves that absorb water and hold it, enabling us to pump it for use. The amount of water that aquifers hold is beyond impressive and can provide us with billions of gallons of water per day.

While this amount of water seems plentiful, groundwater is a major contributor to the Earth's freshwater supply and is responsible for providing up to 40% of freshwater in the world. Therefore, it doesn't have the ability to recollect quickly enough to be continually sourced for our use.(Bierkens & Wada, 2019)

3. **Agricultural needs require a large amount of groundwater**. It's frightening to think that there isn't very much groundwater left when you consider how much water we use on a daily basis to support our population of billions and our personal lifestyles. A large amount of groundwater goes to farming, but the availability of groundwater is steadily declining.

Without it, it will be extremely difficult to provide drinking water and water for crops and animals that would help communities during times of drought. The less water that is available, the less food we have and we will be faced with the issue of great demand and very little supply.(Konikow & Kendy, 2005)

2.2.2 Effects of Groundwater Depletion

Some of the negative effects of groundwater depletion:

- Lowering of the Water Table

Excessive pumping can lower the groundwater table, and cause wells to no longer be able to reach groundwater.

- Increased Costs

As the water table lowers, the water must be pumped farther to reach the surface, using more energy. In extreme cases, using such a well can be cost prohibitive.

- Reduced Surface Water Supplies

Groundwater and surface water are connected. When groundwater is overused, the lakes, streams, and rivers connected to groundwater can also have their supply diminished.

- Land Subsidence

Land subsidence occurs when there is a loss of support below ground. This is most often caused by human activities, mainly from the overuse of groundwater, when the soil collapses, compacts, and drops.

- Water Quality Concerns

Excessive pumping in coastal areas can cause saltwater to move inland and upward, resulting in saltwater contamination of the water supply.(U.S. Geological Survey, 2003)

2.2.3 Groundwater Depletion Solutions

There are many different solutions to prevent the depletion of our groundwater such as implementing responsible water usage tactics in your home, installing water-saving equipment, adopting a plant-based diet, responsible agriculture, pollution prevention, climate change action, and much more. In heavily stressed aquifers mitigation strategies, such as Managed Aquifer Recharge (MAR), are needed to restore depleted groundwater storage. reduced withdrawals (mandatory or voluntarily), improved groundwater management, conjunctive use of surface water and groundwater, and enhanced groundwater recharge. Depletion due to quality considerations can often be overcome by treatment, whereas large volumetric depletion can only be alleviated by decreasing discharge or increasing recharge. Artificial recharge of stormflow and treated municipal wastewater, for example, has successfully reversed groundwater declines.(Wendt et al., 2021)

In an effort to increase the security of groundwater resources, managed aquifer recharge (MAR) programs have been developed and implemented globally. MAR is the approach of intentionally harvesting and infiltrating water to recharge depleted aquifer storage.

The maintenance of diminishing groundwater levels is one advantage of artificial recharge techniques. As aquifers and other groundwater sources are depleted at a rate greater than the recharge rate, artificial recharge is needed to maintain a lasting water supply to prevent complete withdrawal of groundwater in the near future.

To combat over pumping of groundwater and achieve stability in the water table, artificial recharge is another water source that will help alleviate the stress on groundwater supply. For arid climates with little precipitation, recharging groundwater can be achieved through using treated wastewater, natural runoff, and runoff from irrigation. Some of the other methods and techniques for groundwater recharge are roof top rain water, runoff harvesting through recharge pit, recharge trench, tube well, recharge well. Rain water harvesting through gully plug, contour bund, gabion structure, percolation tank, check dam, cement plug, nala bund, recharge shaft, dug well recharge ground water dams, subsurface dyke.(Bouwer, 2002)

2.3 Managed Aquifer Recharge

Worldwide, managed aquifer recharge (MAR) is being effectively used for a variety of goals, including increasing groundwater storage, enhancing ecological advantages, improving water quality, restoring groundwater levels, preventing salt water intrusion, and managing water distribution systems. A managed recharge indicates that the recharge process is under control and guarantees that dangers to human health and the environment are kept to a minimum. MAR is a crucial potential for adaptation for developing nations dealing with water unpredictability and scarcity.(Stefan & Ansems, 2018)

Many aquifers across the world are gradually depleting. Nearly one quarter of the world's population (1.7 billion people) live in areas where water is utilized faster than it can be replenished by nature. When groundwater abstraction is overly extensive, such as for irrigation or direct industrial water supply, over-exploitation occurs. The volume removed from the aquifer cannot be restored by recharge if groundwater is continuously over pumped year after year.

The groundwater level eventually falls well below its initial level, and even after pumping is stopped, the aquifer has difficulty recovering to its previous level.(Jakemann et al., 2016)

Managed aquifer recharge, which is defined as recharge of an aquifer using a source of water (including recycled water) under controlled conditions to store it for later use or for defined environmental benefit and also it describes intentional banking and treatment of water in aquifers. The term 'artificial recharge' has also been used to describe this Managed recharge is an increasingly common approach for increasing groundwater supplies.

It is the umbrella term for a range of technologies that enable the integrated use and management of surface water and groundwater to achieve a wide and growing range of social, economic and environmental benefits(Dillon et al., 2018, 2020). MAR has a long history is likely to see expanded use as population growth raises water demand and as a response to climate change-related increases in water supply variability.

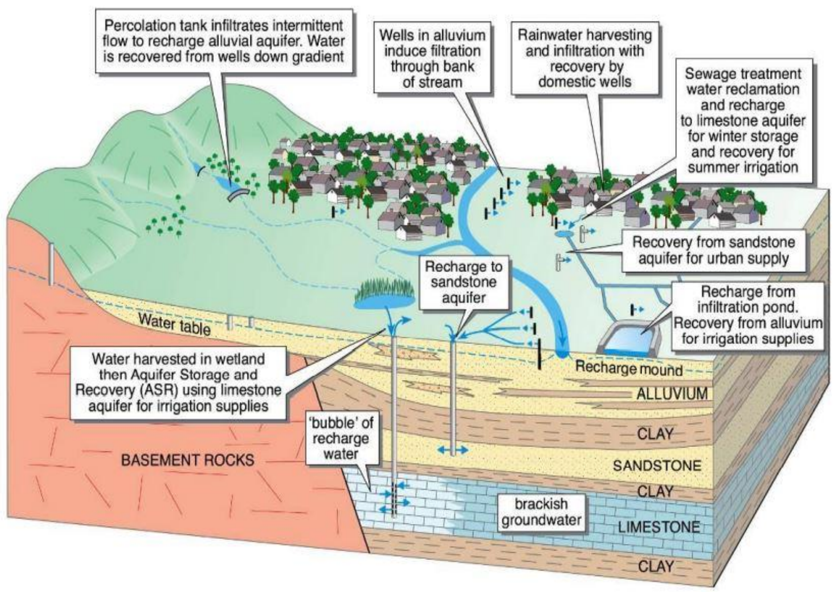


Figure 2.1 A variety of water sources and recharge techniques using multiple separate aquifers for storage, treatment, and recovery

How controlled aquifer recharge is usually customized to the local environment depends on the kind of aquifer, topography, land use, and anticipated uses of the recovered water. This figure illustrates several recharge techniques and water sources that use a number of distinct aquifers for storage, treatment, and recovery with a range of applications. In order to assess the choices available and the technical viability of MAR projects, it is essential to have a basic grasp of the local hydrogeology. Here, wells, percolation tanks, and infiltration basins are used for recharge. Adapted from (Gale, 2005)

With a variety of other techniques, such as surface storage, groundwater extraction, demand control, water reuse, etc., managed aquifer recharge should be viewed as one way to manage water resources. With a variety of other techniques, such as surface storage, groundwater extraction, demand control, water reuse, etc., managed aquifer recharge should be viewed as one way to manage water resources. MAR should take into account the value of the recharged water, its effects on groundwater quality, and preservation of human health and the environment as a "managed" process. The definition of MAR emphasizes the importance of purposeful recharge. Only recharge augmentation that is a deliberate endeavor to control groundwater availability and quality as part of the process is included in managed aquifer recharge. MAR does not apply to recharge by irrigation, leaks from water mains, or inadvertent recharge brought on by cutting vegetation.(Dillon et al., 2022)

MAR types can be divided by two main purposes: one is primarily to provide excessive storage of water and the other is primarily for water treatment. In this case, MAR is mainly use to replenish aquifer to store excessive water and slow down land subsidence and saline intrusion, it is clear that it serves for the first purpose.

2.3.1 Mar types

Aquifer recharge can occur in several ways, including infiltration ponds, wells, and boreholes. MAR can be classified into two broad groupings and five distinct MAR types. (Dupont et al., 2018; Wang, 2017)

	Main MAR Methods	Specific MAR Methods
Techniques referring primarily to getting water infiltrated	Well, shaft and borehole recharge	Aquifer Storage and Recovery (ASR)/Aquifer Storage, Transfer and Recovery (ASTR) Shallow well/shaft/pit infiltration
	Spreading methods	Infiltration ponds & basins Flooding Ditch, furrow, drains Irrigation
	Induced bank infiltration	River/lake bank filtration Dune filtration
Techniques referring primarily to intercepting the water	In-channel modifications	Recharge dams Subsurface dams Sand dams Channel spreading
	Runoff harvesting	Rooftop rainwater harvesting Barriers and bunds Trenches

Figure 2.2 Classification of MAR techniques and methods adapted from (DEMEAU, 2014)

❖ Spreading method

Spreading methods are MAR applications that try to infiltrate water from the surface of the land into subsurface aquifers. Diverting water to infiltration basins or trenches, for example, could improve infiltration across the unsaturated zone (localized land infiltration). Other options include overwatering crops or channeling floodwater to specific regions to allow for infiltration (diffuse land infiltration). The recharged water is kept in the underlying aquifer and retrieved through wells during periods of high demand. Due to the filtration process that occurs when water travels through the unsaturated zone, spreading methods can be advantageous for enhancing water storage as well as water quality.

❖ Induced bank filtration

A series of wells can be placed parallel to a water body to promote the infiltration of water into the earth generated by pumping in cases of low quality surface water (river or lake). The water collected at the wells will be of higher quality since it was filtered as it passed through the river or lake bed, which removed dissolved and suspended contaminants. This

MAR type can also be used in sand dunes, where water seeping through the sediments is retrieved with a higher quality down-gradient.

❖ Well, shaft and borehole recharge

A well, shaft or borehole is constructed, water directly injected to the deep aquifer through the well shaft or borehole. It has two subtypes:

- ✓ Aquifer storage and recovery (ASR)—injection of water into a well for storage and recovery from the same well.
- ✓ Aquifer storage transfer and recovery (ASTR)—injection of water into a well for storage and recovery from a different well, generally to provide additional water treatment.

MAR structure of this type happens below ground level and often request high water quality as the water is directly injected into the aquifer without natural attenuation. It needs less land availability. It can be used to prevent seawater intrusion, land subsidence or storage water in wet period for the usage in dry period.

❖ In-channel modifications

In channels, a structure such as a dam is created to intercept water, hold up a stream, and increase groundwater recharge. Dams of several types can be used to achieve this goal: Recharge dams, subsurface dams, and sand dams are all types of dams.

❖ Runoff harvesting

Rainwater and surface runoff are intercepted using barriers and trenches. It is primarily used to minimize surface runoff and soil erosion in steep areas. Rooftop rain can also be collected and stored in settling tanks before being pumped back into the aquifer through wells or boreholes. Recharge is accomplished by infiltration through surface level permeable material, and the infiltration rates should be able to sustain themselves.(Gale, 2005)

The use of injection wells, another MAR technique, requires less space but produces water of a higher quality because water is injected directly into the aquifer without benefit of natural purification processes. Spreading method is one of these types that is employed the most frequently since it is the simplest and least expensive approach for recharging aquifers. (Rahman et al., 2012) For a better understanding, a schematic of several MAR types is provided in Figure 2.3.

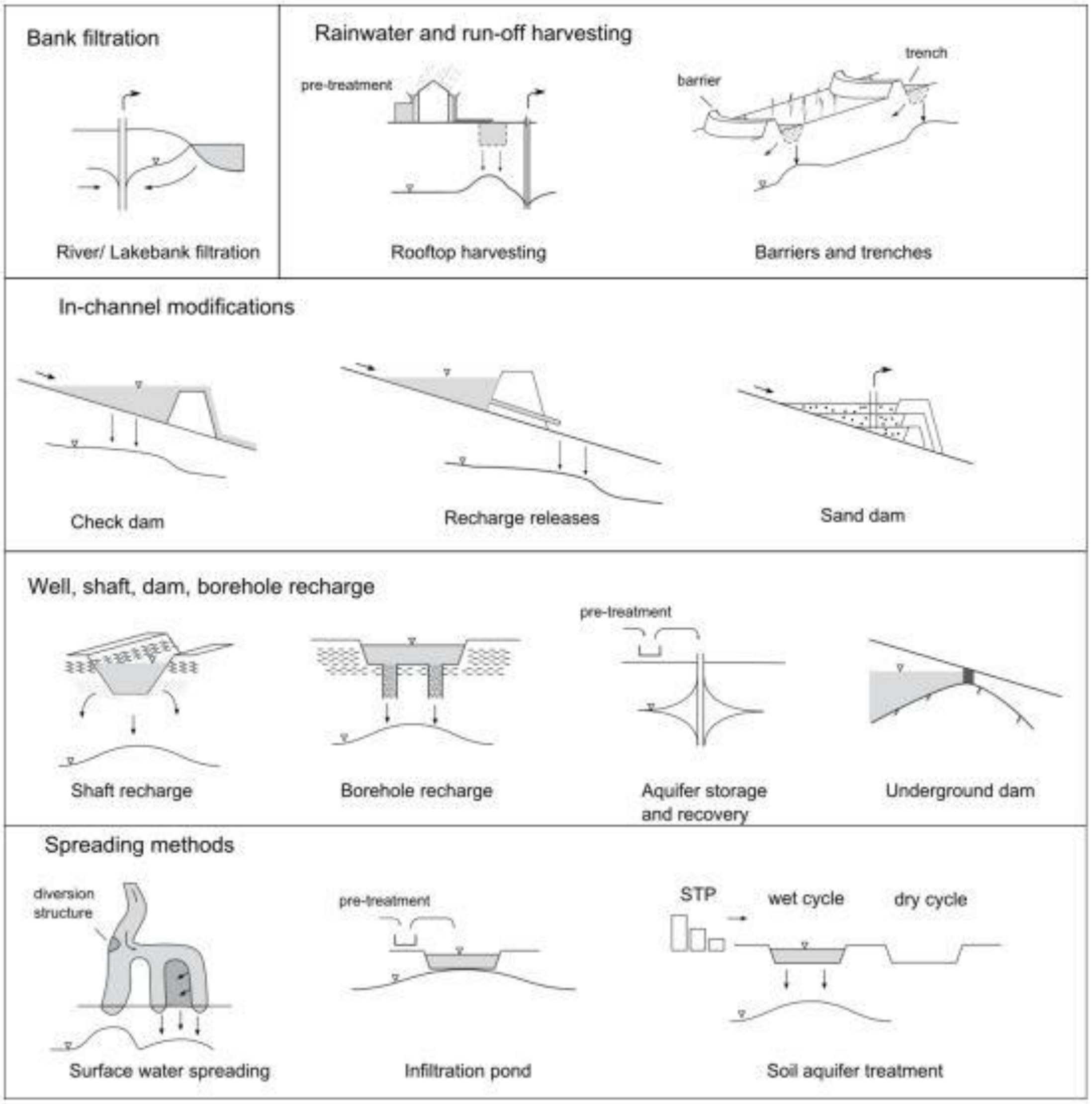


Figure 2.3 Sketches of MAR types (Dillon, 2005)

2.3.2 Purposes of MAR

Depending on the circumstances, MAR may help address a variety of problems, such as water shortages, water security, deteriorating water quality, land subsidence, dropping water tables, seawater intrusion, streamflow reduction, and threatened ecosystems that depend on groundwater. MAR infrastructure has several advantages compared to dams. Among these are lower capital costs, avoidance of evaporation losses, prevention of problems with algae or mosquitoes, and location in proximity to areas with high water demands.

A key advantage is that MAR projects are scalable, allowing for staged implementation. They often start as smaller pilot or demonstration projects. While spreading basins sometimes require large amounts of land, MAR generally results in less loss of prime valley floor land than surface reservoirs, and rarely results in any population displacement. (Dillon et al., 2022) Managed Aquifer Recharge (MAR) can be used to increase groundwater availability, enhance groundwater quality, and manage the environment.

- ✓ Managing water supply: MAR is frequently used to address supply and demand mismatches. This could happen in relation to seasonal timeframes (such as recharging during rainy seasons and recovering during dry seasons), interannual timeframes (such as preventing droughts), or emergency uses (such as for fighting fires or replacing lost water after hurricanes or earthquakes);
- ✓ MAR may be utilized to assist in fulfilling legal responsibilities, such as downstream water rights or compact agreements;
- ✓ Aquifer protection and restoration: MAR can be used to stop land subsidence, manage saltwater intrusion, and restore or prevent additional drops in groundwater levels;
- ✓ MAR can be used to maintain minimum flows and levels in lakes as well as minimum levels in streams and rivers;
- ✓ flood mitigation: using stormwater for MAR could help prevent flooding;
- ✓ protection and improvement of water quality: MAR may be used to maintain or enhance the quality of surface and groundwater or to stop pollutant migration;
- ✓ Reuse of treated wastewater for irrigation and drinkable purposes is increasingly managed by MAR; and
- ✓ Ecosystem maintenance and restoration: examples of MAR used for ecosystems include preserving or repairing wetlands and safeguarding threatened and endangered species' habitats. (Dillon et al., 2022)

In general MAR may offer benefits for environmental management, water quality, and quantity, which include; Decreasing effort required for water treatment (e.g., reducing disinfection byproducts prior to drinking water supply), improving water quality in degraded aquifers (e.g., reducing nutrients from agricultural run-off), For places with minimal surface area, high evaporation rates, and/or run-off losses, to store water in aquifers for future use (such as water supply), to raise groundwater levels where they are overexploited (for aquifer environmental preservation), Prevent soil erosion and storm runoff, conserve the natural flow of rivers and streams, reduce damage from flooding, limiting saline intrusion minimizing land subsidence, Contaminant plume control using hydraulics.(Kumar et al., 2012)

2.3.3 Sources of recharge water

Groundwater extracted from different aquifers or remotely from the same aquifer can be used to recharge an aquifer, as can surface water from rivers or lakes, rainfall that has been collected and treated, and surface water from lakes or rivers. Although it is rarely utilized for MAR, using desalinated water from seawater or brine is another option. Due in part to its accessibility, surface water has been used in the majority of MAR applications. Normal treatment requirements for stormwater or treated wastewater are lower than those for treating natural surface water to address its chemical and microbiological quality. Surface water may be sufficient for recharging in some situations either without treatment or with minimal treatment. Stormwater is typically a plentiful yet erratic resource, but it can be difficult to manage and store so that it can be used as a supply of water for MAR. The year round availability of treated wastewater provides benefits, especially during dry spells when demand is at its peak and traditional resources are scarcer.

Before being recharged, it needs considerable treatment.(Dillon et al., 2022)Reclaimed wastewater from municipal wastewater treatment facilities can be used to recharge aquifers in the context of water reuse through MAR.(Yuan et al., 2016)

2.4 Site suitability mapping for mar

The majority of the MAR guidelines that are now available emphasize the importance of carefully developing MAR schemes in order to achieve sustainability and controllability.(Fisher, 2012; Dillon et al., 2022; Yuan et al., 2016) Another crucial aspect in the design phase of a MAR project is the selection of an appropriate recharge site. The site has an impact on the choice of an appropriate recharge technique, the operation strategy, and the maintenance of the MAR schemes. Since MAR uses a variety of recharge processes, it can be applied to sites with a wide range of features. One of the reasons for evaluating the suitability of a site is to identify the technique that work well for that particular location.(Dillon, 2005; Rahman et al., 2012; Sallwey et al., 2019; Shankar & Mohan, 2005)

Research on MAR suitability has been gaining more focus in the past 20 years with the contribution of research institutes such as IGRAC. On a global scale, numerous studies suggest various standards and techniques for identifying appropriate locations for MAR application. In studies published since 2010, new criteria and methodological approaches for site suitability with various management practices and socioeconomic cultures have been introduced. There are MAR suitability studies available all around the world, such as in Australia (Baskaran et al., 2007), India (Raviraj et al., 2017) Brazil (Shubo et al., 2020) Spain (Escalante et al., 2014) United States of America (Russo et al., 2015) Jordan (Alraggad & Jasem, 2010) Portugal (Rahman et al., 2012) and Tunisia (Chenini and Mammou 2010). Numerous studies conducted in different parts of the world have documented the use of MAR. These researches' main goal was to identify the locations that would make the greatest sites for artificial recharging. In order to locate the suitable sites for MAR, many studies have employed a Geographical Information System (GIS), taking into account surface and subsurface features such as (Ebrahim et al., 2017; Russo et al., 2015; Sallwey et al., 2019; Shaban et al., 2006; Valverde et al., 2016; Wang, 2017)

2.5 Suitability mapping with GIS-MCDA

The first primitive geographic information systems (GIS) were created in the 1980s, and they introduced the concept of merging various datasets with spatial information maps or map layers. The creation and use of geographic information systems have increased due to technological advancements such as computer monitors with higher resolution and color, more powerful computers, and mice. This included the combination of hydrological modeling aided by GIS and remote sensing data. (Burrough, 2008; Burrough & McDonnell, 1998)

The first study found linking MAR site selection and GIS-MCDA was published in 1998 (Saraf & Choudhury, 1998). MCDA studies for MAR site selection started to be increasingly used since 2007 and in recent years, there have been six to ten studies per year. The first nation to use these approaches for MAR site selection was India. The United States, Iran, and Lebanon were the next countries studied in 2005.(Stefan & Ansems, 2018) In the period between 1998 and 2017, 22 GIS-MCDA studies were undertaken in India, making it one of the regions that is still a focus. Iran is the other nation with a lot of applications. There is more emphasis on countries with dry climates (such as Egypt, Iran, and Saudi Arabia), and less on tropical areas (such as Costa Rica, Sri Lanka), or countries with mild climates (UK).(Sallwey et al., 2019)

GIS is a computer-based system that supports decision making by integrating data input, storage and management, data manipulation and analysis, and data output for both geographic and attribute data. It's a special-purpose digital database in which data and information are stored and accessed using a shared spatial coordinate system. It has the ability to integrate spatially linked data with non-graphic features, allowing it to process information. It enables the integration of several geographical technologies such as remote sensing (RS), global positioning system (GPS) and computer-aided design (CAD). These geographic technologies can be combined with decision-making procedures in the future. The ultimate goal of GIS is to aid in the making of spatial decisions (Malczewski, 1999). (MCDM) technique is used for analyzing and integrating number of independent factors.

In an environment where the land is scarce and the resources are finite, the MCDM allows the people to take decisions on a number of issues related to natural resource planning and human sustainability. An effective decision-making on how a particular resource should be utilized is not an easy task. For a given set of conditions, the MCDM offers a viable way where resources planners need to have at their disposal tools that can objectively help in prioritizing land use allocation.

Generally speaking, multicriteria decision making (MCDM) problems contain a set of alternatives that are evaluated on the basis of conflicting and incommensurable criteria. Criterion is a general term that includes both attribute and objective. So MCDM can be divided into two classes: multi attribute decision making (MADM) and multi objective decision making (MODM) (Malczewski, 1999). Both MADM and MODM problems can be further distinguished into single decision maker problems and group decision problems. In present study, the objective is to get suitability map considering a set of conditions. Based on this fact, it fits in a single objective achieved by evaluating several attributes. Consequently, MADM by single decision maker suits in this case.(Malczewski, 1999)

2.5.1 GIS-MCDA Applications to MAR suitability

The selection of suitable areas for the implementation of a MAR site can be a complicated process as several factors need to be considered, including in priority information on the hydrogeological context and surface characteristics such as the geology, land cover, slope…etc. In addition, considerations of the social and financial context, policy and regulations, environmental impacts and others can appear decisive in the definition of suitable area, therefore adding much complexity to the decision process. In (Rahman et al., 2012), GIS-MCDA is presented as a method providing adequate solution procedures to deal with the complexity of MAR suitability at low costs, in comparison with traditional decision support systems and GIS-based analysis methods. This method allows identifying priorities in the considerations of a given MAR project, using and manipulating geographical data according to the decision-maker’s preferences.

2.6 Overview of MAR case studies in Africa

(Ebrahim et al., 2017) stated 1200 case studies found over from over 50 countries documented in the global MAR portal database. There are 42 case studies for Africa on the portal. Three case studies that were misclassified were eliminated, bringing the total number of case studies in Africa down to 39. Through a literature search, two more Tunisian case studies were discovered. Similar case studies addressing different areas of the MAR project frequently emerge from the supplementary literature search. As a result, the total number of case studies examined in this study is 41. Only eight African countries are currently practicing MAR, according to the Global MAR portal database.

This is true especially for Africa where data is difficult to access. (Gijsbertsen & Groen, 2007) for instance, noted that since 1994, the local NGO SASOL (Sahelian Solution Foundation) and the local communities had built more than 500 sand storage dams in Kenya's Kitui District alone. However, there are eight case studies of sand dams from across the nation on the Global MAR portal. The lack of data in some countries does not necessarily mean that there is no MAR practice there; instead, it could indicate that there are insufficient references, most of which are documented in governmental technical studies.

In Africa the majority of MAR experiences found are in regions where physical water scarcity is present or imminent. The spreading method, channel modification, and well, shaft, and borehole recharge methods are the three most popular MAR types. One of the most used MAR types in Kenya, Tunisia, and South Africa is channel alteration employing sand dams, spreading method, and well injection. Egypt is the location of the sole induced bank filtration case study. The main objective of MAR in Africa is to maximizing natural storage. The objectives of maximizing natural storage of groundwater includes increasing groundwater availability, to meet rural domestic demand during dry periods to meet summer peak demand, to meet emergency and drought supplies, and water banking for seasonal peak demands and emergency supplies. Maximizing natural storage and physical aquifer management refers to storing water to meet domestic demand and preventing seawater intrusion.(Ebrahim et al., 2017)

Recharge water for MAR in Africa is sourced from river water, treated wastewater, storm runoff, roof runoff, and groundwater from adjacent compartment. About 63% of recharge water is from river water and about 28% is sourced from treated wastewater. Treated wastewater is used in countries with limited water resources such as Tunisia for agricultural uses. The Willsion case study, South Africa, is a unique example of using groundwater from another compartment to recharge aquifer compartment used for domestic water supply.

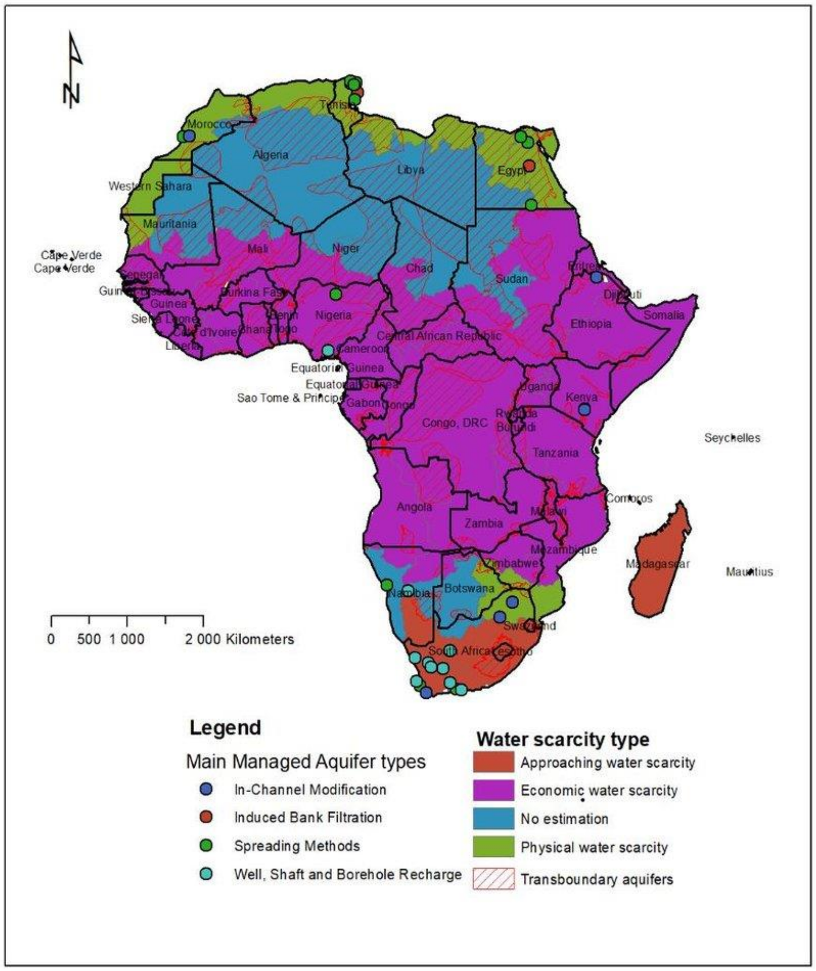


Figure 2.4 Location of 41 MAR case studies in Africa, organized by MAR type, overlaid on an African map of water scarcity and transboundary aquifers.

2.7 Akaki catchment

The Akaki River Catchment has continuously been the site of several geological, hydrogeological, pollution studies, and other related research for a variety of reasons. Several institutes and/or researchers have made various geological, hydrogeological (surface and groundwater potentiality), engineering geology, pollution/water quality/study, drilling, etc. discoveries. The geology of the Akaki catchment has been the subject of numerous papers. The following are earlier studies on the geology that were carried out in Addis Ababa and its surroundings: (Kundo, 1958; Morton et al., 1979)(Girmay & Assefa, 1989)

Numerous articles have been produced about the hydrogeology of the Addis Abeba region, including surface and groundwater potential, ground water hydrochemistry, and the geology of the watershed and its effects on ground water. Some of the relevant works done on the study area were:

(Aynalem Ali, 1999) investigated ground water surface water interaction and water quality assessment in the Sekelo River in the Great Akaki sub-basin.

(Demlie et al., 2007) has conducted hydro geological study of Akaki catchment with special emphasis on the problems of groundwater recharge.

(Dereje Nugussa, 2003) used the DRASTIC technique to undertake GIS-based groundwater potential and aquifer vulnerability analyses in the Akaki River Catchment. The study's output was a map of the catchment's aquifer risk.

(Birhanu Gizaw, 2002) conducted in-depth analyses of the Addis Abeba region's hydro chemical and environmental investigation

(Gebrekidan, 2000) investigated the ionic composition of addis ababa drinking and surface waters. The results of the study showed that the surface waters of Addis Ababa are highly contaminated by the nitrate, nitrite, phosphate, organic matter, sulphate and chloride due to the direct and indirect human activities.

(Gudissa, 2010) studied the movement of subsurface contaminants in the Akaki well field. The study revealed the flow of contaminants in the aquifer and their spatial mobility, as well as their potential movement in a wellfield.

(Tesfaye, 2009) Conducted modeling of the catchment surrounding the Akaki wellfield and steady-state groundwater flow and contamination transport.

(Ayenew et al., 2008) The Akaki catchment's subsurface hydrodynamics are analyzed, and groundwater fluxes are quantified using a three-dimensional steady-state finite difference groundwater flow model with special attention paid to the well field that provides water to Addis Abeba.

(Ayenew et al., 2011) conducted Integrated Groundwater Modeling and Hydrochemical Study in Addis Ababa Area: Towards Developing Decision Support System for Wellhead Protection.

(Ayenew et al., 2018) WEAP-MODFLOW Dynamic Modeling Approach to Evaluate Surface Water and Groundwater Supply Sources of Addis Ababa City. Through water supply scenario analysis, potential effects of anthropogenic and natural stresseon the volume of surface water reservoirs and groundwater storage have been studied.

(Berga, 2011) The study assessed the past and potential future land cover changes, and their impact on the hydrology of the Akaki catchment. The study specifically examined the catchment's historical land cover changes (1973 to 2000) and their impact on the catchment's hydrology. Additionally, the future scenario's change in land cover was used to assess any potential effects on the catchment's hydrology.

(Mekonnen, 2018) Causes and effects of groundwater depletion of the well fields in the Akaki catchment. In this study, deforestation and excessive groundwater pumping were identified as the two main factors contributing to the water table's decline. The study finds that the watershed has substantial ground water scarcity, necessitating rapid intervention.

CHAPTER THREE

THE STUDY AREA

3.1 Location and physiography of the study area

The Upper Awash River sub-basin includes the Akaki watershed. The watershed encompasses Addis Ababa, a rapidly growing city. With an elevation range of 2,000 m (a.m.s.l) to 3,388 m (a.m.s.l), the Akaki has a catchment area of around 1500 km2 (a.m.s.l). The Akaki catchment lies on the Ethiopian Main Rift's western edge. The catchment region is defined by longitudes of 38° 35' 00''–39° 05' 00''E and latitudes of 8° 46' 57''–9° 13' 00''N. It is flanked by high-rising mountain ranges, and the catchment's center rests on an undulating topography with some flat land regions. Following the East-West trending Ambo - Kassam major fault system, the Intoto mountain ridge marks the city's northern limit. The high massive volcanic centers include Mt. Wechecha in the west, Mt. Furi in the south west, and Mt. Yerer in the south east.(Mearg Belay Shibeshi et al., 2019).

The Big Akaki river, which drains the eastern portion of Addis Ababa, and the Little Akaki river, which drains the western section of Addis Ababa, are two sub-catchments. The two rivers join to form one of the awash river's largest tributaries, the Akaki River, which flows into Abba Samuel Lake. In the upstream part of the catchment, three water supply reservoirs (Dire, Legedadi, and Gefersa) are located, while the Aba Samuel reservoir (hydropower plant) is located at the catchment's exit. The Akaki watershed is drained by two major rivers, the Big Akaki and the Little Akaki, which feed the Aba Samuel reservoir. The Bulbula and Kebena rivers are the two main tributaries of the Big Akaki River, with the former draining the north-east peri-urban part of the watershed and the latter draining the north part (the old part of the Addis Ababa city). The Legedadi River feeds the Bulbula River from its headwaters, which are home to the small communities of Dire, Legedadi, and Sendefa. The Legedadi River transports floodwaters from the Legedadi and Dire reservoirs to the Bulbula River, and eventually to the Big Akaki River's floodplain.

The Little Akaki River drains the catchment's northwestern portion. It transports water from the Gefersa reservoir to the floodplains before feeding the Aba Samuel reservoir.(Ayenew et al., 2008)

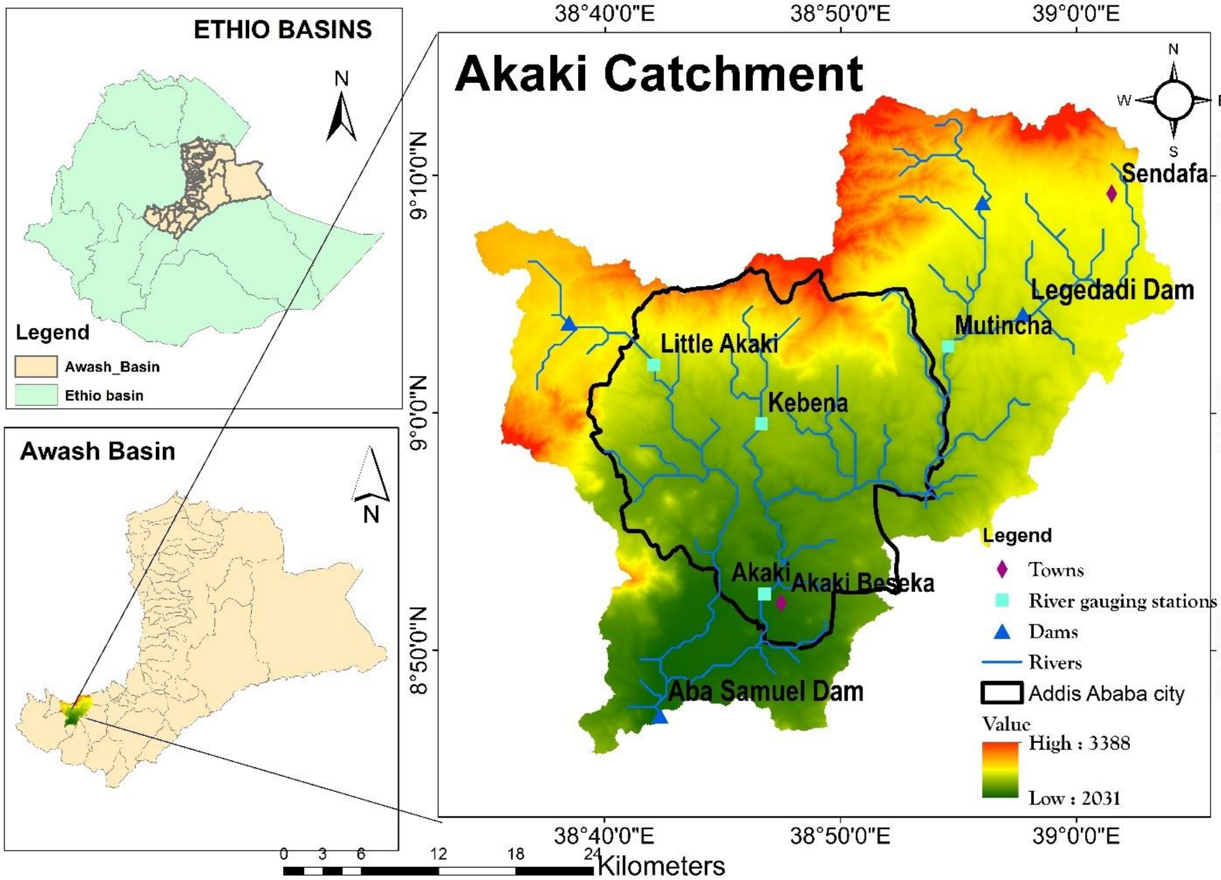


Figure 3. 1 Location map of the study area (Akaki catchment)

3.2 Climate

Ethiopia is a country with diverse climatic regions, ranging from lowland deserts and semi-arid zones to temperate zones and highland areas. The country has a diverse climate and landscape, ranging from equatorial rainforest with high rainfall and humidity in the south and southwest, to the Afro-Alpine on the summits of the Simien and Bale Mountains, to desert-like conditions in the north-east, east and south-east lowlands.

Overall, Ethiopia is considered largely arid, but exhibits a high variability of precipitation Ethiopia's climate is generally divided into three zones: 1) the alpine vegetated cool zones

(Dega) with areas over 2,600 meters above sea level, where temperatures range from near freezing to 16°C; 2) the temperate Woina Dega zones, where much of the country's population is concentrated, in areas between 1,500 and 2,500 meters above sea level where temperatures range between 16°C and 30°C; and 3) the hot Qola zone, which encompasses both tropical and arid regions and has temperatures ranging from 27°C to 50°C. (World Health Organization, 2015)The climate of the country is mainly controlled by the seasonal migration of the Intertropical Convergence Zone (ITCZ) following the position of the sun relative to the earth and the associated atmospheric circulation. It is also highly influenced by the complex topography of the country. (NMA, 2001)

(NMA, 2001) defined the traditional climate classifications of the country based on altitude and temperature which shows the presence of five climatic zones namely: wurch (cold climate at more than 3000 Mts. altitude), Dega (temperate like climate -highlands with 2500-3000 Mts.), woina dega 22 (warm- 1500-2500), Kola (hot and arid type, less than 1500m in altitude), and Berha (hot and hyper-arid type) climates. Classification with respect to rainfall regimes shows the presence of monomial, bi-modal and diffused pattern of rainfall climates. Consideration of the moisture index shows that large portion of the country falls under semi-arid and arid climates.

The study area's climate is typically characterized by two distinct seasonal weather patterns: the wet season, which lasts from June to September, and the dry season, which lasts from October to May. The average monthly temperature in the Akaki catchment ranges from 21.1°C in the wet season to 29°C in the dry season, with a low of 7°C–12°C. The Inter Tropical Convergence Zone's seasonal change affects the wind flow pattern. The average yearly wind speed is 0.68 meters per second. Sunshine hours range from 9.66 hours per day in December to 2.18 hours per day in July. The monthly variation closely follows the rainfall pattern, as one would expect given that the dry months have more daylight hours than the rainy months.

The average yearly relative humidity value is 51.2 percent, with a minimum of 39.8 percent in December and a maximum of 72 percent in August. (Mearg Belay Shibeshi et al., 2019)

3.2.1 Rain fall pattern

Mild climate zones with moderate to cool climates are typical of the Akaki watershed. The distribution of rainfall over the catchment region is influenced by the Intertropical Convergence Zone (ITCZ). Based on rainfall the research area typically shows two distinct seasonal weather patterns: the wet season, which extends from June to September, contributing about 70% of the annual rainfall, and the dry season which covers the period from October to May with a minor rainy season in March and April well known for its failure. Such climates which are characterized by alternating wet and dry seasons may favor. This seasonal variation of rainfall distribution within the study area is due to the annual migration of the inter-tropical convergence zone, a low-pressure zone marking the convergence of dry tropical easterlies and moist equatorial westerlies across the catchment and altitudinal variation are both responsible for the primary seasonal fluctuation of rainfall.(Mekonnen, 2018; Oljira, 2006)

During the primary rainy season, the study area receives rain from the Atlantic Equatorial Westerly, while March and April bring rain from the Indian Ocean and the Gulf of Aden. The amount of rainfall in the other months is low to nonexistent. Addis Ababa is situated in an area where the rainy months are closely spaced out.(AynalemAli, 1999). Rainfall data in the study area was obtained from National Metrological Agency in the year (1995-2021). There are five metrological stations within the catchment area known as Sendafa, Intoto, AddisAbaba Observatory, Addis Ababa Bole, Akaki.

Stations	Jan	Feb	Mar	Apr	May	Jun	Jul	Aug	Sep	Oct	Nov	Dec
Sendafa	14.9	12.8	41.5	79.2	62.0	143.9	323.4	363.1	127.8	26.8	19.8	5.2
Intoto	9.9	20.1	48.2	77.1	93.5	164.9	344.6	341.3	156.7	29.2	14.4	8.3
AA. Obs	14.6	21.1	51.7	85.5	88.9	144.4	274.4	288.7	187.7	35.4	11.1	8.0
AA.	11.3	21.6	51.9	87.5	83.8	121.1	243.4	256.5	143.2	30.2	5	8.1
Akaki	10.5	17.7	48.6	77.1	72.0	112.5	235.7	234.8	116.8	28.5	7.3	4.2

Table 3.1 The five metrological stations' average monthly rainfall value

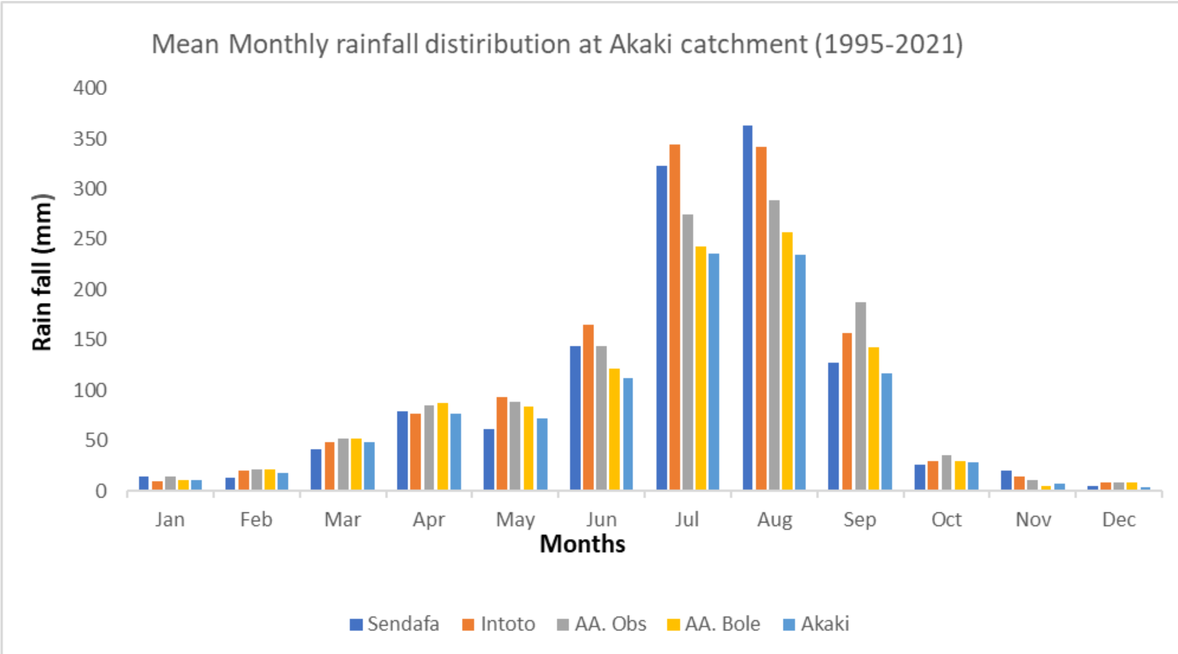


Figure 3.2 Mean monthly rainfall values of the five metrological stations (1995-2021)

3.2.2 Temperature

Elevation plays a significant role in the climatic characteristic of temperature as well. It differs considerably within the catchment. As elevation rises, the temperature does as well. Data on temperature in the study area were sourced from the National Metrological Agency in the year (1981-2005). From three metrological stations, these statistics are available (Addis Ababa bole, Addis Ababa observatory, and Entoto). The mean annual temperature of the area varies from 15.7^{o}c to 16.4^{o}c see Table 3.2 corresponding to Fig 3.3.

Temp	**Jan**	**Feb**	**Mar**	**Apr**	**May**	**Jun**	**Jul**	**Aug**	**Sep**	**Oct**	**Nov**	**Dec**
Max	9.19	10.2	11.5	12.2	12.4	11.7	11.3	11.3	11.3	10.4	9.2	8.6
Min	23.5	24.8	25.1	24.7	24.6	23.0	20.6	20.1	21.2	22.5	22.8	22.8
Mean	16.4	17.5	18.3	18.4	18.5	17.3	15.9	15.7	16.3	16.4	16	15.7

Table 3.2 Maximum and minimum monthly average temperatures in the catchment

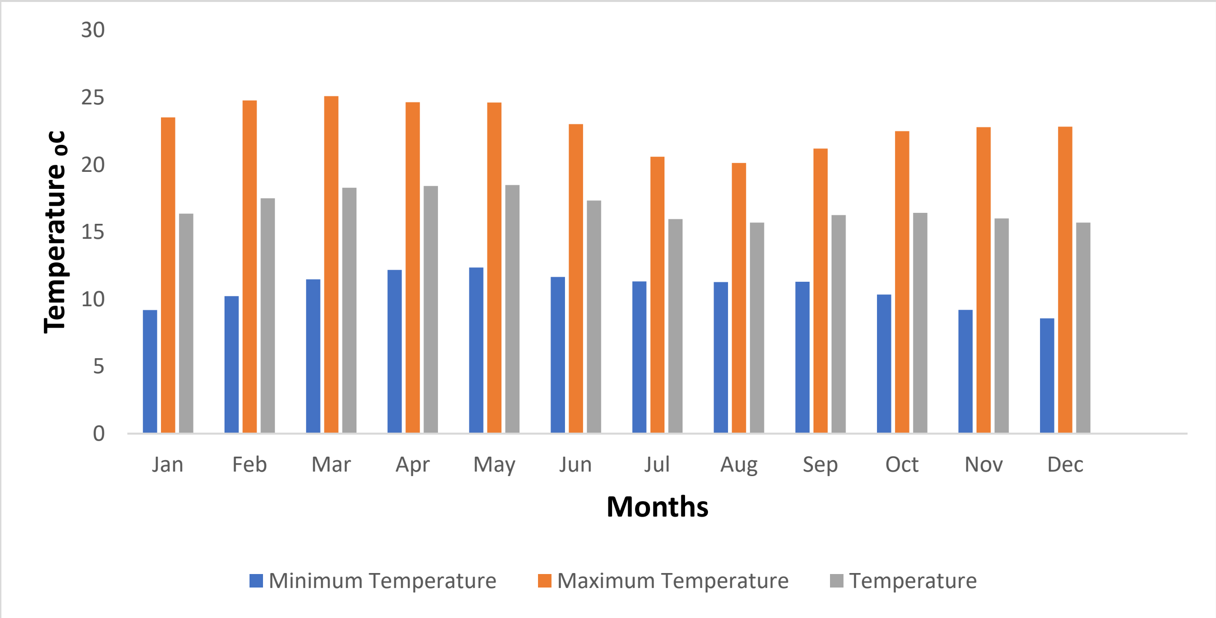


Figure 3.3 Average monthly temperature variations in Akaki catchment

3.3 Geology

The geological history of the Akaki catchment is an essential component of the growth and development of the Ethiopian Plateau and the rift system due to its placement along the western margin of the MER. The catchment is covered in volcanic rocks, which are then covered with fluvial and residual soils, the majority of which are black cotton soils with thicknesses ranging from a few centimeters to around 20 m.(AAWSA et al., 2000) Basalts, rhyolites, trachytes, scoria, trachy-basalts, ignimbrites, and tuff are among the principal lithologies. The circulation and storage of groundwater is favored by these severely weathered, fractured lithologies.

- **Alaji formation**

The Alaji group volcanic rocks (Alaji rhyolite and IntotoSilicics) were outpoured in this area of the escarpment from the end of the Oligocene to the middle of the Miocene. This unit is dominant in the northern half of the research region, extending from the crest of Intoto (a ridge that runs across Addis Ababa's northern suburbs) to the north.(Mearg Belay Shibeshi et al., 2019) Rhyolites, trachytes, tuff, agglomerate, and aphanitic basalt are the principal rock types found in this unit.

Massive Oligocene fissure-basalt, rhyolites, and trachytes with little welded tuff and obsidian make up the EntotoSilicics. The northern and central parts of the country are dominated by this unit. This series was previously classified into Alaji rhyolites and Intoto Silicics (Zanettin & Justin-Visentin, 1974).

- **Addis Ababa basalts**

The Intoto Silicics are overlain by these basalts, which encompass the center and southern parts of Addis Ababa. Individual flows are usually visible, and paleosoils and scoraceous layers can be found in several locations. In central Addis Ababa, olivine porphyritic basalt outcrops with thicknesses ranging from 1 meter or less in the foothills of Intoto to more than 130 meters in the heart of the city. and overlain by lower welded tuff of the Nazareth group stratigraphically. It has a porphyritic texture and is mostly found in the city's core area, as well as southern parts of Addis Ababa. Olivine porphyritic basalts of various thicknesses outcrop around Merkato, Teklehamanote, and Sidest Kilo. Near the building college, the Kolfe Police School, the KokebeTsebah School, and the Yeka Mariam church, the Lower Welded tuff covers Olivine porphyritic basalt. The olivine porphyritic basalt, on the other hand, is solely overlain by the plagioclase porphyritic basalt in the Ketchene stream gorge.

- **Younger Volcanics**

The Nazareth Group and the Bishoftu Formations are part of this group. Lower welded tuff, aphanitic basalt, and upper welded tuff are the units identified in the Nazaret group. Addis Ababa basalt underpins the Nazaret group, which is overlain by Bofa basalts. The Bofa Basalts are found south of the Akaki River in the form of boulders with a thickness of 10 meters. In the city's south-east corner, they are constrained and dominated. This rock is distinguished by large vesicles filled with calcite. The tuffs that cover the welded tuff lie beneath this basalt. The rock predominantly outcrops south of the Filowha fault and extends to Nazaret. Aphanitic basalts, welded tuffs, ignimbrites, trachytes, and rhyolites make up the rocks.

Olivine porphyritic basalt, scoria, vesicular and scoraceous basalt, and trachy-basalt lava flows make up the Bishoftu Formation. They are concentrated in the south and range in thickness from 20 to 40 meters in the Akaki wellfield. It is covered by scoria, tuff, sand, and gravel locally. This unit is the region's primary aquifer.

- **Recent deposits**

Alluvial, residual, and lacustrine deposits are examples. Near river banks in the south, the thickness varies between 5 and 50 meters (AAWSA, 2000). Darker, younger black cotton clayey soils frequently cover it. Some alluvial deposits can be found along the Little and Big Akaki rivers, especially to the south and southwest of Addis Ababa. The middle, southeast, northeast, and western flatplains have residual soils.

3.4 Hydrogeology

The hydrogeological qualities of the material, specifically hydraulic parameters such as porosity, permeability, and, influence groundwater circulation and pollution dispersion.

The kind of lithology, distribution, thickness, and structure of hydrogeological units through which groundwater flows determine its source, flow, and chemical composition. Furthermore, the hydrogeochemical properties of earth materials are governed by stresses caused by tectonism and weathering. The area's primary rock outcrops are basalts, rhyolites, trachytes, scoria, trachy-basalts, welded and unwelded tuffs, and trachy-basalts. In addition, unconsolidated materials of various origins are found in the research area. These rocks provide the majority of Addis Ababa's groundwater supply.

The watershed is made up of both inter-granular and fracture permeability aquifers, according to the available data. Alluvial sediments and pyroclastic and scoraceous volcanic rocks constitute the upper more permeable layer of the inter-granular porosity aquifers. Basalts, ignimbrites, trachytes, and rhyolites make up the fractured aquifers, which have a less permeable bottom second aquifer system. Basalts and ignimbrites are suitable aquifers because they are often extremely fractured and permeable. Up to 1296 m3/day can be obtained from scoraceous and vesicular basalts. Ignembrites and basalts with faults generate good aquifers, whereas less fractured and jointed basalts, such as the Addis Ababa area's alkaline flood basalts, form moderate aquifers with yields of up to 432 m3/day and 260 m3/day, respectively.

Fine-grained alluvial sediments with volcanic ash and lacustrine deposits make up poor aquifers. In contrast to popular belief, alluvial sand and gravel deposits give a high yield when it comes to building shallow aquifers. Confined aquifers have been found in Addis Ababa based on the examination of existing well data as well as data obtained for this study. These are primarily hot waters around the Filwoha fault, which are isolated and have no direct relationship to the unconfined system.

As a result, prior studies have classified the primary aquifers in the Akaki basin into three groups:

- Shallow aquifer: worn volcanic rocks and alluvial sediments along river valleys form the shallow aquifer.
- Boreholes are drilled for drinking water supply in deep aquifers consisting of cracked volcanic rocks.
- Thermal aquifer: aquifer with a depth of more than 300 meters.(Ayenew et al., 2008; Tesfaye, 2009)

As cited in (Mekonnen, 2018) thesis, previous report (Shaqa, 2010) had identified regional groundwater flow direction which is assumed to be north-south from Addis Ababa towards the Akaki well field. (Wang et al., 2001) Assumed groundwater flow direction in the well field is from the NE towards the SW. The groundwater flow system can be schematized with depth into two major categories: a shallow zone of active fast flow and a deeper zone of relatively slower flow and longer residence time. The shallow systems are confined to the upper permeable soil, sediment, and weathered rock zone (usually less than 50 meters). This zone is considered to be the phreatic near surface aquifer with high permeability supplying water to hand dug wells, low-discharge springs, and river base flows. Below this zone, there exists a fractured rock zone and volcano clastic deposits in places inter bedded with paleosols (up to a maximum of 230 m depth). This zone is a major aquifer of the catchment dominantly confined in central and southern Addis Ababa.

In the highlands, groundwater reserve is limited due to the absence of large faults and the existence of non-fractured massive volcanic forming the mountainous areas along the watershed boundaries. The aquifers of the Akaki Well Field and its surrounding, the study area, are also of volcanic origin, largely related to processes of lava flow and tectonic fractures. Volcanic deposits of scoria, scoriaceous and vesicular basalts are the predominant rock types in the area. Tectonic activities in the region developed intensive and network fracturing/fissuring, which resulted in favourable conditions for groundwater circulation. In the study area and its surrounding, (Girma, 1994) showed that there are four types of aquifers in the Akaki area.

The first aquifer type, which is highly productive, is constituted by scoria deposits, scoracious basalt and alluvial sediments. The second type of aquifer comprises of highly fractured and fissured basalt while the third aquifer is of a salt with moderate productivity having fractures, vesicles and sparsely spaced joints, ignimbrite and agglomerates. The scoria cones and surge deposits from the last group of aquifers, which has low productivity.

3.5 Hydrology

With a catchment area of 1500 km2, the Akaki River, a left bank tributary of the Awash River, has a large drainage system. It flows about 95 kilometers from its source in the Intoto range north of Addis Ababa, dropping 600 meters along the way to its confluence with the Awash River in Dodota. The Akaki river watershed is divided into two sections: the Akaki proper (large Akaki river), which drains the eastern half of the catchment area, and the Little Akaki, which drains the western half. These two rivers meet in Abba Samuel reservoir, a man-made lake created in the 1930s by damming the Akaki River. The Akaki river has carved a gorge up to 100 meters deep south of the Abba Samuel dam.(Tesfaye, 2009) The basin was divided into three sections so that the Akaki River and the related land use along its course could be better described. These three divisions are higher, middle, and lower. Small streams that pour from various areas of Mount Entoto, Geferesa, and Legedadid dams make up the upper catchment. These streams eventually merge to form the Little Akaki, which flows from the west to the south, and the Great Akaki, which descends from the north to the south.

The entire length of the river inside the city before it exits Akaki- Kality's suburbs is included in the intermediate catchment. There are more tributaries in this section of the river than in the upper watershed. A site close to Bihere Tsige Park is where the Little Akaki join the main river after draining the Addis Ababa cement industry. While the final Great Akaki is created by joining the Great Akaki and Bulbula below Arsema Church around Worku sefer. Additionally, a densely inhabited and significant business area of the city is traversed by the river. The lower catchment passes through the rural parts of the city and finally enters into the Aba-Samuel reservoir. In this part of the catchment, there is a point source where wastes are discharged from Kaliti sewage treatment plant. After treatment of the collected sewage from the city, the final waste is disposed into Little Akaki. This catchment is also used for agricultural and domestic purposes.

3.6 Water resources

In the outskirts of the city four water reservoirs were built for two main purposes. Gefersa, Legadadi, and Dere dam were built for public water supply, while Aba Samuel dam was built for hydroelectric power generation. As a consequence, Lake Gefersa in the northwest, Lake Dere and Legedadi in the northeast and Lake Aba Samue (due to siltation and pollution it is not functional at present) in the southern outskirts of the city were formed at different times. Gefersa was the first dam built in 1944 about 18 kms west of Addis Ababa. At present the dam has a reservoir capacity of 6.5 million cubic meters and the maximum capacity of the treatment plant is 30,000 m3 of water per day. Due to rapid growth of the population and expansion of the city from year to year, there is a serious shortage of water in different parts of Addis Ababa. To alleviate the problem Legedadi and Dire dams were built in 1970 and 1999 at about 33 kms east of Addis Ababa. The treatment capacity of Legedadi plant was upgraded from 50,000 m3 to 150,000 m3 of water per day.

CHAPTER FOUR

MATERIALS AND METHODOLOGIES

4.1 Methods

The mapping of the suitability of the catchment to MAR was developed for this study based on the knowledge of the study area and followed the scheme for a GIS-MCDA as described in 4.2. The overall study concept involved integration of thematic layers (seven criteria) of drainage density, slope, geology, land use, water level, soil and rainfall using ArcGIS software and application of multi-criteria decision analysis approaches, including weighted overlay and AHP to find suitable sites for the application of MAR in the study area. In this study, seven criteria were selected by considering the expected scale, accuracy of the work, site conditions, the influence of each criterion, and adequate availability of information. These criteria were selected after reviewing the related literature and checking the availability of data for the study area. According to (Sallwey et al., 2019), these seven criteria are commonly used and are the most important criteria for MAR site selection. An overview of the strategies employed in this study is provided in this section.

In this research, seven criteria maps geology, land use/land cover (LULC), slope analysis, soil texture, drainage density, water level, and rainfall were produced using the already-existing conventional maps, data on water levels, rainfall, and satellite data. All these maps where digitized and integrated into a GIS platform using ArcGIS 10.8. Conventional data sets, such as topographical maps and field data, were used along with advanced data sets, such as satellite data. Using ArcGIS 10.8, all of these maps were digitised and integrated into an Arcgis software.

According to the relative importance of each theme for MAR in relation to the set of criteria, it was separated into various classes, and rankings were assigned. Seven factors were compared to one another, and the variables with the greatest influence on making a location more suitable were given higher weights.

The seven themes were reclassified, given ranks and weights, and standardized using AHP Criteria based on their relevance and importance. For the Raster overlay analysis, every weighted theme was resampled using 30×30 m cell size.

The AHP normalization took into account all seven parameters, and overlay analysis was completed on ArcGIS Platform. During this procedure, a pairwise matrix was created, and each parameter's weight was established by taking into account how important each of the other values was in relation to the other parameters.

The detailed workflow adopted for this study is shown in (Figure 4.1), and the major steps are described below.

i. Identifying suitable MAR techniques using INOWAS, a web-based tool for narrowing down the available MAR techniques;
ii. Processing of datasets including digitization of raster maps using ArcGIS;
iii. Preparation of thematic layers for the study area and GIS processing for reclassification of criteria maps;
iv. Assignment of suitability scores to various features within each thematic layer (Standardization of all the criteria to bring to the same level);
v. Assigning weight to each thematic layer using AHP modelling (pair-wise comparison matrix and consistency verification) which is ranking of all maps according to their relative relevance;
vi. Generation of the final MAR suitability map using Weighted Linear Combination (WLC).

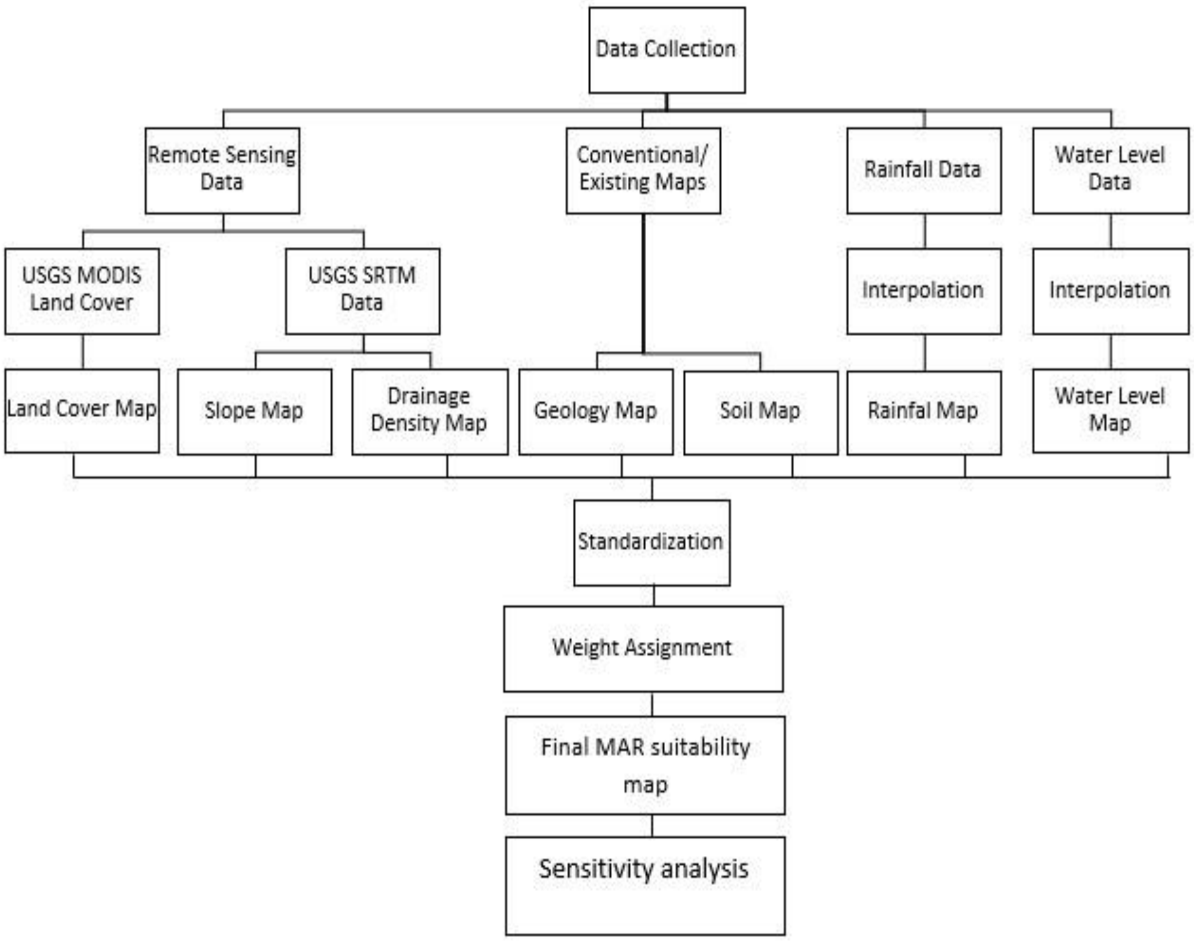


Figure 4. 1 Flow chart illustrating the various phases of the proposed MAR suitability mapping approach

4.2 Geographic Information System Multi-Criteria Decision Analysis (GIS-MCDA)

Multi-criteria decision analysis (MCDA) has been combined with geographical information systems (GIS) for solving geospatial problems to numerous scientific areas. The combination of both approaches is called geographical information systems multi-criteria decision analysis (GIS-MCDA). GIS-MCDA is described as a group of techniques and instruments for merging preferences (value judgments) with spatial data to produce information for decision-making. While MCDA includes a wide range of methodologies, tactics, and procedures that direct the decision-making process, GIS offers the ability to automate, organize, and analyze a variety of spatial data. The ranking of the available areas is done using GIS-MCDA and decision rules that specify how the standardized criteria are combined.

(MCDM) approach is employed for the analysis and fusion of numerous independent elements. The MCDM enables the people to make decisions on a variety of matters connected to natural resource planning and human sustainability in a setting where land is limited and resources are finite. Making an efficient choice about how to use a specific resource is not a simple process. The MCDM provides a workable method where resource planners need to have available instruments that can objectively aid in allocating land use priorities for a certain set of conditions.(Malczewski, 1999)

Using an MCDA integrated into GIS may allow for more thorough and affordable rating of suitable MAR locations. The tool includes a step-by-step approach to perform GIS-MCDA for MAR suitability analysis through a web-GIS and supporting tools. The process of MCDA for site selection follows the scheme developed in (Rahman et al., 2012) and is divided into:

1) problem definition;
2) screening of suitable areas (constraint mapping);
3) suitability mapping, which includes classifying thematic layers or criteria; standardization; weighting of the criteria and layers overlaying; and
4) sensitivity analysis.

Not every stage in the suitability analysis process is necessary; for instance, the constraint mapping step may be avoided based on the data at hand and the nature of the problem.(INOWAS, 2022)

4.3 Problem Definition

The first necessary step to conduct a successful GIS-MCDA is to clearly define the goal of the study.

The spatial problem should be characterized by one or several specific and measurable objective(s), attainable in the time frame available. The problem definition is a decisive step as it will greatly affect the rest of the study by influencing the selection of criteria and their respective weights.

The brief introduction to the environment and state of water resources in the Akaki catchment and the groundwater depletion in the area helped to develop a hypothetical context in which the catchment needs implementation of a new MAR site. The main need for MAR in the region is to ensure the stability of piezometric levels especially in dry periods and eventually to help store water in aquifers for future use (such as water supply), to raise groundwater levels where they are overexploited (for aquifer environmental preservation), Prevent soil erosion and storm runoff, conserve the natural flow of rivers and streams, reduce damage from flooding. Being based only on a hypothetical need of MAR suitability, financial and legislative matters are not included in the process.

4.4 Selection of Evaluation Criteria

The spatial information that is used in GIS-MCDA is called criterion. Each criterion should be measurable, complete, comprehensive, non-redundant and decomposable attribute. Specifying the objectives and then achieving them through a specific attribute is how evaluation criteria are chosen. There is no general method for choosing evaluation criteria; instead, it is dependent on the specific problem.

The number and type of parameters that could be used to develop a suitability map depend on the type of MAR envisioned, the geology, and the physical geography including climate, among other possibilities. There is no single guideline as to what is good or what should be done. It has been noted, however, that there is a tendency to use as many parameters as available rather than looking at what is really required and expedient. In several cases, it is clear that more parameters have been used than would have been necessary to have a similar outcome. The best method to identify suitable MAR sites will depend on the type of MAR, the geological and physical-geographical parameters of the area, and the availability of data. (Sallwey et al., 2019) noted that “areas that have been identified as suitable for MAR should be investigated with subsequent in-situ measurements to characterize the hydrology and hydrogeology of the site.”

There are 4 to 21 criteria employed in different literatures, but 90% of research include fewer than 10 criteria (Sallwey et al., 2019). Some studies, e.g., (Rahman et al., 2012) used a very large set of criteria including groundwater quality and water table depth. It is known that regional MAR suitability maps based on a few factors are of little use for developing new MAR sites without further site-specific analysis, such as the MAR objectives, the source of water, and the available budget. One important source of variability in MAR suitability maps comes from the initial choice of criteria. To assess the tendencies and preferences applied by the scientific community for MAR site selection using GIS based Multi-Criteria Decision Analysis (GIS-MCDA) a review of available literature was conducted by INOWAS. It resulted in a database with 66 scientific documents from more 18 countries. The slope criterion was the one that was used in 57 papers for the selection of the MAR site, according to the database query tool of INOWAS. land use/land cover was the second most often used term, followed by Geology/lithology.(INOWAS, 2022) The list of the 20 most used criteria in literature for MAR site suitability mapping was used to determine the most relevant criteria to include in the Akaki catchment case study, depending on the aim of study, the knowledge of the area and data availability.

In the context of (Sallwey et al., 2019) review, 63 studies were identified that applied GIS-MCDA for MAR site selection. The literature review turned out 467 criteria, all of which have been harmonized and regrouped. The five key criteria groups' analysis reveals that surface characteristics are the application's primary focus.

There are five sub-criteria under the surface criteria. Among the criteria used to define the surface, geomorphology is the one that all MAR approaches employ the most. It contains the slope criterion, which is the one that is applied the most frequently. It is employed in 87% of all research. Another crucial area of criteria for all MAR approaches is soils (used 59 times).

49% of the 59 soil characteristics have been used to categorize the kind of soil, and 32% have been used to categorize the soil's capability for infiltration. Information about drainage order numbers and drainage density is included in the hydrography category. The second individual criterion after slope that has been used most frequently to characterize surface features is land use, which has been employed in 65% of all studies. After surface characteristics, aquifer characteristics are the second most often utilized criterion group. This group's focus is on the aquifer's storage capacity, which is revealed by discrete criteria such aquifer thickness (32% of studies) or groundwater level (27% of studies). General knowledge of geology and lithology is the most frequently employed single criterion in the group of aquifer features (46% of studies). Management criteria comprise a large variety of parameters that cover economic aspects of MAR site selection, such as distance to infrastructural entities or to water supply sources. Hydrometeorology parameters are used the most for studies with stormwater or surface runoff as the source for recharge. 84% of all criteria used within this category coincide with this water source. The last criteria group groundwater quality has its biggest focus on the quality of the groundwater to be recharged. (Sallwey et al., 2019)

For the purpose of this study, based on the objectives, the proposed MAR techniques and the resources available 7 criterias have been chosen. Even though all parameters are relevant, their importance depends on the respective MAR technique. Combining a high relevance and high data availability, and providing unique information the following criterions were selected to assess the suitability of MAR Akaki catchment;

- Slope
- Land cover/land use
- Drainage Density
- Geology/lithology
- Soil (HSG)
- Rainfall

- Ground water level

Accordingly, the most used four criterions have been chosen for surface criteria. Slope (geomorphological), drainage density (hydrography), land use/cover and hydrological soils (the second-most used criterion from the soils category), are among them. In addition, the two criteria that were applied the most commonly from aquifer characteristics (Geology/lithology and groundwater level), from hydrometeorology the most applied criteria (rainfall) were selected.

Due to management criteria, mapping information is typically not easily available and must be tediously digitalized this category is not considered in this study. The purpose of this study does not take groundwater quality into account hence this category is also not taken into account.

4.5 Data Sources

Once the criterions are selected the next step is to find data sources for them. USGS MODIS Land Cover (USGS Earth Explorer 2021), Shuttle Radar Topography Mission Digital Elevation Model (SRTM DEM) at 30-m resolution, and existing maps were all used as data sources. Geology map was prepared from the existing map within 100km Radius of Addis Ababa at a scale of 1:250,000 Published by Water Works Design and Supervision Enterprise (WWDSE) in 2016. Soil map was produced by digitizing a soilmap produced by Ministry of Water Resources, Electricity and Irrigation for the study area Drainage density was computed using the spatial analyst tool in ArcGIS utilizing the SRTM DEM, flow accumulation, and stream linkages. The slope map was created using the spatial analyst tool and the SRTM DEM (USGS Earth Explorer 2021). Rainfall map was produced using Rainfall data obtained from National Metrological Agency in the year (1995-2021). The inverse distance weighting (IDW) interpolation method was used to produce a groundwater level map that included data from the water level data obtained from the Addis Ababa Water and Sewerage Authority (AAWSA) and Water Works Design & Supervision Enterprise boreholes (WWDSE).

A LULC map was created as well using ESRI global LULC map derived from ESA Sentinental-2 imagery at 10m resolution for the year 2020. Table 4.1 reports the sources of each map used in GIS-MCDA for this study.

MAP	SOURCE
Rainfall Map	National Meterology Agency
Drainage Density	Shuttle Radar Topography Mission Digital Elevation Model (SRTM DEM) at 30-m resolution
Soil Map	Ministry of Water Resources, Electricity and Irrigation
Geology Map	Water Works Design and Supervision Enterprise (WWDSE)(WWDSE, 2016)
Slope	Shuttle Radar Topography Mission Digital Elevation Model (SRTM DEM) at 30-m resolution
Land use	ESRI 2020 Landuse/Landcover map(*Esri Land Cover*, n.d.)
Groundwater level	-Addis Ababa Water and Sewerage Authority -Water Works Design & Supervision Enterprise

Tabel 4. 1 Details of data used in GIS-MCDA

4.6 Preparation of Criteria Maps

After the criterions have been chosen and the appropriate data sources for them have been acquired the next phase was the preparation of criteria maps. The satellite data of DEM served the purpose of obtaining the basin boundary shapefile. For the preparation of slope maps, the Shuttle Radar Topography Mission Digital Elevation Model (SRTM DEM) at 30-m resolution was processed in ArcMap 10.8. By using the same DEM, first streams and drainage lines were obtained, and subsequently drainage density was computed in a GIS environment. To develop the soil map for the study area the soil texture map was used to generate HSG classification for further process in ArcMap to generate a thematic map of the soil. Existing geological map was utilized to generate a thematic map for the study area. The thematic map of the water table for natural aquifer recharge sites was constructed using the observations from different boreholes in the study area using ArcMap 10.8.

A land use land cover map was produced by utilizing Sentinel-2 based on supervised classification. Precipitation data for a period of 9 years (2011–2020) helped to create a mean annual rainfall map.

Seven influencing factors were selected for this study area and their thematic map was prepared in ArcMap 10.8. Furthermore, they were reclassified, ranked, and assigned with weights (based on the AHP).

4.7 Standardizing Criterion Maps

All of the requirements for the criterions are given in their own unique and linguistic form, so they cannot be compared with each other. It is not possible to do an overlay on different raster layers in ArcGIS without using values. As a result, standardizing the criterions and assign values for each catalog are needed for further steps. The two standardization methods are step-wise and linear functions(Valverde et al., 2016)

Despite the fact that GIS-MCDA is commonly used for MAR suitability mapping, there is no agreement on which criteria to apply or how to assign values. Such suitability is a type of goal-specific task which enables selection of preferred attributes or requirements at the backdrop of a specific purpose. The various criteria are laid out in the planning process as factors affecting our aim and are assigned attributes with respect to different degrees of preferences or favors one may seek from them. It normalizes the factors/criterion by assigning suitability scores to multi-attributes represented by thematic information provided under each factor of influence designated as thematic layers over a GIS domain on a common scale of ranking by applying comparisons among themselves. The various criteria must be transformed into a single scale in order to unite them and decrease their dimensionality. Each layer must be classified separately, and classification is based on the layer's content. Classification may be based on language categories like "good," "moderate," or "bad" or on numerical values. Different criteria maps may be treated with various methodologies. It is necessary to define ranges and their corresponding functions before applying standardization functions, which might take on several forms. Typically, the user must define these functions using book references or own experience.

This method in this study is based on the researcher's understanding of the research area, the availability of data, and the study's aim. In terms of MAR, each criterion map is separated into suitable classes.

Scores are assigned on a scale of 1–5 where 1 denote most suitable and 5 representing least suitability A higher score implies a low level of suitability, while a lower score indicates higher level of suitability. So far, the criterion map has been converted to a digital map that ArcGIS can manipulate. It's important to remember that the developer's choices for giving values to criteria are primarily based on personal judgment and understanding of the study area. The factor criteria are standardized using an index ranging from 1 (highest suitability) to 5 (lowest suitability).

4.8 Determination of Criterion weights (Weight assignment)

The relative relevance of the criteria is essential since each criterion has a distinct importance to the final objective. Criterion weighting is the process of allocating relative value to several criteria. As not all of the criteria have the same level of influence on the application of MAR, they must be given varying weights when integrating suitability maps because not all of them should be given the same weight. The theoretical principles and ease of use of weighting techniques vary.

It can be done by giving a criterion a value, or a weight, to indicate its relevance in comparison to other criteria. The more weight a criterion has, the more essential it is. This process, however, is dependent on and varies depending on the decision makers. Criterion weighing can be done in a variety of ways. The ranking methods, rating methods, pairwise comparison method, and multi-influence factor approach are among them (Malczewski, 1999).

The next step of this study involves determining the weight of each factor or thematic layer in GIS. Weights are determined basically by various methods like rating, ranking or adoption of analytic hierarchy process (an AHP model) to develop pair-wise comparison matrices and calculating the weightage factors of each parameter. In the rating technique the most appropriate factors are given lower numerical values whereas in the ranking method the opposite is true the higher the suitability the higher the rank. The distribution of weights gets less rational as the number of criteria increases. Under such case, a pair-wise comparison strategy in the form of a matrix enables to compare only two factors at a time. Among the three types of weight assignment strategies, the first two methods do not have any theoretical support while the pair-wise comparison method is statistically secured. Following that, four different strategies are compared. Hence for the study under consideration, pair-wise comparison matrix approach is adopted for weight assignment. because it is hierarchical, simple to use, has a high level of trustworthiness, and is quite precise. This approach is more intricate and is theoretically-based (statistical/heuristic). It is still rather simple to use and comprehend. Because only two factors are taken into account at once, the pairwise comparison's nature is simple to understand. It was developed by (Saaty & Vargas, 1980). This AHP method works on the technique where we obtain the weights or priority vectors of the factors or the criteria in the required direction to fulfil an aim. This method involves pairwise comparisons by creating a ratio matrix. It takes the ratio matrix as input and the relative weights as output (Malczewski, 1999).

The steps for pairwise comparison are:

1. Develop pairwise comparison matrix.
2. Compute criterion weights.
3. Estimate consistency ratio.

AHP involves dividing the problem into multiple issues before starting the decision making and which may be then, further divided according to prudence of the user to chalk out a clear hierarchy of issues These issues are in consideration of the aim of solving the main problem.

4.9 Decision rules (Suitability)

The goal of multicriteria analysis is to determine which option is the most favored, and to rank the options from best to worst. Multi attribute decision making (MADM) problems can be solved using a variety of decision rules.

The goal of choice rules is to devise a method for overlaying all of the possible maps together while taking into account their relative relevance. The simple additive weighting method, value/utility function approaches, the analytic hierarchy process, ideal point methods, and concordance methods are all described in Malczewski (1999). An AHP (Analytical hierarchy process) modeling is used for this specific study.

An AHP modelling includes creation of a fuzzy pair-wise comparison matrix for the individual criteria/factors under consideration. The matrix undergoes adjustments for computation of consistency index for a most likely value, affecting the consistency ratio lastly thereby. Then, the entire matrix is retained as or readjusted for a standing value of C.R.< 0.1 in consistency verification step. The fuzziness in expert judgements is said to attenuated and consistency verification claimed if and only if C.R.< 0.1. The PCM is then, used for ascertaining weights of the individual factors as their percent influence for a final ranking towards decision-making. Comparison among the factors is made through relative assessment to provide for every available alternative and choice by estimating the importance of each relative to the other in drawing out the finite elements of a PCM matrix. By determining the importance ratios for each pair of options or alternatives, a pair-wise matrix shall be constructed in the outcome having all comparison ratios. The decision rule is the fundamental part of the suitability mapping and therefore GIS-MCDA dictates how to rank the alternatives.

Applying decision rules is required to combine these factors after the weights for the criteria have been determined. The best way to rank alternatives or choose which option is favored over another is determined by decision rules. Datasets and weighting preferences are combined in this process. One of the most widely used decision rules is weighted linear combination (WLC). WLC is based on the weighted average notion, in which the decision-maker assigns a weight to the relative relevance of each criterion. By adding up all the results of the standardized criterion maps multiplied by their corresponding weights, one may determine a site's suitability. It is simple to understand and operate. Based on this fact, current study considered weighted linear combination method for decision rules.

The GIS based WLC method can be achieved by the following steps: define the evaluation criteria (map layers) and feasible alternatives; standardize each criterion map; define criterion weights; create weighted standardized criterion maps by multiplying standardized criterion map by its corresponding weights; compute overall score of each alternative by adding (overlay) all the weighted standardized criterion maps; finally rank all the alternatives according to the overall score, the alternative with the highest overall score is the best.

4.10 Description of the criterions

A detailed description of each of the criteria used in the present study is presented in the next section.

4.10.1 Slope

In MAR suitability mapping, the slope is a significant parameter. The flat surface creates suitable infiltration conditions. Run-off increases as the slope increases, whereas infiltration decreases. The most essential element of terrain topography influencing groundwater infiltration is slope. which is one of the primary parameters that controls natural recharge in a basin's water balance. The slope is the inclination of a straight line connecting two landmarks and their heights. It has been claimed that the subsurface flow declines with increasing slope angle under steady conditions with a rainfall rate substantially greater than the saturated hydraulic conductivity. As a result, slope has a significant impact on infiltration rates. In addition, the slope of the terrain affects water velocity. Runoff is more erosive on steep slopes, allowing unattached sediments to be easily removed and transported down the hill. As a result, soil instability is a possibility. Furthermore, infiltration basins cannot be installed on steeper slopes. As a result, gentle slopes boost infiltration rates and are acceptable for aquifer recharge, whereas steep slopes have low groundwater penetration and are thus unsuitable. The slope classification map (Figure 4.2) for the akaki catchment was generated from a USGS Shuttle Radar Topography Mission (SRTM) digital elevation model (DEM) with a resolution of 1-arc second, or 30 meters which was acquired from USGS. With DEM map, by using “Slope” tool in ArcGIS, Slope map was created.

Currently, there are two main ways to represent slope, one by degree and one by percentage. It is simple to transfer them by equation however internationally, slope is mostly shown in percentage. For this study slope map is prepared on the scale of percent rise unit.

Percentage = 100% × tan(degree)

Previous research has employed a variety of methods to characterize the slope in terms of MAR appropriateness. The slope related findings held a crucial credit in them as the pattern of Ground water flow is largely controlled and governed by them. In most of the study area slope is <8%.

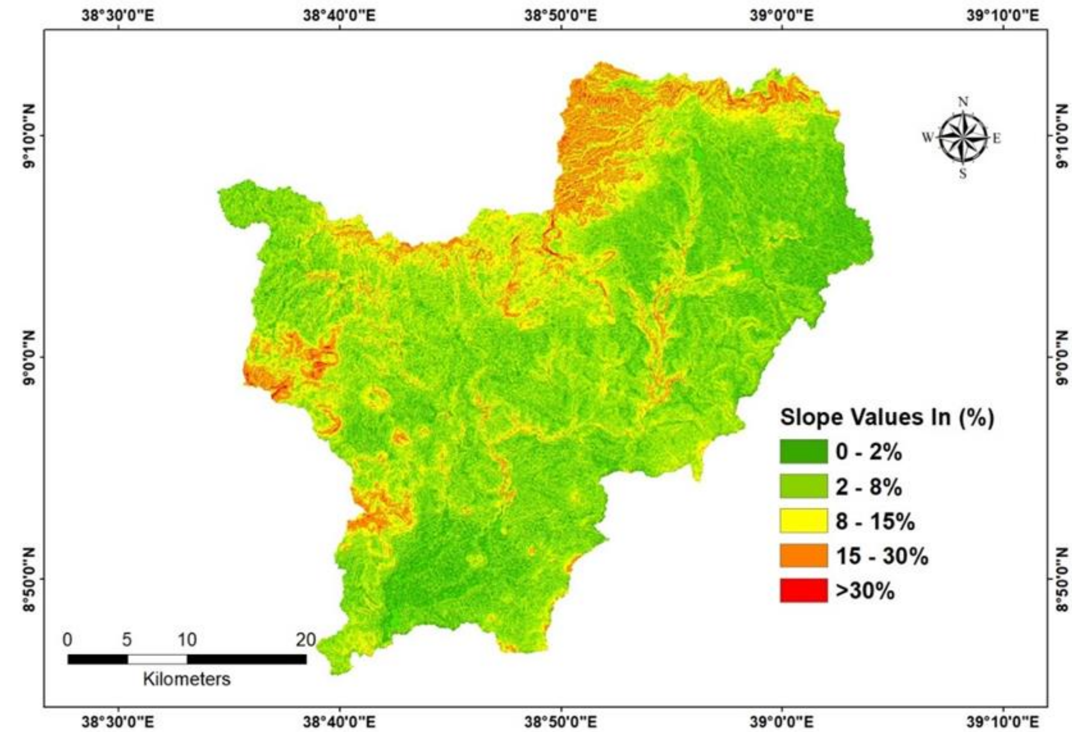


Figure 4. 2 Slope map of Akaki catchment

Slope (%)	Classification	Groundwater storage potentiality
0–2	Flat	Very high
2–8	Undulating	High
8–15	Rolling	Moderate
15–30	Moderately steep	Low
30–60	Steep	Very low

Tabel 4. 2 Slope Classification

4.10.2 Drainage Density

The permeability of the underlying material is inversely proportional to the drainage density. High run-off and drainage density are caused by less permeable materials. The drainage density, according to (Shaban et al., 2006) is one of the most essential morphometric features of a drainage system. Drainage network density, also known as drainage density, is a measure of a terrain's natural infiltration a higher drainage density indicates more runoff, and hence less infiltration; or the denser the drainage network, the lower the recharge rate. Surface runoff and permeability affect infiltration less permeable soil formation allows for less infiltration, whereas permeable ground leads to low drainage density. As a result, locations with low drainage densities are thought to be good for MAR.

Drainage networks for a broad area can be easily identified using capabilities available in GIS software (Arc-Hydro Processing). Filling sinks, determining flow direction, estimating flow accumulation and stream definition, and generating drainage density are some of the stages that must be performed. Drainage network density is computed by dividing the total length of all rivers in the basin by the basin's area. Drainage density is inversely related to the permeability of the underlying material. Less permeable material leads to high run-off and high drainage density. For most of the study area, drainage density is less than 1.5 km/km2 which is good for MAR implementation.

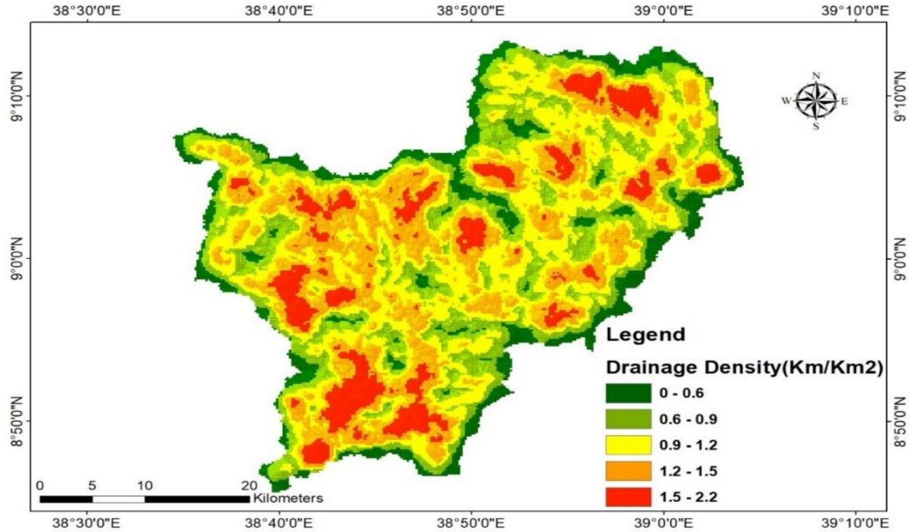


Figure 4. 2 Drainage Density Map of Akaki Catchment

4.10.3 Land cover

Hydrologic condition is affected by land use and it represents the surface conditions in relation to infiltration and runoff. The land cover has an influence on surface runoff and gives information relative to the availability of land for implementation of MAR sites. The optimum terrain for recharging is Bare ground, which provides wide areas for infiltration without causing numerous conflicts. Sparsely vegetated land (trees) is the second-best option. It usually has a high rate of infiltration and a low rate of economic loss. Cultivated land (Crop land) is the third best option. Cultivated land has intrinsic qualities such as good soils with high infiltration capacity and water availability, making it a viable option. However, persuading the owners to donate their property (which they use on a regular basis for farming) to MAR is challenging. Since MAR require a more permeable soil zone with abundant granular weathering profile, seeking LULC knowledge of the area formed an essential part of the study. Remote Sensing techniques provide best and quick approach for preparation of LULC map with less efforts and time. The final LULC map (Fig 4.4) is prepared from MODIS Landcover data (USGS Earth Explorer 2021) which is detailed, timely, accurate and 10-meter resolution map of Earth's land surface from 2017-2021. The produced LULC map have seven representative major classes as shown in figure (4.4). The study area is highly dominated by agriculture and built areas also cover a large part of it.

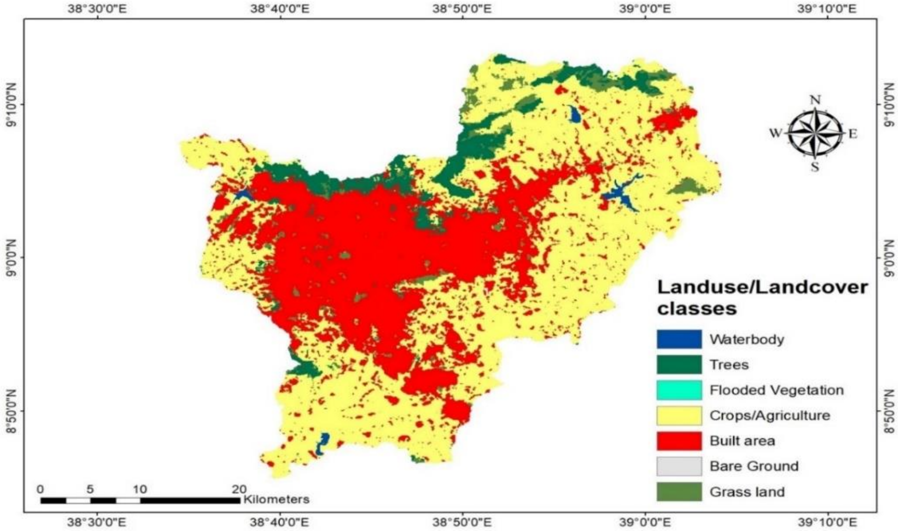


Figure 4. 4 Land use Land cover map of akaki catchment

4.10.4 Rainfall

Because the supply of water is necessary to examine before using the MAR approach, using rainfall as one factor to assess the study area's suitability is critical. Rainfall increases the amount of water available for MAR, hence areas with a lot of rain are thought to be favorable for MAR.

The study areas rainfall intensity map for 26 years (1995-2021) was produced using ArcGIS utilizing data obtained from the Ethiopian office of the National Meteorology Agency. The data is gathered from 5 stations known as Addis Ababa Observatory, Addis Ababa Bole, Akaki, Sendafa and Intoto. The study is characterized mostly by high amount of rainfall.

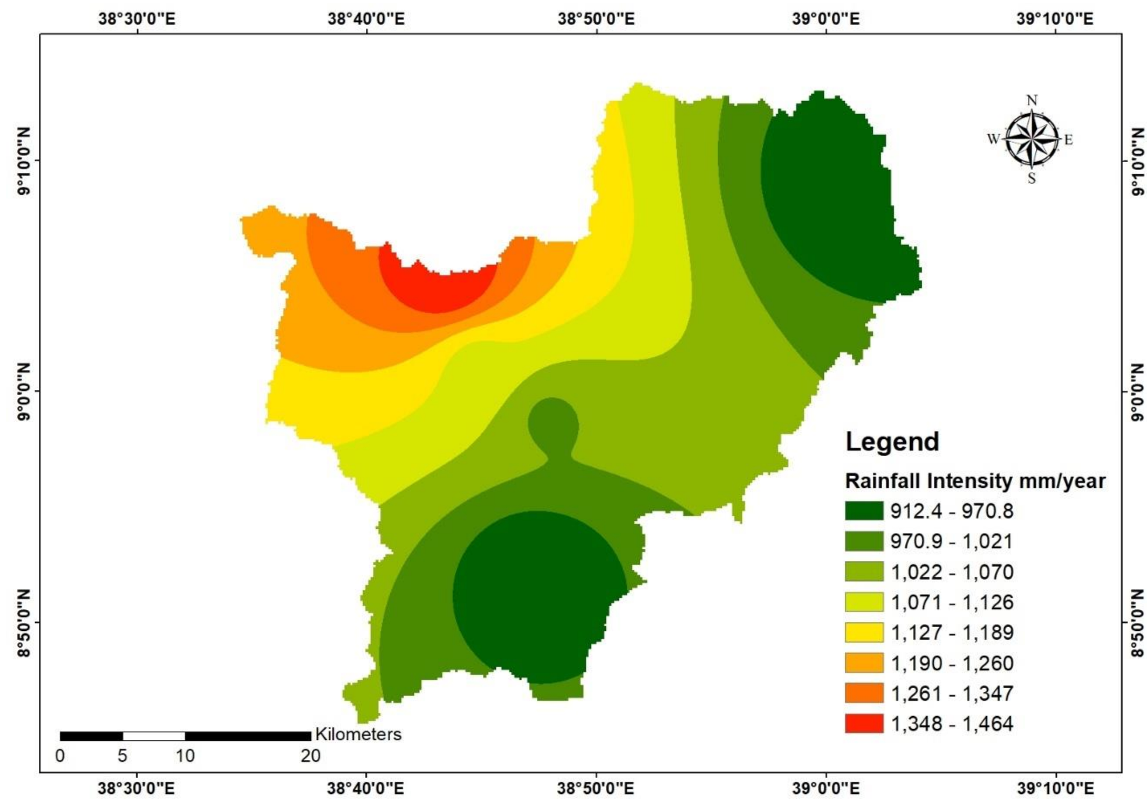


Figure 4. 5 Rainfall Intensity Map of Akaki Catchment (1995-2021)

The variation in the seasonal distribution of rainfall in Ethiopia can be attributed by the reference to the position of the Inter-Tropical Convergence Zone (ITCZ), the relationship between upper and lower air circulation, the effects of topography and the role of local convection currents and the amount of rainfall.

According to classification of Ethiopia's rainfall region, Addis Ababa is located in the region where the rainy months are contiguously distributed (Regime IE). In this region there are seven rainy months from March to September/and the small rains occur from March to May. The big rains are from June to September. High concentration of rainfall occurs in July and very high concentration in August.(Tesfaye, 2009)

4.10.5 Geology

The groundwater circulation depends on the hydrogeological characteristics of the material more specifically hydraulic properties such as porosity, permeability. The origin, flow and chemical constituent of groundwater is controlled by the type of lithology, distribution, thickness and structure of hydrogeological units through which it moves. Moreover, the stresses due to tectonism and weathering govern the hydrogeochemical characteristics of earth materials. Volcanic rocks mainly basalts, rhyolites, trachytes, scoria, trachy-basalts, welded and unwelded tuffs are the dominant rock outcrops in the area. Besides, unconsolidated materials of different origin also occur in the study area. These rocks are the major groundwater supply for large parts of Addis Ababa. The aquifer properties in the Akaki catchment are controlled by the litho-stratigraphy of the volcanic rocks and the structures that affect them. More specifically, the hydraulic complexity of these volcanic rocks is caused by their complex spatial distribution, their different reciprocal stratigraphic relationships, their significant compositional, structural and textural variability, and their different levels of tectonization and weathering.

- ❖ Bereh basalt: The unit mainly consists of thick sequence of basalt exhibiting textural and compositional variations vertically and subordinate trachytic domes and flows.
- ❖ Foota Basalt: The unit is mostly made up of basalt, which has a variety of textural characteristics, including aphanitic, porphyritic, vesicular, scoriaceous, and, in rare cases, amygdaloidal. Agglomerate and rare trachytic domes and flows are also present.

- Porphyritic Basalt and Agglomerate: The porphyritic variety is mainly plagioclase phyric and olivine phyric basalts often exposed at the top with isolated patchy outcrop pattern exhibiting spheroidal weathering.
- Entoto trachyte and lappli tuff: The association mainly consists of highly weathered and jointed trachyte and lappli tuff with sporadic ignimbrite representing the east-west trending Entoto mountain.
- Wechecha trachyte and pyroclastics: This map unit comprised of products of Wechecha, Furi, Menagesha, and Yerer silicic centers. Wechecha, Furi, and Menagesh define elliptical composite volcanoes, represented by widespread trachyte, subordinate trachybasalt and pyroclastics.
- Scoria: Isolated scoria fallout deposits and scoriaceous basalt are encountered at the northwestern escarpment around Akaki. The scoria often forms isolated cones, sometimes broad-based gentle-sloping semi-circular to elliptical bodies.
- Ignimbrite, tuff and volcanic ash: The association is known in the literature first as Nazaret Series and latter ammended to Nazret Group. It represents flat lying area around Addis Ababa and Sendafa. It consists of thick succession of mainly ignimbrite, tuff, and volcanic ash.
- Basalt and agglomerate: The unit mainly consists of very thick succession of basalt (with various textural attributes), agglomerate, with subordinate lacustrine sediments intercalations at different stratigraphic levels. This unit is collectively known as Trap Series in the literature.

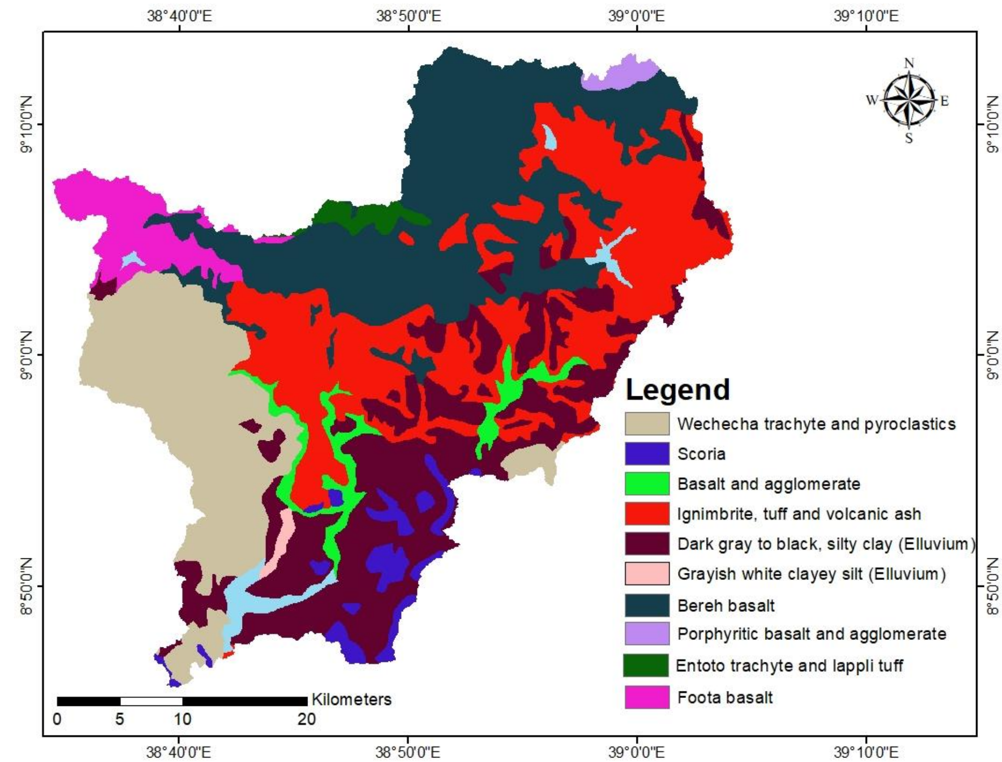


Figure 4. 6 Geology Map of Akaki Catchment

4.10.6 Groundwater level

One of the main advantages of mapping groundwater level is the identification and categorization of zones. It can be water heads of low, medium and high level. This helps understand the level of water subjected to seasonal and temporal changes. And above all, help plan the water management principles accordingly. The depth to the groundwater level depends upon the recharge and discharge of the groundwater. Groundwater level data collected from, Water Works Design & Supervision Enterprise and Addis Ababa Water and Sewerage Authority (AAWSA) boreholes used for water level maps.

The data used to create this water level map was compiled from 143 deep boreholes in the research region, which were located at elevations between 1969 and 2096, with depths between 120 and 598 meters and yields between 0.10 and 27.88 meters. It has been generated by the inverse distance weighting (IDW) interpolation method. Normal depth to water level within the study area ranges between 0 and 61.2 mbgl.

The depth to water level map is categorized into five classes. The thematic representation of the depth to water level shows that the eastern and south eastern part of the study area is found as an area of low groundwater level.

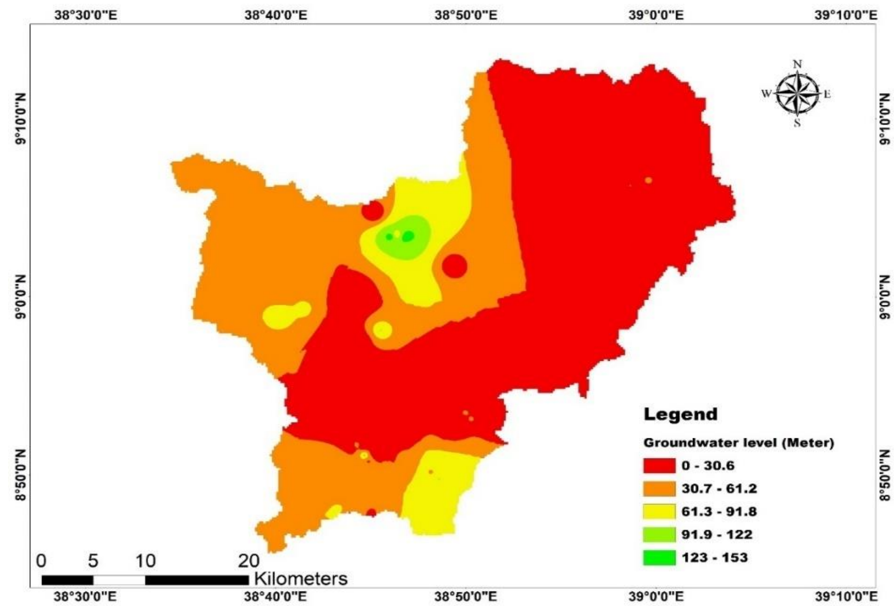


Figure 4.7 Groundwater level map of Akaki catchment

4.10.7 Soil

The upper layer of the earth where plants grow is known as soil. Soil plays the role of purifying the surface water as it infiltrates. Areas without a soil cover have low suitability for the implementation of the intended MAR methods because the absence of soil cover poses a great threat of contamination. However, regions without soil cover are not eliminated from suitability mapping because water can also be purified when it percolates through rocks in addition to soils. Soil texture defines the water retention capacity, permeability, and infiltration rate of the soil. Large particle size increases permeability and surface infiltration. The soil map was prepared by digitizing the existing conventional map in ArcGIS and reclassified. The soil types in the study area are Sandy clay, clay loam, clay and silts. The Hydrologic Soil Group classification simplifies soil classification by infiltration capacity, runoff potential, and permeability rates (Table 4.3).

These regulating elements determine the rate at which water enters the soil from the surface and the rate at which water travels through the linked voids and interstices inside the soil (Vishwakarma et al., 2021). The research areas hydrologic soil group map was generated from the soil texture class. Based on their runoff capacity, the map has three Hydrologic Soil Groups (HSGs). Hydrologic soil groups (HSGs) are a fundamental component for estimation of rainfall runoff. The four standard classes A, B, C, and D correspond to soils with low, moderately low, moderately high, and high runoff potential, respectively.

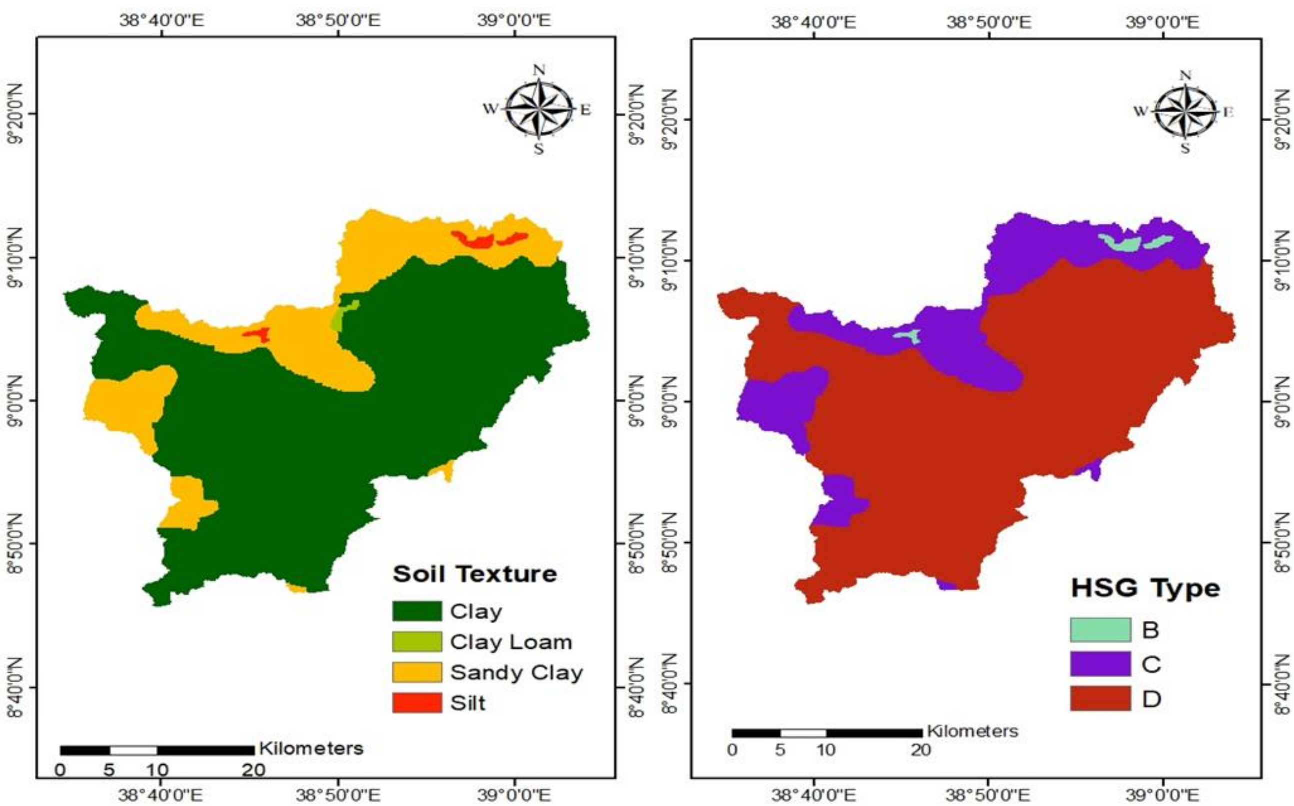


Figure 4.8 Soil texture and Hydrologic Soil group map of Akaki catchment respectively

Hydrologic Soil Group	Characteristics of Soils
Low Runoff Potential A	High infiltration rates even when thoroughly wetted. Deep, well-drained sands or gravels with a high rate of water transmission. Sand, loamy sand, or sandy loam.
B	Moderate infiltration rates when thoroughly wetted. Moderately deep to deep, moderately well-drained to well-drained, moderately fine to moderately coarse textures. Silt loam or loam.
C	Slow infiltration rates when thoroughly wetted. Usually has a layer that impedes downward movement of water or has moderately fine to fine textured soils. Sand clay loam.
D High Runoff Potential	Very low infiltration rate when thoroughly wetted. Chiefly clay soils with a high swelling potential; soils with a high permanent water table; soils with a clay layer near the surface; shallow soils over near-impervious materials. Clay loam, silty clay loam, sandy clay, silty clay, or clay.

Tabel 4. 3 Classification scheme used to develop hydrologic soil groups (HSGs).

The research area soil texture map was characterized using the above classification methodology. The primary kind of soil in the study area is D hydrologic soil group, which has a significant potential for runoff.

CHAPTER FIVE

RESULT AND DISCUSSION

5.1 The Selection Of The MAR Technique Through The INOWAS Platform

Managed aquifer recharge (MAR) represents the purposeful recharge of an aquifer for later water recovery or for environmental benefits. To meet various site specific requirements, different water infiltration techniques are available, making MAR a reliable instrument for sustainable groundwater management. Despite its demonstrated economic and ecological benefits, MAR is still not widespread, partly due to poor access to information and lack of knowledge. To address these challenges, INOWAS platform promote technical innovation and the development of smart planning tools. The INOWAS Platform fills these gaps by providing a free, web-based modeling platform for planning, assessment and optimization of MAR applications.

The online INOWAS platform was used in the first stage to help reduce the number of potential MAR alternatives for the research area.(INOWAS, 2022) INOWAS offers recommendations for the most appropriate MAR methods based on the database of MAR studies by mentioning some of the study area's features, such as the soil type, land use, MAR purpose, and typical study scale.(Sallwey et al., 2019)

Based on the climatic and geomorphological circumstances of the study area and the techniques disadvantages, some methods recommended by INOWAS were appropriate and some weren't. Twelve different MAR methods were suggested by INOWAS for the study area. The suitable ones included recharge trenches, ditches and furrows, excess irrigation, rooftop harvesting, shallow wells, shafts and pits infiltration, barrier and bunds and flooding.

MAR Method	Suitability	Details
Infiltration ponds	Unsuitable	Unsuitable because they can be applied only to unconfined aquifers, need high temperatures and high sedimentation rates.
Flooding	Suitable	Benefits include ecological improvement, flood risk reduction, and widespread aquifer recharge.
Ditches and Furrows	Suitable	Structures have low capital, operating, and maintenance expenses and can be installed over rough terrain.
Excess irrigation	Suitable	Affordable operating, maintenance, and capital costs and widespread aquifer recharge
Induced bank filtration	Unsuitable	High costs, a high risk of clogging the well, and complex design, construction, operation, and maintenance.
Aquifer storage and recovery (ASR)	Unsuitable	High quality source water and intensive system performance monitoring
Aquifer storage, transfer, and recovery (ASTR)	Unsuitable	High quality source water, intensive system performance monitoring, and a high risk of well clogging are all necessary.
Shallow wells, shafts and pits infiltration	Suitable	Recover groundwater levels and utilize existing infrastructure to reduce cost
Barrier and bunds	Suitable	Simple design, low cost, and prevention of soil erosion.
Trenches	Suitable	Affordable operating, maintenance, and capital costs
Rooftop rainwater harvesting	Suitable	It is a useful technique since it can be applied at the household level (small scale).
Soil Aquifer Treatment (SAT)	Unsuitable	High maintenance cost and risk of clogging

Table 5.1 MAR methods suggested by INOWAS and their suitability for the study area.

5.2 Suitability Map

Criteria and final suitability maps for the research area were developed as a result of the investigation. The effect of all parameters on final MAR suitability can be tracked using the criterion suitability maps. As previously stated, suitability mapping entails the following steps: Standardizing criterion maps, weighting all criteria, and deciding on a decision rule for overlaying the criterion maps are all steps in the process. In this GIS-MCDA analysis, the problem is defined as the identification of sites with the best intrinsic conditions for MAR application in Akaki catchment based on Seven criteria.

5.2.1 Map reclassification and Standardizing

Each criterion is represented by a map of a different type, such as a classed map (for example, land use) or a value map (for example, infiltration, slope); it is difficult to compare the two maps in ArcGIS because they have different types. For instance, a slope map with categories of 20%, 50%, etc. is not equivalent to a land-use map with categories of urban, forest, and water bodies. However, the comparison is simple when each category on the criterion map is given a numerical value depending on its relative significance for MAR appropriateness. All maps were reclassified and ranked as indicated in Table 5.2 due to the fact that MCDA requires that all data be standardized and translated to the same format (Sallwey et al., 2018). This was done by looking at frequently used classes, the distribution of the data, and parameter ranges. Seven criterions were chosen based on the objective for the study area suitability mapping. Hence seven map layers must be standardized. The standardization of the factor criteria follows an index ranging from 5 (minimum suitability) to 1 (maximum suitability), as presented in Table 5.2.

Suitability Class	Index
Highly Suitable	1
Suitable	2
Moderately suitable	3
Low suitability	4
Unsuitable	5

Tabel 5. 2 Correspondence between scale of standardization index and suitability level

Criteria Layers	Range	Suitability class	Suitability rank
Slope	0-3.5%	Highly suitable	1
	3.5-8%	Suitable	2
	8-15%	Moderately suitable	3
	15-30%	Low suitability	4
	>30%	Unsuitable	5
Drainage Density (per Km²)	0-0.6	Highly suitable	1
	0.6-0.9	Suitable	2
	0.9-1.2	Moderately suitable	3
	1.2-1.5	Low suitability	4
	Above 1.5	Unsuitable	5
LULC	Grass land	Highly suitable	1
	Vegetation	Suitable	2
	Crops/Agriculture	Moderately suitable	3
	Trees/forest	Low suitability	4
	Bare land	Low suitability	4
	Built area	Unsuitable	5
	Water body	Unsuitable	5
Rainfall (mm/year)	912-992	Unsuitable	5
	992-1076	Low suitability	4
	1076-1176	Moderately suitable	3
	1176-1295	Suitable	2
	1295-1464	Highly suitable	1
Soil (HSG)	B	Suitable	2
	C	Low suitability	4
	D	Unsuitable	5
Water table(m)	0-26	Unsuitable	5
	26-45.6	Low suitability	4
	45.6-63	Moderately suitable	3
	63-87	Suitable	2
	87-154	Highly suitable	1
Geology	Wechecha trachyte and pyroclastics	Low suitability	4
	Basalt and agglomerate	Moderately suitable	3
	Bereh basalt	Suitable	2
	Foota basalt	Suitable	2
	Ignimbrites, unwelded tuffs and volcanic ash	Highly suitable	1
	Scoria	Highly suitable	1

	Entoto trachyte and lappli tuff	Low suitability	4
	Porphyritic basalt and scoraceous agglomerate	Suitable	2
	Dark grey to black, silty clay	Unsuitable	5
	Grayish white clayey silt	Highly suitable	1

Table 5.3 Ranking of the suitability factors

5.2.1.1 Slope

In comparison to elevated locations with higher slopes having high runoff and low infiltration rates, flat plains are capable of storing more rainfall and facilitating recharge. The study area was separated into five slope groups based on slope. A slope from 0 to 3.5 % is considered optimum for infiltration schemes followed by four more classes (3.5% to 8, 8% to15, 15% to 30% and above 30%) Based on these classes, four breaking points are chosen for the terrain slope: from 0 to 3.5% a value of 1 is assigned, the next breaking point is at a slope 8% with a value of 2, 15% with a value of 3 and 30% with a value of 4, finally, values above 30% are assigned a value of 5.

Most of the study area has a slope lower than 8% which is the best for MAR sites. They are mainly located in southeast, central and eastern part of the catchment. The areas with higher slope distribute in northeast part. These are less suitable for MAR sites.

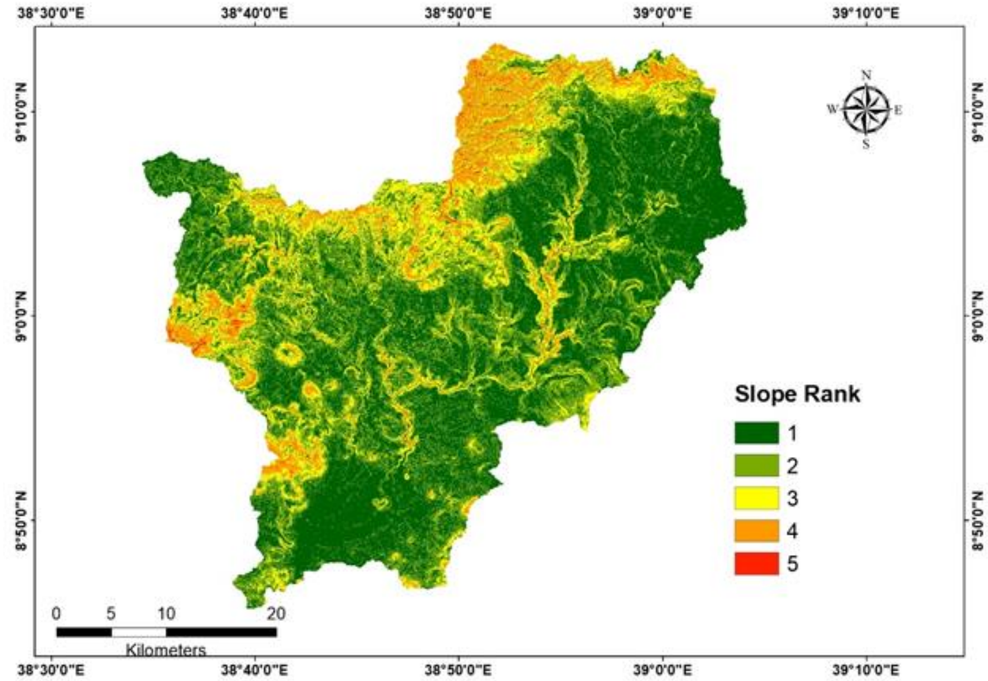


Figure 5. 1 Slope map standardized for MAR suitability mapping

5.2.1.2 Drainage Density

The drainage density, measured in km per km², reflects how closely spaced the channels are from one another. Thus, it offers a numerical measurement of the typical length of stream channels in various regions of the study area. The inverse relationship between permeability and drainage density reveals if a region is suitable for groundwater recharge. The drainage density is an inverse function of permeability and thus indirectly indicates the suitability for groundwater recharge of an area. Based on the fact that the drainage network density is an indicator of terrains with good infiltration rate, but not of unsuitable infiltration sites, (Valverde et al., 2016) these values were regrouped to produce a standardized drainage density map that was classified into five categories, i.e., a value of 1 was assigned to 0-0.6, 2 to 0.6–0.9 and 3 to 0.9-1.2, 4 to 1.2-1.5, and 5 to >1.5 for the catchment area. Drainage pattern reflects the major characteristics of the surface as well as subsurface formation. More the drainage density, higher would be the runoff.

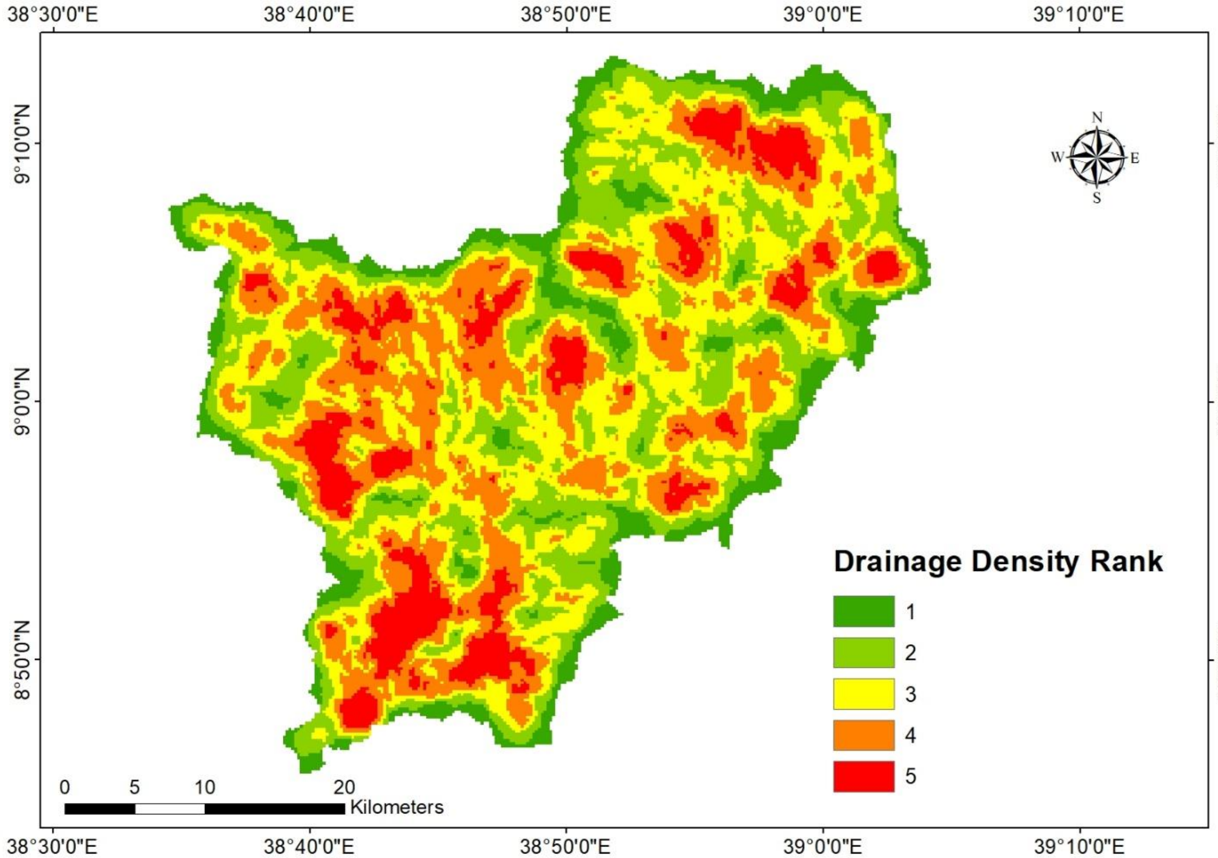


Figure 5. 2 Drainage density standardized map for MAR suitability mapping

5.2.1.3 Land cover

The land cover affects surface runoff and provides details on the area's suitability for MAR site implementation. The categories found on the created landcover map served as the basis for standardization. According to their influence on infiltration and surface runoff, availability, and potential environmental impact, the five suitability classes used in this study to categorize the existing land cover. The specific landcovers that are included in each class and the justification for this decision are as follows:

- Highly suitable: Given a value of 1, grassland is regarded as the best candidate for MAR implementation since it typically has good infiltration rates and involves less economic loss when occupied. as these terrains are likely to offer large areas for spreading methods, with soils of sufficient infiltration potential and little conflict in term of land disturbance as they usually do not have a specific use.

- Suitable: Flooded vegetation land principally occupied by agriculture with significant areas of natural vegetation as these terrains are also likely to offer large areas forMAR site, with soils of sufficient infiltration potential. A value of 2 is given because they always have good infiltration and availability to water.
- Moderately suitable: Crop/agriculture land is regarded as the third-best option since it is generally in good shape, including good access to water and good soil conditions for plants to grow in, including good infiltration rate. Although removing cultivated land can result in economic loss, it is listed as the third-best option and given a value of 3.
- Low suitability: forests(Trees) and bare land as this land use type is not suitable for MAR as the available area and infiltration potential are low. Moreover, converting forests into sparsely vegetated areas should not be done intentionally. A value of 4 is given.
- Unsuitable: Built area and water body is the next category to be taken into account. Due to the dense population in the study area, it is less likely that residential neighborhoods will have large access to land. Additionally, as residential areas are mostly built-up, there is less water infiltration there. water body and buit area categories are considered and a value of 5 was assigned.

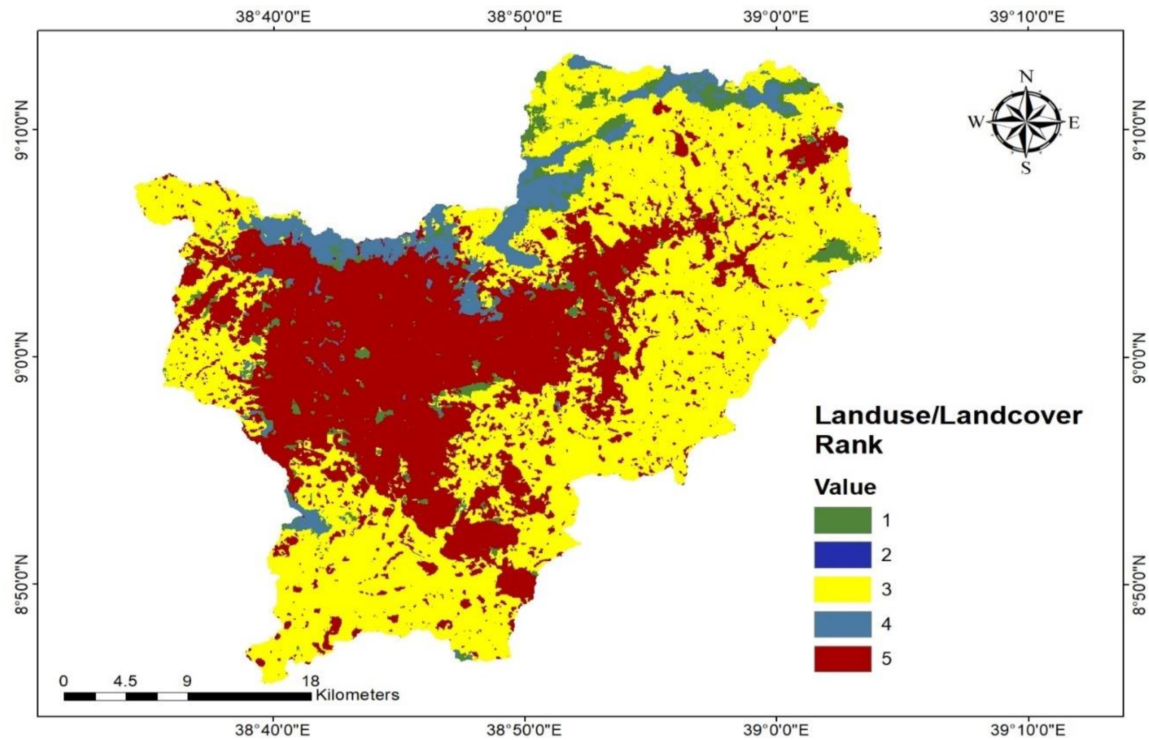


Figure 5. 3 Land use map standardized for MAR suitability mapping

Land use plays an important role in selecting suitable sites for artificial recharge and evaluating the feasibility of whether any structure could be constructed on the selected site. In this study, grass land, agriculture areas, barren land and tree covered areas have been selected as appropriate land-use types for MAR application (Fig.5.3). Planning for MAR sites may face less land acquisition issues for these types of land.

5.2.1.4 Rainfall

The most important factor affecting subsurface recharge is rainfall. Due to the significant volume of water available for groundwater recharge, regions with heavy rainfall are thought to be particularly suitable for MAR. The study area's rainfall criterion map was divided into five categories: It was given a value of 5 for (912-992 mm), a value of 4 for (992-1076 mm), a value of 3 for (1076-1176), a value of 2 for (1176-1295) and It was given the value of 1 (1295-1464 mm) (Figure 5.4). The North-Western region of the research area has substantial rainfall, which suggests that it is very suitable for MAR.

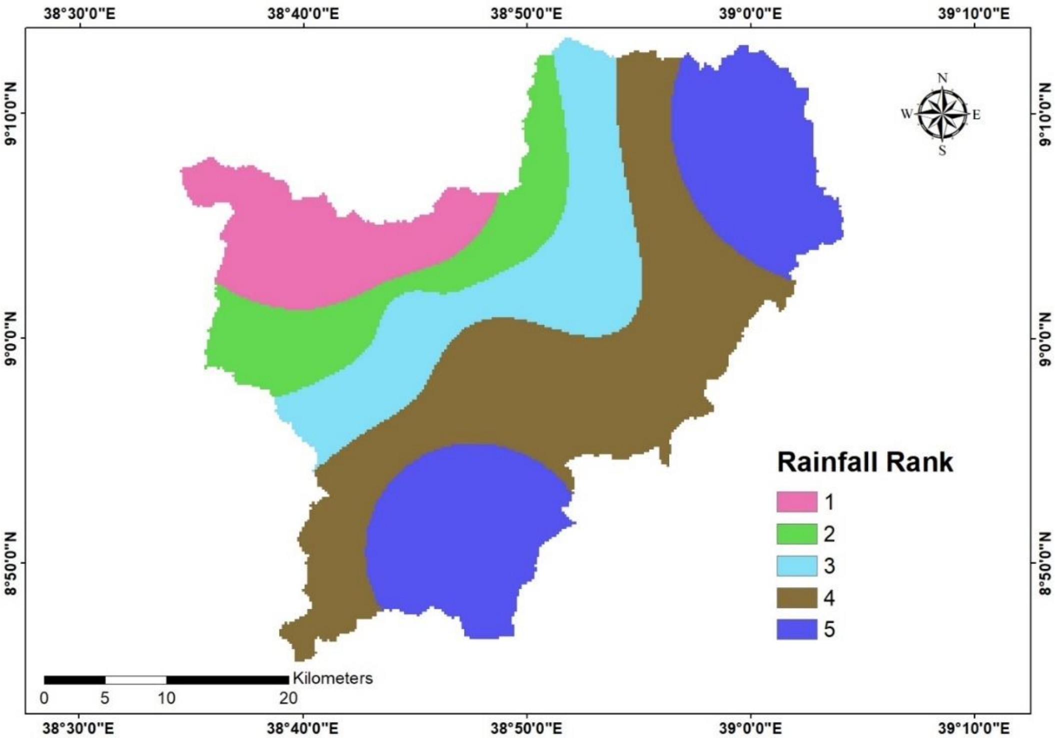


Figure 5. 4 Rainfall map standardized for MAR suitability mapping

5.2.1.5 Soil (Hydrological soil Groups)

The rate at which water permeates the soil at the soil surface is known as the infiltration rate. Surface conditions determine how it behaves. HSG also displays the speed at which water transmits through the soil. The study areas soil group (HSG) was reclassified based on their runoff potential as follows;

- Group B: is silt loam or loam. It has a moderate infiltration rate when thoroughly wetted and consists chiefly or moderately deep to deep, moderately well to well drained soils with moderately fine to moderately coarse textures therefore it is assigned a value of 2
- Group C: When soaked through, the soils in this group have a moderately high potential for runoff therefore they are assigned as 3. There are some limitations on how much water can go through the soil. Group C soils typically feature loam, silt loam, sandy clay loam, clay loam, and silty clay loam textures and contain 20–40%–50% clay and less than 50% sand.
- Group D: The soils in this group have high runoff potential hence they are assigned a value of 4. The ability of water to travel through the soil is severely constrained. Group D soils often feature clayey textures, more than 40% clay, and less than 50% sand.

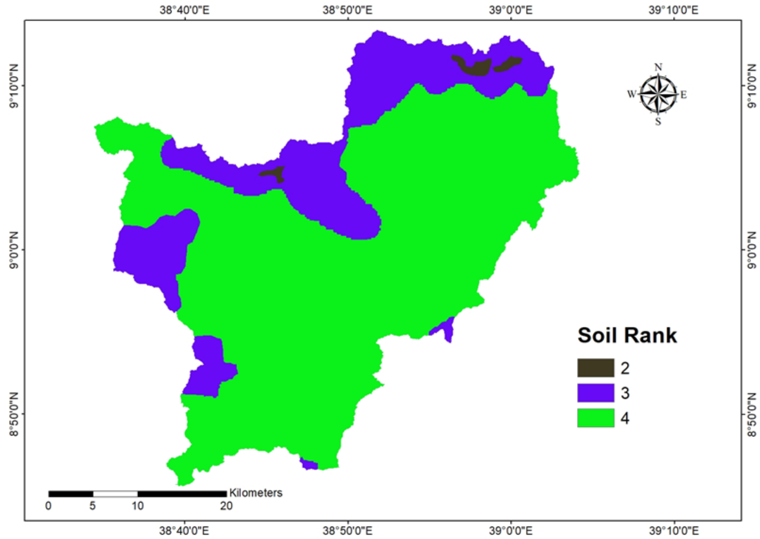


Figure 5. 5 Soil map standardized for MAR suitability mapping

5.2.1.6 Geology

The type of rock and soil is the most important component for groundwater potential due to the infiltration process primarily depending on the permeability of particular types of rock. Basalts, rhyolites, trachytes, scoria, trachy-basalts, ignimbrites and tuff are the main geological formations found in the catchment. High weight is assigned for basalts, ignimbrite, fractured tuff, and trachyte because these formations are highly weathered and fractured.

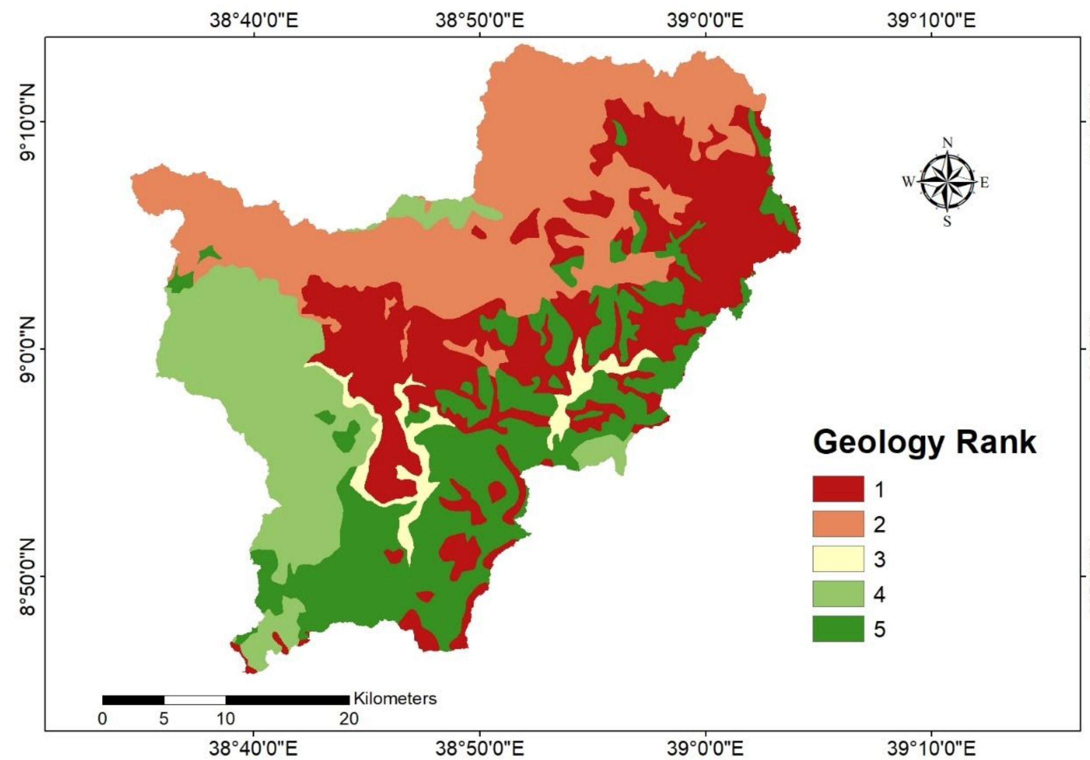


Figure 5.6 Geology map standardized for MAR suitability mapping

The project area's geology map was evaluated according to the impact that various lithologies had on the surface and groundwater systems there.(WWDSE, 2016)

- Dark gray to black, silty clay (Elluvium): Cohesive soil, forming barrier to ground water infiltration ranked as a value of 5.
- Grayish white clayey silt (Elluvium): Residual soil that allows water infiltration to the subsurface ranked as a value of 5.

- Wechecha trachyte and pyroclastics: Alternation of cohesive very strong rock and loose tuff, occurring on high groundsleads to surface runoff ranked as a value of 4.
- Entoto trachyte and lappli tuff: Alternation of cohesive very strong rock and loose tuff, occurring on high groundsleads to surface runoff ranked as a value of 4.
- Porphyritic basalt and scoraceous agglomerate: Alternation of trachy basalt, basaltic agglomerate, scoria and vesicular basalt, shows columinar joint and wide fractures. It may form local aquifer or lead to infiltration ranked as a value of 2.
- Foota basalt: Alternation of trachy basalt, basaltic agglomerate, scoria and vesicular basalt, shows columinar joint and wide fractures. It may form local aquifer or lead to infiltration ranked as a value of 2.
- Bereh basalt: Alternation of trachy basalt, basaltic agglomerate, scoria and vesicular basalt, shows columinar joint and wide fractures. It may form local aquifer or lead to infiltration ranked as a value of 2.
- Basalt and agglomerate: Very strong apahanitic basalt alternating with well compacted agglomerate, Columinarly jointed basalt with fractures occurring at lower stratigraphic levels. It is presumed to be barrier but also might form local fracture aquifer ranked as a value of 3.
- Scoria and scoraceous basalt: V.Good local aquifer ranked as a value of 1.
- Ignimbrite, tuff and volcanic ash: Alternation of highly compact to moderately welded and locally loose pyroclastic deposit. Ignimbrite commonly exhibit irregular columnar jointing that might lead to infiltration ranked as avalue of 1.

5.1.2.7 Groundwater level

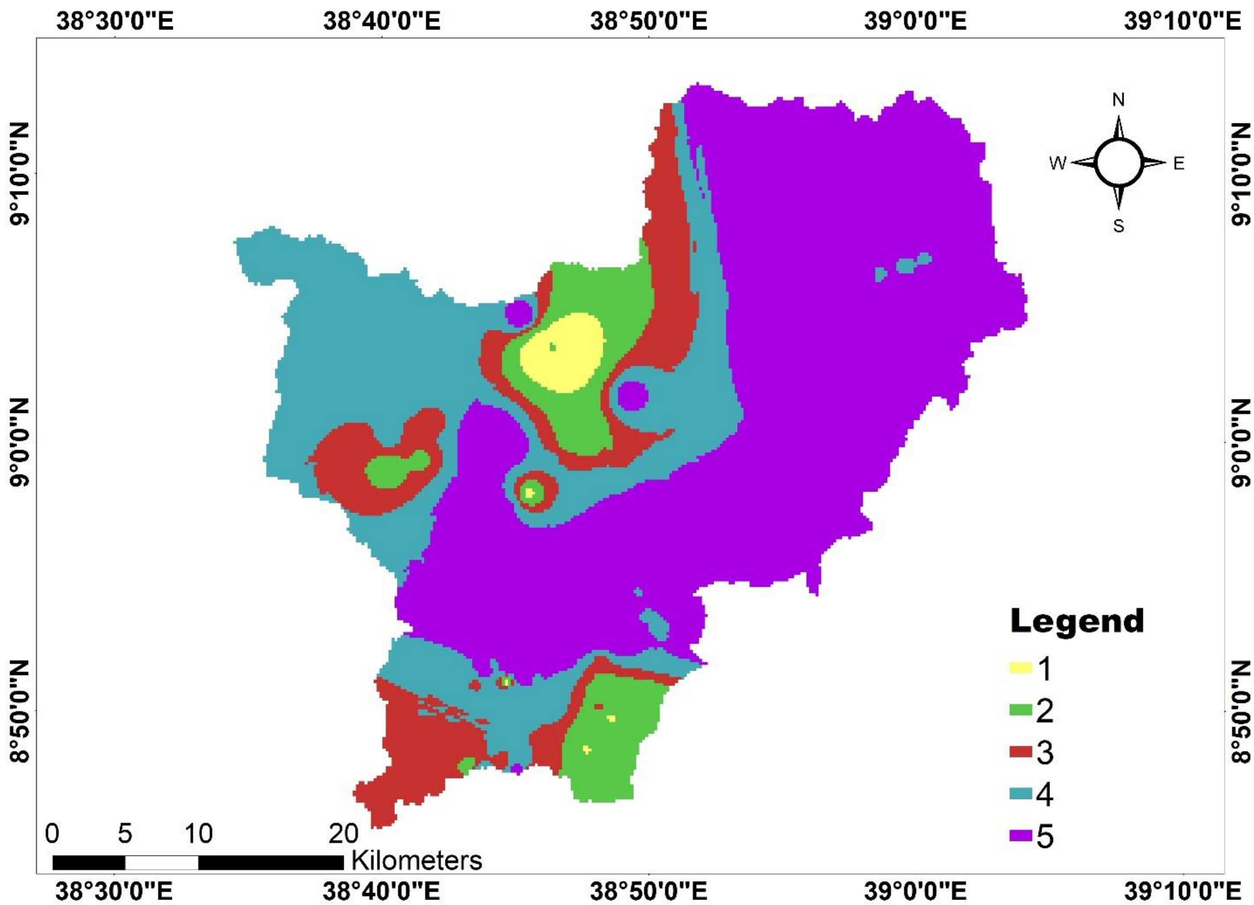


Figure 5.7 Groundwater level map standardized for MAR suitability mapping

Water table (W) depth is the altitude of the top of the water in the aquifer. The study area groundwater depth varied from 0 m to 154 m. Sites on the water table map were reclassified into five groups; 1) <26 m 2) 26-45.6 m, 3) 45.6-63 m, 4) 63-87m and 5) 87-154 m. The higher the depth of the water table renders, the higher the chance of storage capacity or percolation of water through soil pore spaces into the aquifer. In contrast, in areas with less water table depth, soil pore spaces are essentially fully saturated, thus there is very little chance for water to percolate into the aquifer.

5.3 Criterion Weighting

5.3.1 Analytical Hierarchy Process (AHP)

One of the most important methods for making decisions in a variety of areas, including site selection, land use allocation, and solid waste management, is the analytical hierarchy process (Saaty, 1980). Pair-wise comparisons of factors are utilized to evaluate and rank their importance level using the well-researched and frequently used AHP technique for decision making. In this study, the weights of the selected variables for the identification of recharge sites have been determined using the AHP approach proposed by(Saaty, 1980).

The AHP approach was used to complete the weighting process. When there are many alternatives to choose from, the AHP matrix approach is preferable to a number of pairwise comparisons and results compilation. Weights need to be assigned to each criterion reflecting their relative importance within the set of criteria. Several methods exist to assign criteria weights, including the 'Pairwise comparison', as part of the AHP. Each criterion is compared one by one to every other criterion in a pair-wise comparison matrix (Table 5.5) in which a grade from 0 to 9 reflecting the importance of one criterion compared to the other (below 1, the criterion is judged less important than the other; 1 means that both are judged equally important; from 2 to 9, the criterion is judged more important than the other) is assigned. Each score is then normalized and converted into relative weights. The Analytical Hierarchy Process (AHP) includes the 'Pairwise comparison approach,' which is a framework for evaluating an issue by deconstructing it into a hierarchy of sub-problems. The decision maker uses this method to compare each criterion to the other criteria Each method assigns a numerical value to each weight, resulting in a total weight of 1. By first creating a pairwise comparison matrix based on (Saaty & Vargas, 1980) guidelines and using a numerical scale of 1–9 to determine the relative importance of the criteria, AHP was employed in this study to determine weights for the reclassified and standardized criteria.

Scale	Numerical Rating	Reciprocal
Extremely Preferred	**9**	**1/9**
Very strong to extremely	8	1/8
Very strongly preferred	**7**	**1/7**
Strongly to very strongly	6	1/6
Strongly preferred	**5**	**1/5**
Moderately to strongly	4	1/4
Moderately preferred	**3**	**1/3**
Equally to moderately	2	1/2
Equally preferred	**1**	**1**

Tabel 5.4 Thomas Saaty 1–9 Scale for AHP Pairwise Comparison

As discussed before, pairwise comparison method was chosen and the results are as follows:

I. Develop pairwise comparison matrix

In order to express relative importance and rank the influence of each component, relative priority in this study is assessed on a scale from 1 to 5 (equal importance to strong importance). The key justification for using a scale of up to 5 is that it is similar to the scale used by ArcMap's weighted overlay tool, which uses a scale of 1 to 5. The amount of input factors (reclassified maps of theme layers) determines how many pairwise comparison factors are formed, or A (m2). The pairwise comparison matrix method was used in this study. According to how one element interferes with the other factors to effect recharging, parameter pairs were chosen for the matrix and pair weights were assigned.

Criterion	Geology	Slope	Soil	Lulc	Drainage density	Rain fall	Water level
Geology	1	1	2	2	3	2	4
Slope	1	1	1	2	3	2	4
Soil	1/2	1	1	1	3	2	5
Lulc	1/2	1/2	1	1	2	2	3
Drainage density	1/3	1/3	1/3	1	1	1	4
Rain fall	1/2	1/2	1/2	1/2	1	1	5
Water level	1/4	1/4	1/5	1/3	1/4	1/5	1

Tabel 5.5 Pairwise comparison matrix of the evaluation criteria

The matrix is filled in from upper left corner to the lower right corner above value 1 cells. The upper right part is filled in based on decision maker's idea. For instance, Geology is considered equally preferred to slope, as both of them controls source of water needed for mar, but in different layers, so a 1 value is assigned. The remaining upper right cells are determined like this. Next, it is assumed that the comparison matrix is reciprocal. That is, if criterion A is twice preferred than criterion B, then criterion B is half preferred than criterion A. To be more specific, if criterion A has a score of 2 comparing to criterion B, criterion B has a score of 1/2 compared to criterion A. Use this logic, the lower left of the matrix is filled in. Until now, the whole matrix is complete.

This method resulted in 'Geology' 'Slope' and 'soil' as the most important criteria, according to the following reasoning: The distribution and occurrence of groundwater are significantly influenced by geology. Geology has a major influence on drainage density, landcover, soil and the recharge processes.(Shaban et al., 2006) It is therefore considered the most important criterion. The criterion 'slope' was considered as the second most important criterion as MAR cannot be applied on steep slopes even if all other criteria are highly suitable as most of the water available will be lost by runoff. The slope of the area influences the land cover, soil (as erosion is high on steep slopes (Magesh et al., 2012).

'Soil type' has a influence on the recharge and drainage density(Valverde et al., 2016) therefore it is considered as the third most important criterion. The type of 'land cover' affects the availability of land for MAR operation and the infiltration capacity of the ground, so it is assigned as important after soil type. 'Precipitation' is included in the present study and assigned to have a minor influence on MAR. 'Drainage density' is inversely related to the permeability of the underlying material. Less permeable material leads to high run-off and high drainage density. Therefore, less drainage density is directly related with low runoff. Finally, the criterion 'water level' resulted in the lowest weight as it does not limit the suitability to implement a MAR site.

II. Compute criterion weights

This step entails three operations:

- sum the value of each column;
- divide each cell of the matrix by its column total got in step (1);
- Compute the average value of each row. The weights of the criterion have been allocated up to this point, and the importance of each criterion is evident.

  The criteria weights are 23%, 21%, 18%, 12%, 11%, 11% and 4% for geology,slope, soil, landcover, drainage density, rainfall, and water level.
- Estimate consistency ratio

  After building a pair wise comparison matrix, consistency is checked, this can be done by Consistency index (CI) and Consistency ratio (CR) proposed by Saaty to verify the consistency of the comparison matrix. CI and CR are defined as follows:

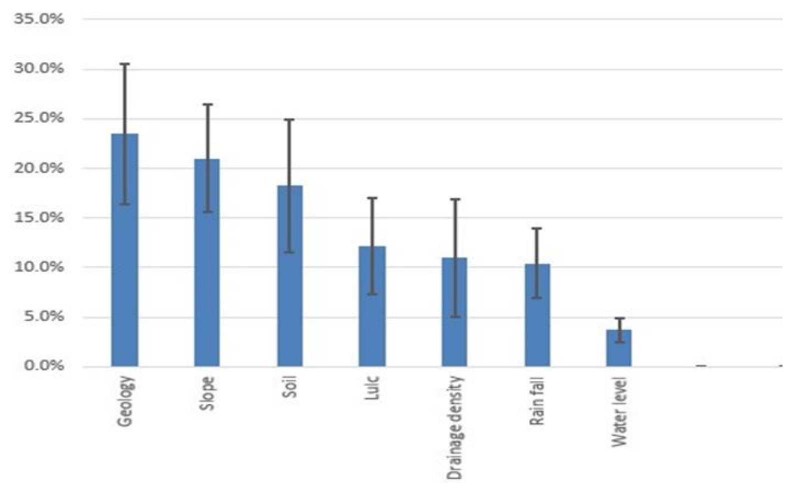
$$CI = \frac{\lambda max - n}{n - 1}$$

Where 'ƛmax' is the maximum Eigen Value of the Normalized Pair wise matrix, 'n' is the dimension of comparison matrix and CI is Consistency Index.

$$CR = \frac{CI}{RI}$$

This step is to verify if the comparison results are consistent. Constructing a pair-wise comparison square matrix of order with matrix property of precise consistency is a difficult task for decision-makers in practice, especially when there are a large number of confusing circumstances. As a result, the square matrix of type (n*n) should have the properties of reciprocity and consistency. Matrices differ in their degree of consistency, with one lacking consistency by only two or three elements while the other isn't even close to bearing consistency. Calculating the Consistency Ratio is a straightforward way to check for consistency

For all practical purposes, a CR equal to 0.1 or below would render higher consistency and the acceptability of results obtained by AHP. The value of CR can be explained as: if CR < 0.10, the result shows a reasonable level of consistency in the pairwise comparisons. On the contrary, if CR ≥ 0.10, the values are inconsistent judgements and shall tantamount to rejection of the matrix or change of its elements by reconsideration strategy and revising from the beginning. (Rahman et al., 2012; Xu et al., 2021) In present case, a consistency ratio of 0.04 is much smaller than 0.10, consequently the ratio indicates a reasonable level of consistency in the pairwise comparison.



III. Resulting criteria weights

Tabel 5.6 Resulting criteria weights

5.4 Decision rules

5.4.1 Weighted overlay analysis

The overlay analysis is the last step in the process of creating the MAR suitability map. In a weighted overlay analysis, the relative weight and standardized appropriateness score are used to overlay all the criteria. This is accomplished by adding the weight of each criterion to its standardized rank (1–5) for each cell. There are various overlay techniques, including the weighted linear combination utilized in this study. Five levels, ranging from 1 to 5, are assigned to the final suitability map. A very poor suitability area for MAR implementation is indicated by a value of 1, whilst a very good suitability area is indicated by a value of 5. The final MAR suitability map is obtained by overlaying all the criteria maps according to their respective ranges/common scale (0-5), weights and final suitability class in the spatial analyst tool of ArcGIS.

5.5 Assessment of Final MAR suitability map

In this study, the study area with an area of about 1461 km2 , has been investigated for MAR site selection. Based on the literature review and available data for this area, effective criteria have been selected. To determine the most suitable areas for MAR in the study area, drainage density, rain fall, slope, land use, soil, geology have been considered. For each criterion, the raster thematic layer with a pixel size of 30 × 30 m was prepared in a GIS environment.

In the weighted overlay method, each thematic layer was prepared and classified based on scores of 1–5: 1 for highly suitable, 2 for suitable, 3 for moderately suitable, 4 for low suitable and 5 for unsuitable class. Then, all thematic layers were combined using the weighted overlay tool in the ArcGIS software with respect to their degree of influence which was assigned using the pair wise comparison method for all criteria in this study. The final suitability map from the weighted overlay analysis is illustrated in Figure(5.8). Results show that the southern part is categorized as low suitable area, and moderate suitability Classes are available throughout the study area, although most are predominantly in the north east. The suitable classes are found on the northern part of the catchment. As well as mostly north western part is ranked as suitable.

The final suitability map was used to delineate the regions suitable for MAR implementation by combining different criterion maps using GIS-MCDA. The suitability map was classified into five categories, i.e., high suitablilty, suitable, moderate, low, and very low (Figure 5.8). The final suitability map reveals that most part of the region shows moderate MAR suitability in the catchment. About 71.54% of the study area falls in the moderate, 9.8% suitable, and 18.66% low MAR suitability zone. The spatial distribution of the suitability zones typically demonstrates a mirror reflection of the significant contributing factors.

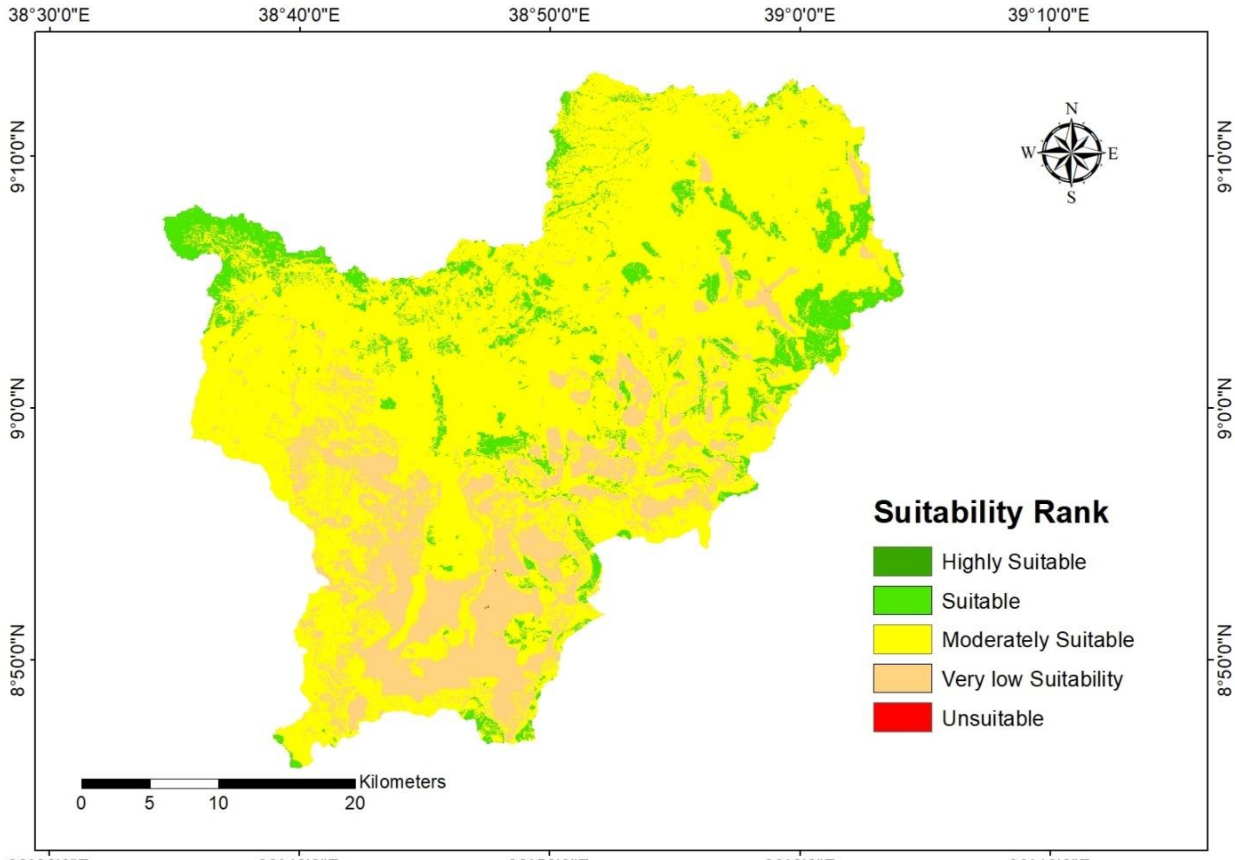


Figure 5. 8 Final suitability mapping of Akaki catchment

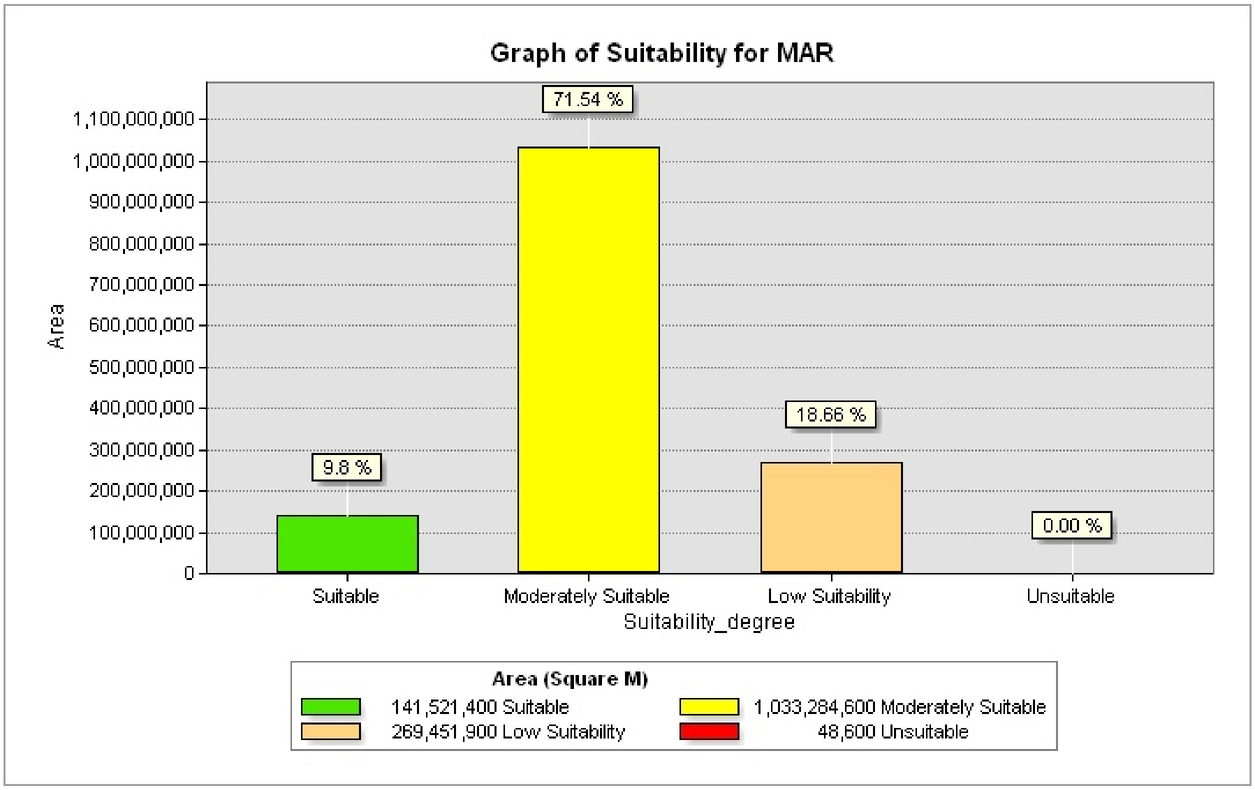


Figure 5. 9 Graph representing suitability of Akaki catchment for MAR

This study aims to provide a broad recommendation on the suitability of Akaki catchment for MAR implementation, and it did not target any specific user group i.e., domestic, agriculture, and industrial (detail studies are required for each user group). In addition, data on water usage can further enhance the map, as the required water quality for drinking, agriculture, and industry varies significantly. Finally, while mapping the suitability of MAR is one component, socioeconomic factors such as cost, land requirements, expertise, and public acceptability all contribute to the success of MAR. By increasing the number of criteria, the accuracy of the MAR suitability map increases, but the data availability also influences it. Therefore, due to the data limitations and scope of the current study, the above parameters were not included in MAR suitability mapping.

5.6 Sensitivity analysis

Sensitivity analysis in MCDA is defined as a collection of techniques for evaluating the degree of uncertainty in the output of the multi-criteria model and the significance of the model input parameters as the weights and values of the criteria. The primary sources of uncertainty in the GIS-MCDA are these variables (criterion values and criterion weights). Sensitivity analysis results in a more reliable decision rule for site suitability selection. These consist of "variance-methods" and "one-at-a-time" techniques. Sensitivity analysis has been used to show the impact of changing the criterion weights on the suitability mapping's spatial distribution. The aim for multicriteria spatial sensitivity analysis is to measure the influence of the errors caused by input criterion maps and the decision maker’s preferences on the decision outcomes (Malczewski, 1999; Rahman et al., 2012; Shankar & Mohan, 2005).

In this study sensitivity analysis was performed by omitting one of the criteria. First, drop one of the criterion. Next, update the pairwise comparison matrix of the remaining criteria to redistribute the weights of the criteria. Finally, apply WLC to obtain new overall values for all alternatives. estimating the percentage of alternatives that have changed and their fluctuating range, and finally doing analysis with the results. A number of combinations of weights were calculated and the resulting suitability maps compared to a base map. The smaller the differences between the base map and the maps with varying weights, the more robust the assigned weights were assumed to be.

The current study is focused on the effects of the criteria. Sensitivity analyses were performed by deleting each criterion one at a time and observing how the final suitability map changed. To be more specific, run the pairwise comparison once more with the updated criteria and weights. The criteria's standardization is unchanged. New suitability maps can be obtained using WLC.

5.6.1 Criterion Weighting

The revised weights were assessed using pairwise comparison as before. The pairwise comparison matrix for the new criteria is shown below.

Criterion	Geology	Slope	Lulc	Drainage density	Rain fall	Water level
Geology	1	1	2	3	2	4
Slope	1	1	2	3	2	4
Lulc	1/2	1/2	1	2	2	3
Drainage density	1/3	1/3	1	1	1	4
Rain fall	1/2	1/2	1/2	1	1	5
Water level	1/4	1/4	1/3	1/4	1/5	1

Table 5.7 Pairwise comparison matrix of criteria without considering soil texture

Consistency ratio is 0.04 < 0.1, the ratio indicate a reasonable level of consistency in the pairwise comparison.

Criterion	Geology	Soil	Lulc	Drainage density	Rain fall	Water level
Geology	1	2	2	3	2	4
Soil	1/2	1	1	3	2	5
Lulc	1/2	1	1	2	2	3
Drainage density	1/3	1/3	1	1	1	4
Rain fall	1/2	1/2	1/2	1	1	5
Water level	1/4	1/5	1/3	1/4	1/5	1

Table 5.8 Pairwise comparison matrix of criteria without considering slope

Consistency ratio is 0.04 < 0.1, the ratio indicate a reasonable level of consistency in the pairwise comparison.

Criterion	Geology	Slope	Soil	Drainage density	Rain fall	Water level
Geology	1	1	2	3	2	4
Slope	1	1	1	3	2	4
Soil	1/2	1	1	3	2	5
Drainage density	1/3	1/3	1/3	1	1	4
Rain fall	1/2	1/2	1/2	1	1	5
Water level	1/4	1/4	1/5	1/4	1/5	1

Table 5.9 Pairwise comparison matrix of criteria without considering land cover

Consistency ratio is 0.03 < 0.1, the ratio indicate a reasonable level of consistency in the pairwise comparison.

Criterion	Geology	Slope	Soil	Lulc	Rain fall	Water level
Geology	1	1	2	2	2	4
Slope	1	1	1	2	2	4
Soil	1/2	1	1	1	2	5
Lulc	1/2	1/2	1	1	2	3
Rain fall	1/2	1/2	1/2	1/2	1	5
Water level	1/4	1/4	1/5	1/3	1/5	1

Table 5.10 Pairwise comparison matrix of criteria without considering drainage denisty

Consistency ratio is 0.03 < 0.1, the ratio indicate a reasonable level of consistency in the pairwise comparison.

Criterion	Slope	Soil	Lulc	Drainage density	Rain fall	Water level
Slope	1	1	2	3	2	4
Soil	1	1	1	3	2	5
Lulc	1/2	1	1	2	2	3
Drainage density	1/3	1/3	1	1	1	4
Rain fall	1/2	1/2	½	1	1	5
Water level	1/4	1/5	1/3	1/4	1/5	1

Table 5.11 Pairwise comparison matrix of criteria without considering geology

Consistency ratio is 0.03 < 0.1, the ratio indicate a reasonable level of consistency in the pairwise comparison.

Criterion	Geology	Slope	Soil	Lulc	Drainage density	Water level
Geology	1	1	2	2	3	4
Slope	1	1	1	2	3	4
Soil	1/2	1	1	1	3	5
Lulc	1/2	1/2	1	1	2	3
Drainage density	1/3	1/3	1/3	1	1	4
Water level	1/4	1/4	1/5	1/3	1/4	1

Table 5.12 Pairwise comparison matrix of criteria without considering rainfall

Consistency ratio is 0.05 < 0.1, the ratio indicate a reasonable level of consistency in the pairwise comparison.

Criterion	Geology	Slope	Soil	Lulc	Drainage density	Rain fall
Geology	1	1	2	2	3	2
Slope	1	1	1	2	3	2
Soil	1/2	1	1	1	3	2
Lulc	1/2	1/2	1	1	2	2
Drainage density	1/3	1/3	1/3	1	1	1
Rain fall	1/2	1/2	1/2	1/2	1	1

Table 5.13 Pairwise comparison matrix of criteria without considering water level

Consistency ratio is 0.04 < 0.1, the ratio indicate a reasonable level of consistency in the pairwise comparison.

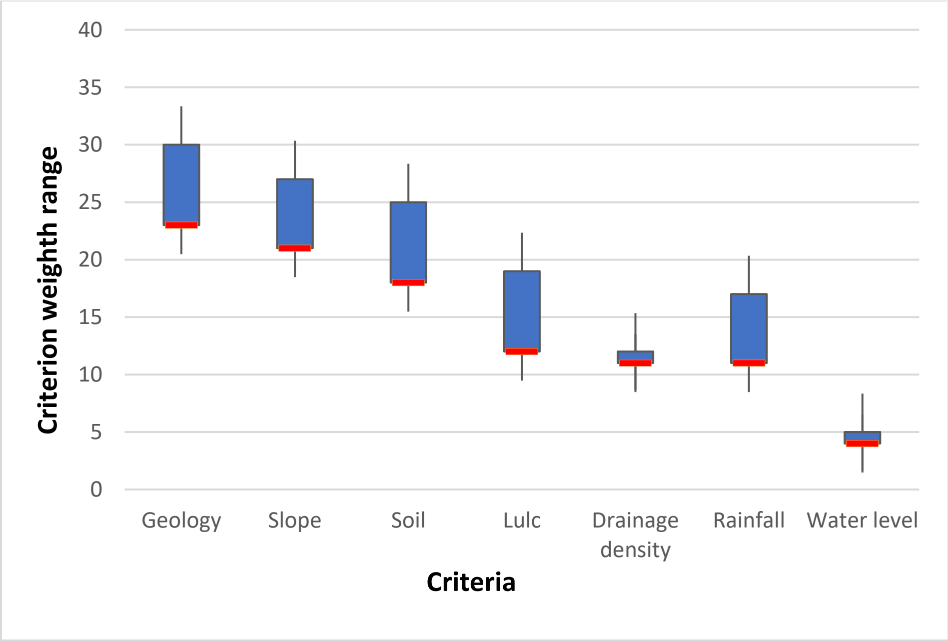


Figure 5.10 Range of weights for the criteria used in the sensitivity analysis

The figure illustrates the fact that by eliminating one of the criterion, the remaining factors are all given more weight. The weight for the losing criterion is correspondingly shared and gained by other criteria, which is a straightforward explanation for this.

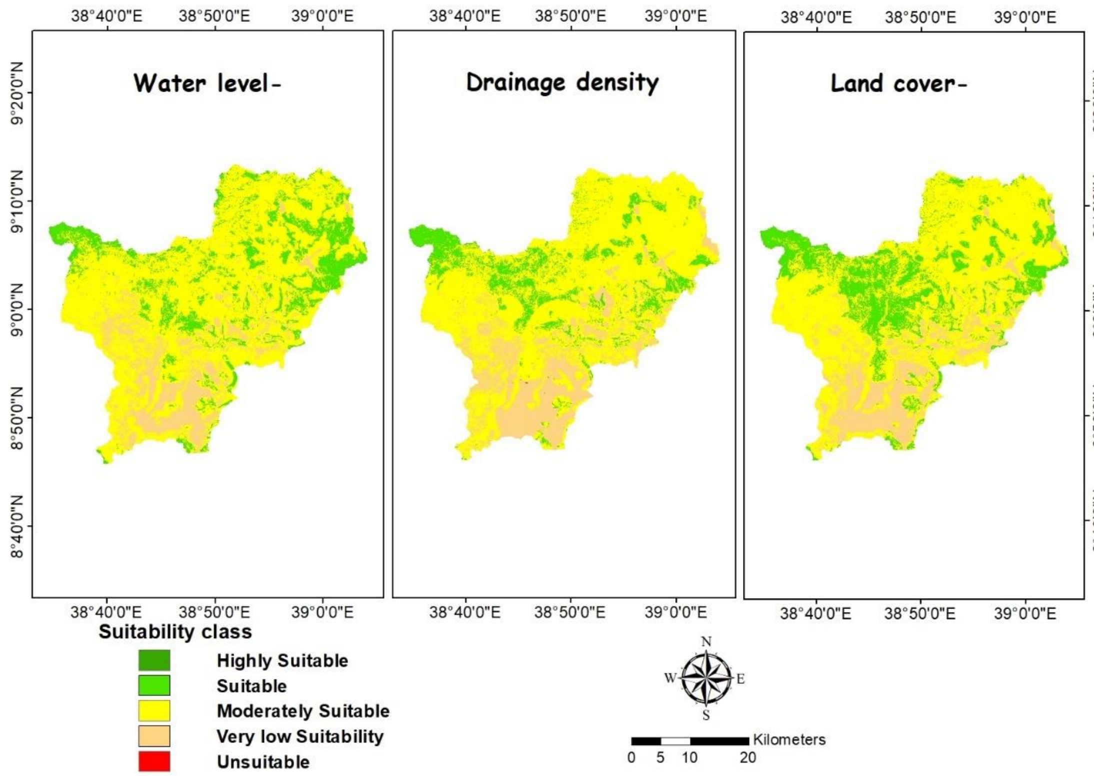
Criteria	Slope-	Land cover-	Geology-	Drainage density-	Rain fall-	Soil-	Water level-
Geology	30	27	0	26	27	27	26
Slope	0	24	27	23	24	27	23
Soil	22	22	25	19	20	0	19
Lulc	19	0	19	12	12	14	13
Drainage density	11	10	11	0	12	11	11
Rainfall	13	13	13	16	0	17	10
Water level	5	4	5	4	5	5	0

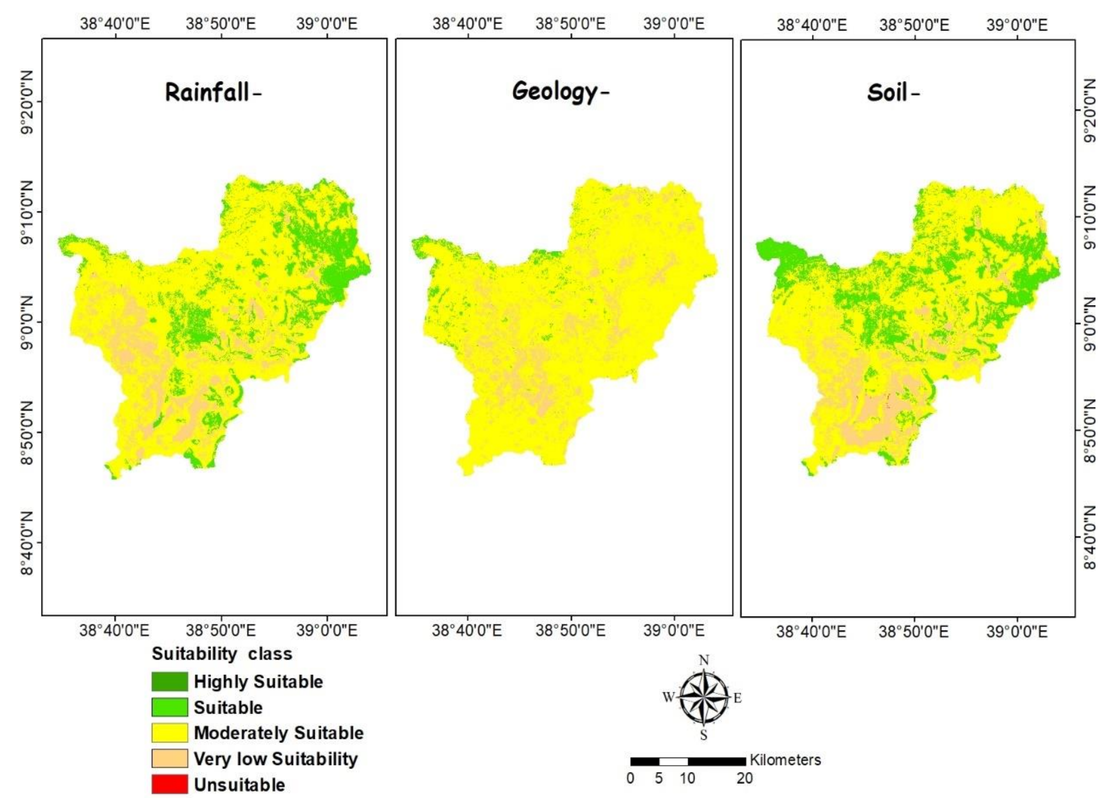
Table 5.14 Weights assigned for sensitivity analysis by removing one criterion at a time

	Unsuitable	Low suitability	Moderate suitability	Suitable	High suitability
Water level-	0.0006	14.79	68.68	16.53	0
Drainage density-	0.007	20.36	67.01	12.63	0
Slope-	2.16	35.12	58.07	4.65	0
Land cover-	0.004	17.24	63.03	19.73	0
Geology-	0.0003	14.15	83.04	2.81	0
Soil-	0.019	15.35	62.75	21.87	0.0059
Rainfall-	0.0009	14.7	67.38	17.92	0.00006

Table 5.15 Suitability areas in % for maps produced by the different weighting schemas used for sensitivity analysis

In the tables, Slope- means removing the criterion ofslope, Landcover- means removing the criterion of landcover, Drainage density- means removing the criterion of drainage density, Soil- means removing soil, Geology- means removing the criterion of geology, Rain fall- means removing rainfall and water level- means removingwater level criterion.


Water level-
Drainage density
Land cover-
38°40'0"E
38°50'0"E
39°0'0"E
9°20'0"N
9°10'0"N
9°0'0"N
8°50'0"N
8°40'0"N
Suitability class
Highly Suitable
Suitable
Moderately Suitable
Very low Suitability
Unsuitable
N
W
E
S
Kilometers
0 5 10 20


Rainfall-
Geology-
Soil-
38°40'0"E
38°50'0"E
39°0'0"E
9°20'0"N
9°10'0"N
9°0'0"N
8°50'0"N
8°40'0"N
Suitability class
Highly Suitable
Suitable
Moderately Suitable
Very low Suitability
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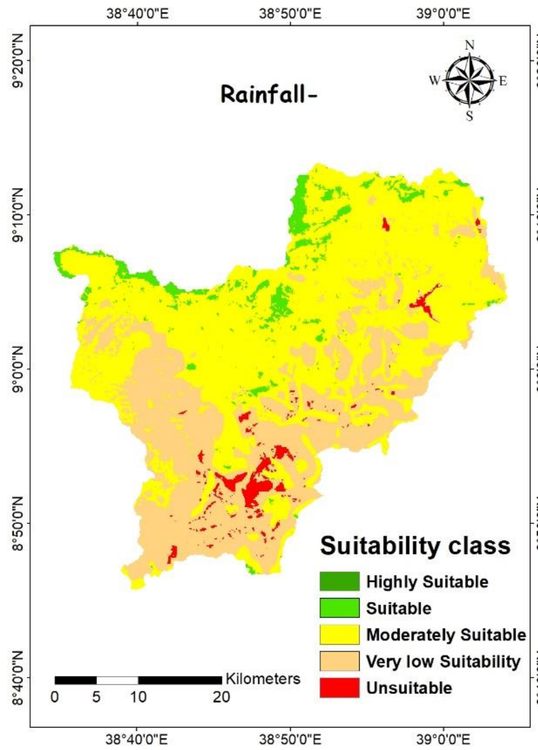

Figure 5.11 Spatial distribution of sensitivity analysis scenario without criterion of water level, drainage density, land cover, rainfall, geology, soil texture, and slope, respectively

Except for the geology- and slope -, the sensitivity analysis produced consistent result for the site suitability maps by applying the various weighting from Table 5.14. Figure 5.11 illustrates the spatial distribution maps of seven sensitivity analysis scenarios. The two scenarios where the switch between classes is higher are when a minor slope and geology criterion is removed one at a time. In the geology- scenario, erasing the geology criterion almost half of the switch is from suitable to moderate suitability. The second highest switch is achieved when removing terrain slope criterion with the area changing from moderate suitability to low suitability.

CHAPTER SIX

CONCLUSION AND RECOMMENDATION

6.1 Conclusion

Groundwater resources are under increasing strain due to population growth and the expansion of agriculture, which has led to overuse of groundwater. Akaki catchments water table is rapidly dropping as a result of heavy pumping. It is urgent to deal with this issue using MAR techniques. Identification of suitable MAR methods and delineation of suitable MAR sites were done in this study. Twelve different MAR methods were suggested by INOWAS for the study area. The suitable ones included recharge trenches, ditches and furrows, excess irrigation, rooftop harvesting, shallow wells, shafts and pits infiltration, barrier and bunds and flooding. MAR suitability mapping by integrating various influencing factors provides a comprehensive view of a study area and divides it into zones of different ranking.

These MAR suitability maps, which are the first ones made for Akaki catchment, hold the potential to be integrated into sustainable groundwater management plans for Addis Ababa and around areas and are intended to be used as a basis for further studies and field investigation for MAR site selection. The combined approach, methodology and results gained from this study can be used as auxiliary for MAR suitability mapping for any groundwater depleted areas in Ethiopia.

This study was carried out to identify the most suitable areas for managed aquifer recharge (MAR) application based on multi-criteria decision analysis (MCDA) techniques. The overall study concept involved the integration of seven thematic layers of hydrologic soil type, drainage density, slope, rain fall, geology, water level and land use. The multi-criteria decision analysis methods used were weighted overlay analysis method.

The usage of a GIS framework simplifies the challenging decision-making effort over a greater spatial extent where many factors must be examined with varied relevance. It offers a simple and rapid method for lowering sample size for further ground validation, as well as a solid support system for ultimate site selection.

The consistency brought about by an analytic hierarchy approach decreases the possibility of any erroneous outcomes emerging from inaccurate weightage assignment to specific criteria by considering a larger number of regulating parameters and employing them as theme layers in multi-criteria analysis.

Because weight assignment is the most crucial phase in obtaining an accurate result, the suitable weight assignment strategies must be carefully selected. Pair-wise comparisons are used. The use of pair-wise comparison matrix helps to compare the suitability of each criterion with others sequentially and provides a strong statistical support for decision-making ahead. If advanced research in the field of hydrologic modelling, simulation and validation is aspired in the future and more emphasis placed further on spatial science technology, this multi-criteria evaluation-based study shall always form an existing platform for preliminary investigations and enquiry in policy making exercises.

The final MAR suitability map was developed by overlaying all criterion maps based on the ranking and weighted values. The study area is divided into five categories based on MAR suitability, i.e., high suitability, suitable, moderate suitability, low suitability, and unsuitable. The final MAR suitability maps show that the catchment lies in moderately suitable zone (71.54%). Suitable and low suitability zones cover an area of 9.8% and 18.66% respectively. Therefore, if correctly designed and managed, MAR has the potential to alleviate the water scarcity and increase the underground water storage in the catchment. It is important to note that regions with low suitability scores should not be ruled out for MAR implementation, as MAR suitability mapping reveals the relative suitability of various components of an area. The MAR suitability map generated in this study can be used as a starting point for conducting focused studies on MAR implementation. This study demonstrates that, despite its inherent shortcomings, GIS-MCDA is a helpful tool for resolving real-world groundwater problems.

The results of the present study can serve as guidelines for planners, decision makers and hydrogeologists for planning future artificial recharge projects in the study area in order to ensure dependable water supply and sustainable groundwater utilization on a long-term basis.

The databases and the results obtained can also be useful in developing a conceptual model of the study area for future modeling studies. In conclusion, the integration of MCDA and GIS is recognized as an effective method. Future work can concentrate more on the suitable sites proposed in this study, as well as include and evaluate more effective criteria for the environment, economic and social factors, and water-source availability and accessibility, which have not been covered in this study.

As the map only has intrinsic criteria, it is an open tool for any potential water user, such as drinking water suppliers, agriculture sector and others. As the original aim of the map was to prioritized areas for further research, it is important to recall that the map is not intended for the actual selection of sites for the implementation of a full-scale MAR project.

For the last (actual site selection), more information at a better scale is needed as well as a feasibility study of the proposed MAR project. The low suitable zone accounts for only 18.66% of the total area. Therefore, if correctly designed and managed, MAR has the potential to alleviate the water scarcity and increase the underground water storage in the catchment.

6.2 Recommendation

It is expected that the study's findings can be used to create an environmentally friendly water management strategy for the province that lacks access to water. Based on these preliminary findings, future research can concentrate on local-scale high-resolution MAR suitability evaluations. Because the needed quality of water for drinking, agricultural, and industrial usage differs, data on water use can help improve the analysis. The suitability map can also be considered as one aspect, combining with other aspects, such as population, water demand, and access to water resources, to choose priority for implement MAR sites. Therefore, current study can be used as a general guidance of choosing suitable spreading MAR sites.

The procedures used in this work can be used to map MAR suitability in any water-scarce environment using remote sensing data. Cost, land requirement, knowledge, and public acceptability of MAR, among other socioeconomic factors, all play a part in MAR's effectiveness. When preparing a focused and rigorous MAR appropriateness investigation, these variables should be taken into account.

Ethiopia only has a small percentage of MAR projects at the moment, despite the urgent need for MAR implementation in places with limited water supplies. Lack of financing for applying and monitoring is a contributing factor for institutional and socioeconomic limitations. Additionally, there is a lack of institutional capability to develop MAR initiatives at the ministerial level as well as a lack of knowledge and comprehension of MAR procedures. Currently, the proportion of MAR projects in regions like Akaki catchment is quite low despite the urgent need for MAR implementation is in such areas. It shows us the opportunities of MAR in these areas, which can mitigate the water crisis and help expedite sustainable development

For new MAR projects it is recommended to increase the involvement of the local community in MAR activities and to give awareness to evaluate the effectiveness of MAR schemes. In addition, a national MAR strategy and regulations should be developed. The approach could be applied for similar assessments of basins in other countries. Criteria selection, classification and weighting are adjustable to suit the local conditions and availability of data.

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