EVALUATING THE IMPACTS OF LAND USE AND CLIMATE VARIABILITY ON WATER AVAILABILITY IN HARGEISA WATERSHED, SOMALILAND

ABDIRAHMAN IBRAHIM HASHI

A THESIS SUBMITTED TO THE DEPARTMENT OF WATER RESOURCE ENGINEERING
PRESENTED IN PARTIAL FULFILLMENT OF THE REQUIREMENT FOR THE DEGREE OF MASTER'S IN HYDROLOGY AND WATER RESOURCES MANAGEMENT

COLLEGE OF CIVIL ENGINEERING AND ARCHITECTURE

SCHOOL OF POSTGRADUATE STUDIES
ADAMA SCIENCE AND TECHNOLOGY UNIVERSITY

OCT, 2025
ADAMA, ETHIOPIA

EVALUATING THE IMPACTS OF LAND USE AND CLIMATE VARIABILITY ON WATER AVAILABILITY HARGEISA WATERSHED, SOMALILAND

ABDIRAHMAN IBRAHIM HASHI

ADVISOR: DR. BOJA MEKONNEN (Ph.D.)

A THESIS SUBMITTED TO THE DEPARTMENT OF WATER RESOURCE ENGINEERING
PRESENTED IN PARTIAL FULFILLMENT OF THE REQUIREMENT FOR THE DEGREE OF MASTER'S IN HYDROLOGY AND WATER RESOURCES MANAGEMENT

COLLEGE OF CIVIL ENGINEERING AND ARCHITECTURE

SCHOOL OF POSTGRADUATE STUDIES
ADAMA SCIENCE AND TECHNOLOGY UNIVERSITY

OCT, 2025
ADAMA, ETHIOPIA

DECLARATION

I hereby declare that this Master's Thesis, entitled "**Evaluating the Impacts of Land Use and Climate Variability on Water Availability in Hargeisa, Somaliland,"** is my original work. That is, it has not been submitted for the award of any academic degree, diploma, or certificate in any other university. All sources of materials that are used for this thesis have been duly acknowledged through citation

Abdirahman Ibrahim Hashi	___________	_______________
Name of student	Signature	Date

RECOMMENDATION OF ADVISOR

I, the major advisor of this research thesis, hereby certify that I have closely advised the student while developing this thesis and reading the draft thesis entitled "**Evaluating the Impacts of Land Use and Climate Variability on Water Availability in Hargeisa, Somaliland,"** prepared under my guidance by Abdirahman Ibrahim. Therefore, I recommend the submission of the proposal to the department for further review and evaluation.

Major Advisor	Signature	Date

APPROVAL SHEET

I hereby certify that the recommendations and suggestion given by the thesis review committee are appropriately incorporated into the final thesis entitled "**Evaluating the Impacts of Land Use and Climate Variability on Water Availability in Hargeisa, Somaliland"** by Abdirahman Ibrahim.

Major Advisor	Signature	Date

We, the undersigned, members of the Board of Examiners of the thesis by Abdirahman Ibrahim have read and evaluated the thesis entitled "**Evaluating the Impacts of Land Use and Climate Variability on Water Availability in Hargeisa, Somaliland**" and examined the candidate during open defense. This is, therefore, to certify that the thesis is accepted for partial Fulfillment of the requirement of the degree of Master of Science in water resources engineering

Chairperson	Signature	Date
Reviewer 1	Signature	Date
Reviewer 2	Signature	Date

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

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

ACKNOWLEDGMENT

First and foremost, all praise and thanks are due to Allah, the Almighty, for granting me the strength, knowledge, and perseverance to complete this journey.

I would like to express my deepest and most sincere gratitude to my advisor, **Dr. Boja Mekonnen**. His invaluable guidance, unwavering support, and insightful feedback have been the cornerstone of this research. His mentorship has not only shaped this thesis but has also profoundly influenced my academic and professional growth.

I extend my heartfelt thanks to the **Adama Science and Technology University**, particularly the Department of Water Resource Engineering, for providing me with the opportunity and the resources to pursue this master's degree. I am also grateful for the financial support provided by the University for this Research.

My appreciation also goes to the staff at the **Ministry of Agriculture of Somaliland and the Ethiopian Meteorological Agency** for their assistance in providing the crucial data that made this study possible. I am also grateful to the **134** residents of Hargeisa who generously gave their time to participate in the surveys; your voices are the heart of this research.

Finally, I repay a special debt of gratitude to my family. Their constant encouragement, patience, and belief in me have been my greatest source of strength throughout this journey. This accomplishment would not have been possible without them.

TABLE OF CONTENTS

LIST OF TABLES

LIST OF FIGURES

ABBREVIATIONS

LUCC	Land Use and Climate Change
SWAT	Soil and Water Assessment Tool
HWA	Hargeisa Water Agency
USGS	United States Geological Survey
FAO	Food and Agriculture Organization
SWALIM	Somali Water and Land Information Management
IDMC	Internal Displacement Monitoring Center
LULC	Land Use and Land Cover
GIS	Geographic Information Systems
NCA	National Climate Assessment
HRC	Hargeisa Region Committee
EHT	Environmental Health Team
M&E	Monitoring and Evaluation
NBSAP	National Biodiversity Strategy and Action Plan
NGO	Non-Governmental Organization
WRC	Water Resources Committee
IPCC	Intergovernmental Panel on Climate Change
CBO	Community-Based Organization
UN	United Nations

ABSTRACT

Hargeisa, Somaliland, faces a critical water crisis driven by rapid urbanization and a volatile climate. This study provides the first comprehensive hydrological assessment for the region, aiming to quantify the impacts of historical land use change (2000–2024) and past climate patterns (1995–2024) on water availability, and to identify the resulting socio-economic impacts on the community. To overcome the challenge of an ungauged watershed, a regionalization approach was employed using the Soil and Water Assessment Tool (SWAT+). The model was successfully calibrated and validated against a physically similar gauged watershed, achieving satisfactory performance (Calibration: $R^2=0.55$, $NSE=0.52$; Validation: $R^2=0.53$, $NSE=0.50$). This successful validation provided a scientifically sound foundation for quantifying the drivers of water scarcity. The climate analysis revealed a statistically significant warming trend (Tmax increased by 0.037°C/year and Tmin by 0.025°C/year), while precipitation showed high inter-annual variability but no significant long-term trend. The study integrated these hydrological simulations with an analysis of satellite-derived land use maps and socio-economic data from a survey of 134 residents. The findings reveal a profound landscape transformation: fueled by population growth, urban areas expanded by 377%, primarily converting natural grasslands. Hydrological simulations show this has critically impaired the watershed's ability to store water, increasing surface runoff by 24.1% while reducing groundwater percolation by 25%. This provides a direct scientific explanation for the hardship reported by 75% of residents, who find their water supply insufficient. The study concludes that Hargeisa's water crisis is a direct consequence of uncontrolled urban expansion, a condition significantly worsened by the region's inherent climate variability. This research provides a crucial, data-driven foundation for policy, highlighting the urgent need for integrated water management strategies, such as protecting groundwater recharge zones and implementing urban rainwater harvesting, to ensure Hargeisa's future water security.

Keywords: Land use change, urbanization, water availability, SWAT+ modeling, QGIS, SWAT modeling, ArcGIS, Hargeisa watershed, regionalization**.**

CHAPTER ONE

INTRODUCTION

1.1. Background

Water is valued resource to be beneficially managed. Management of water resources most often deals with complex systems composed of many interconnected parts. One of the challenges faced in contemporary water resources management is how to use water sustainably to respond to the increasing demand of society and how to mitigate the environmental consequences related to human questions for survival that affects the quality and quantity of water for the desired use. The contemporary approach to water resources management requires a clear quantitative understanding of the water balance in order to provide secure and sustainable allocations. Catchment characteristics and climate control water balance. Climate factors are natural and cannot be directly influenced, but catchment modification is mainly human activity for survival. Understanding the catchment processes and how modifications affect hydrologic systems is very important in the management of water resources; however, this is always limited due to inherent uncertainties in the processes and complexities of the systems, which themselves are dynamics (Pagan and Crase, 2004).

Water resource managers need to develop effective and adaptive polices on how to manage water resources for sustainability and also improve their management through understanding the past, predicting the futures and appreciating factors that drive hydrologic systems at a given management unit. Terrestrial vegetation has been acknowledged as the key player in the water balance (Gerten et al., 2004)

Since the 1970s, there has been rapid progress in developing remote sensing technology and hydrological models (Dong, 2018). To achieve a more rational distribution of water resources, an increasing number of scholars are making efforts to quantify, visualize, and improve the assessment and analysis of regional water supply through model-based simulations (Li et al., 2022). Climate and land cover changes have altered West African countries' hydrological cycles (Flörke et al., 2018). Land use and climate are two significant elements that directly impact irrigation water supply, and understanding their implications is critical for land use planning and management (Neupane & Kumar, 2015). It has been shown that climate variability and land use planning have a greater impact on regulating seasonal streamflow distribution than the regulation of mean annual streamflow (Liu et al., 2020). Climate variability is expected to produce highly variable rainfall and increased temperatures, making water availability uncertain (Kotlarski et al., 2023).

Since the 20th century, climate variability is believed to have caused changes in global precipitation patterns, and the effects of climate and LULC changes on hydrological processes and water resources will probably continue to increase, particularly in arid and semi-arid regions characterized as vulnerable (Yin et al. 2017). According to YIN et al (217), the effects of climate and LULC changes on runoff can generally be recognized by using hydrological models, these models provide precious frameworks for investigating the modifications among numerous hydrological pathways that are due to climate and human activities, distributed hydrological models, which use input parameters that immediately represent land surface characteristics, were applied to evaluate the effects of climate changes in runoff in water resource management Ares. During the next few decades, climate and land use change are major global issues, and proper studies highly demand finding their relationships and their impacts on the future (Isabirye et al., 2012).

In 2014, the National Climate Assessment recognized water availability as one of the key impacts of climate change in the southeast US, and forecasts indicate that much of the region will experience an increasing deficit in human demand and supply. Consistently with global trends, the US Southeast is expected to experience a doubling in urban areas in 2060, leading to an increase in the average annual temperature and expected greater frequency and severity of droughts and floods (Martin et al. 2017).

Water availability in Somaliland relies heavily on underground reservoirs, as the country lacks major rivers or permanent surface water bodies. Historically, rural Somaliland depended on berkads (traditional water cisterns) and earth dams to supplement water availability. In the 1980s, the Somali government, supported by the World Bank through the Rural Water Development Project, developed six earth dams lined with plastic pavement to retain water for 3–4 months after the rainy season. However, due to poor maintenance and the loss of skilled personnel, three of these dams collapsed. Similarly, many berkads fell into disrepair due to prolonged droughts and the economic impacts of the civil war after 1991 (Muthusi et al., 2007).

Somaliland's current water resources include small surface structures, such as berkads and earth dams, and groundwater sources, including shallow wells, boreholes, and springs. The availability and yield of groundwater vary significantly depending on local geology and hydrology. While seasonal aquifer recharge is reported, decentralized water resources tapping into upper aquifers are seen as more sustainable compared to the over-extraction of deeper aquifers used for bulk water supply in Hargeisa (Petersen & Gadain, 2012).

Hargeisa, the capital and largest city of Somaliland faces severe water supply challenges driven by rapid population growth, institutional inefficiencies, and the impacts of climate change. The city's water supply primarily depends on seasonal rainfall during the spring (April–June) and autumn (September–November). However, prolonged dry periods and changes in rainfall patterns caused by climate change have exacerbated water scarcity. The Hargeisa Water Agency (HWA), the main utility managing the water grid, is hindered by limited technical capacity, poor infrastructure, and financial constraints. Consequently, large parts of the population rely on private water trucking businesses that source water from boreholes and shallow wells around the city (Yonis, 2015).

Urbanization and land use changes in Hargeisa have further strained water resources. Deforestation and urban expansion disrupt natural recharge processes, increasing runoff and reducing infiltration. While Hargeisa’s stream network contains sand deposits that could theoretically enhance water retention, these streams do not carry significant runoff, limiting their utility. Efforts to address these challenges include a master plan to supplement Hargeisa's water supply, notably through additional extraction from the Geed Deeble water fields and improved infrastructure. However, significant water deficits persist, highlighting the urgent need for integrated land use planning and climate adaptation strategies to ensure sustainable water availability (Abdishakur et al., 2022)

1.2. The statement of the problem

Hargeisa, the capital of Somaliland, faces significant challenges regarding water availability due to the combined effects of land use and climate change. Rapid urbanization, agricultural expansion, and deforestation have transformed the natural landscape, disrupting the hydrological cycle and diminishing water resources. Additionally, climate change has resulted in increased variability in rainfall patterns, exacerbating water scarcity and impacting both urban and rural communities. This study aims to evaluate how these factors interact to influence water availability in Hargeisa, underscoring the urgent need for sustainable water management strategies. In many parts of the country, reliance on groundwater as the primary water source has led to severe shortages due to the absence of alternative water supplies. Consequently, excessive groundwater consumption has resulted in declining water levels and increased scarcity (Jama & Mourad, 2019).

Despite the clear challenges, there have been no studies exploring the effects of land use, land cover changes, and climate change on water resources using hydrological models in the Hargeisa watershed. This represents a critical knowledge gap. Groundwater extraction and consumption are not based on a comprehensive understanding of water availability, and the potential impacts of anthropogenic and climatic pressures remain unquantified. This lack of data-driven insight directly hinders the ability of local and national bodies to formulate effective water management policy. Addressing this gap is not only a scientific necessity but also a strategic priority, as the challenges of water scarcity directly threaten the goals outlined in Somaliland's National Development Plan II (NDP-II), which explicitly prioritizes sustainable water resource management. Therefore, by estimating water availability using the SWAT model, this research aims to provide the foundational evidence needed to facilitate proper future utilization of water resources in the Hargeisa watershed.

1.3. Research Objectives

1.3.1. General Objective

To evaluate the effects of land use changes and climate variability on water availability in Hargeisa, Somaliland, in order to inform sustainable water resource management and climate adaptation strategies.

1.3.2. Specific Objectives

1. To analyze historical land use and land cover changes in Hargeisa and their impact on local hydrology and water availability.
2. To assess historical trends and variability in climate parameters over recent decades in the study area.
3. To evaluate the combined effects of land use changes and climate variability on water resources.
4. To identify the socio-economic impacts of water scarcity on communities in Hargeisa, focusing on access to water and its effects on livelihoods.

1.4. Research Questions

1. How have historical land use and land cover changes in Hargeisa affected local hydrology and water availability over time?
2. What are the trends and variability in climate parameters in Hargeisa during recent decades?

3. How do land use changes and climate variability interact to influence surface and groundwater resources in Hargeisa?
4. What are the socio-economic impacts of water scarcity on communities in Hargeisa, particularly regarding water access and its effects on livelihoods and well-being?

1.4.1. Hypothesis

Based on the preceding research questions and the identified knowledge gaps, this study will test the following central hypothesis:

The rapid conversion of natural grassland to urban impervious surfaces is the primary driver of reduced water availability in the Hargeisa watershed. It is hypothesized that this land use change, significantly exacerbated by regional climate variability, leads to measurable declines in groundwater recharge and a quantifiable increase in water insecurity for the local population.

1.5. Significance of the study

Land use and climate change have a significant influence on hydrological processes within watersheds, altering surface hydrology and water availability. These changes ultimately impact the availability and security of water resources worldwide, as highlighted by (Warku et al., 2022) In the context of Somaliland, and particularly Hargeisa, the region's vulnerability to climate change is heightened by frequent droughts and extreme weather events.

This study evaluates the impacts of land use and climate change on water availability in Hargeisa, Somaliland. By examining the biophysical and meteorological factors that influence water resources in the region, the research aims to provide critical insights for the sustainable development, management, and efficient utilization of water resources. Furthermore, the findings of this study will serve as a baseline for future research on water availability and resource management in Hargeisa and its surrounding areas.

As the central hub for governance and commerce, Hargeisa's growing population and urban expansion further intensify the need to evaluate water availability under the combined pressures of land use and climate change.

Furthermore, this research directly supports the strategic goals outlined in Somaliland's National Development Plan II (NDP-II), which explicitly prioritizes sustainable water resource management as a cornerstone for national development and climate resilience. By providing robust, data-driven insights into the key drivers of water scarcity, this study will equip local and national stakeholders, including the Hargeisa Water Agency (HWA) and municipal planners, with the scientific evidence needed to formulate effective land use policies and climate adaptation strategies.

1.6. Scope of the Study

This study aims to analyze the sources, processes, and factors influencing water availability in the Hargeisa watershed. Key components assessed include recharge, runoff, interception, and actual evapotranspiration losses within the watershed. The research focuses on the Hargeisa watershed, situated in the Ogo Mountains at an elevation of 1,334 meters above sea level.

1.7. Limitation

The study may face significant challenges in obtaining reliable observed climate data due to the absence of national meteorological services in Somaliland. To address this, open-source datasets will be utilized, including those from USGS, World Climate Data, FAO, and SWALIM. These datasets incorporated blended satellite data to provide critical climate insights.

A further limitation, related to the regionalization approach, is the source of the observed streamflow data for the donor watershed. This data was provided by the Ethiopian Meteorological Agency. This is acknowledged as a potential source of uncertainty, as hydrological data such as streamflow is more commonly curated and provided by a national Ministry of Water and Energy (MoWE). This reliance on a meteorological agency for streamflow data is noted as a limitation of the study's inputs.

To overcome this fundamental limitation, this research employed a strong and scientifically accepted regionalization approach. This methodology involved the careful selection of a gauged watershed (the Jarar Valley) that shares key physio-climatic and geological characteristics with the Hargeisa watershed. By first developing, calibrating, and validating the SWAT model on this gauged donor watershed, a reliable set of hydrological parameters for the region was established. These parameters were then transferred to the Hargeisa model, providing a strong scientific basis for the simulations.

CHAPTER TWO

LITERATURE REVIEW

2.1. Theoretical framework

Impacts and enhance water resilience in vulnerable regions. The impacts of land use and climate change on water availability in arid and semi-arid regions are profound and multifaceted. Research indicates that both anthropogenic activities and climatic shifts significantly influence hydrological systems, leading to reduced water availability Can climate Change effect? Studies predict a continuous rise in temperatures and a decline in precipitation in arid regions, exacerbating water scarcity(Abdullaeva, 2024). For instance, the Middle Tapi Basin is expected to experience a decrease in monsoonal rainfall contribution, leading to reduced streamflow (Sharma et al., 2023)

Increased temperatures result in higher evapotranspiration rates, further diminishing surface runoff and groundwater flow (Sharma et al., 2023). Land use changes, such as urbanization and agricultural expansion, significantly impact streamflow. In the Talar River basin, human activities accounted for a 60% influence on monthly average streamflow (Ruigar et al., 2023) Ecosystem services are benefits humans derive from ecosystems, including provisioning, regulatory, supporting, and cultural offerings (Geng et al., 2015). Environmental services are the basis of human survival and are closely related to human well-being (Deng et al., 2013). According to Geng et al. (2015), the environment is one of the important needs to manage, which might be vital for maintaining the provision of natural services. It is necessary to consider climate change as well as land use/land cover change (LUCC) in the relevant ecosystem carrier assessments, particularly when analyzing water-related environmental services. More-over, water supply is one of the most essential environments since adequate freshwater sup-ply is fundamental for ensuring the sustainability of agriculture, industry, and the natural environment (Belete et al., 2020).

The water resource and its driving mechanism have received more and more attention, and analysis of the impact of LUCC and climate change on the water resources are essential for formulating adaptive management strategies (Boithias et al., 2014). Drinking water and demand can vary from place to place with availability and accessibility sources of water supply, including groundwater, rivers, lakes, springs, and small streams. At present, the world’s people are withdrawing 30% of the runoff that is accessible; however, about 20% of the total runoff is remote and not readily available to meet water consumption. Water demand is the outcome of unplanned urbanization, industrialization, and rapid population growth.

Water demand also can exist if groundwater is tapped out without replenishment when a rate of exploitation exceeds its restoring capacity (Ali, Mushir, Terfa, 2012).

The changes in land use and climate affect the groundwater supply and significantly distress water demand in crop production because of a loss of freshwater availability (Kirby et al., 2016). This requires hydrological modeling to understand climate changes and LUCC's influences on water availability. Therefore, the effect of climate and LULC changes on water resources has become a topical hydrological issue that requires investigation. Again, future climate variability is essential information in impact assessment to useful resource decision-making (Nyatuame et al., 2020). Land use/cover change is motivated by several reasons from environmental and social dimensions in a land system (Gong et al., 2015). Thus, the land cover dynamic becomes an issue of the 21st century with dramatic implications for human life (Elias et al., 2019).

Different land-use types represent diverse risks to water resources, with urban and agricultural areas being the land-use types most liable for water quality degradation globally. Thus, managing the instant human necessities whilst retaining a long-time period of water supply capacity is an urgent need and a great challenge to the country. LULC change is related to increased water demand; population growth and climate change are probably going to greatly affect water resources (Mello et al., 2020).

To visually synthesize the theoretical connections between the core components of this study, a conceptual framework has been developed (Figure 2.1). This framework identifies the key variables and illustrates their hypothesized relationships, following a classic research model. It establishes a clear causal pathway from the independent variables (Drivers of Change) through the mediating variable (Hydrological Processes) and moderating variable (Watershed Characteristics) to the final dependent variables (Observed Impacts).

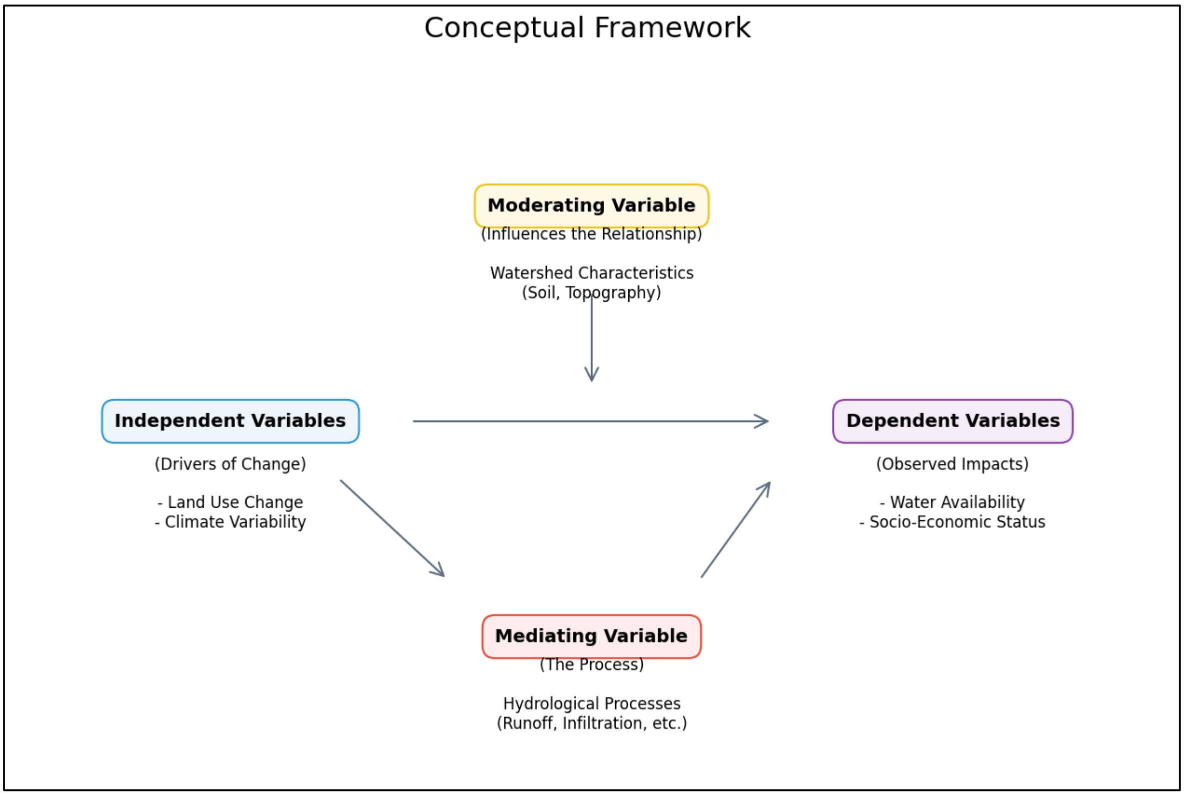


Figure 2.1: Conceptual Framework of Research Variables.

2.2. Water Scarcity and Urbanization

Water scarcity in Hargeisa is meaningfully influenced by rapid urbanization, which exacerbates existing challenges in water management. As urban areas expand, the demand for water increases, leading to unsustainable practices and resource depletion. This situation necessitates a comprehensive understanding of the interplay between urban growth and water availability, which can be explored through several key aspects.

Hargeisa, like many cities in developing regions, is experiencing rapid urbanization, driven by population growth and migration due to factors such as drought and conflict (Internal Displacement Monitoring Center (IDMC), 2020). The urban population is projected to rise, increasing pressure on already limited water resources (Abderrahman, 2000)

Water supply in Hargeisa is primarily reliant on groundwater, which is being depleted due to over-extraction and insufficient recharge from urban development (Mishra et al., 2020) Sustainable urban water management strategies are essential, including the integration of geographic information systems and scenario modeling to optimize resource use (Hanoon et al., 2022).

Climate change exacerbates water scarcity through altered rainfall patterns, leading to more extreme weather events and prolonged dry periods (Mishra et al., 2020) Urbanization contributes to increased impervious surfaces, which heighten storm water runoff and reduce groundwater recharge, further straining water supplies (Mishra et al., 2020).

Urbanization in Hargeisa has profound implications for social dynamics, governance, and environmental sustainability. The rapid growth of the urban population has led to increased segregation, socio-economic disparities, and environmental challenges. Understanding these impacts requires a multifaceted approach that considers historical, spatial, and economic dimensions.

Urban settlement in Hargeisa is characterized by clan-based segregation, a phenomenon rooted in historical governance practices and contemporary dynamics (Tahir, 2017). The hybrid governance structure complicates interactions between state institutions and local communities, often exacerbating land conflicts and social divisions (Tahir, 2017).

Urbanization has resulted in significant rural out-migration, driven by income disparities between urban and rural areas (Hs et al., 1983). This migration contributes to changes in investment patterns and settlement hierarchies, impacting local economies and social structures (Hs et al., 1983).

Increased urbanization correlates with heightened environmental degradation, primarily due to rising energy consumption and carbon emissions (Hassan et al., 2024) Policymakers are urged to implement sustainable urban planning to mitigate these environmental impacts while promoting economic growth (Hassan et al., 2024).

2.3. Land use impacts on water availability

The impact of land use on water availability is multifaceted, influenced by changes in vegetation, soil properties, and hydrological processes. Various studies highlight how different land use strategies can significantly alter water balance, affecting surface and groundwater resources. The following sections outline key findings regarding these impacts.

Replacing conifer forests with mixed forests can reduce total evapotranspiration by up to 11%, enhancing groundwater recharge (Luo et al., 2024)(Smith, 2023). In the Rupit watershed, land use changes led to significant variations in soil water content, with a surplus from November to April and deficits from May to October (Nurhikmawaty et al., 2024). In the Zuli River Basin, urbanization increased surface runoff by 14.26% to 36.15%, while forest expansion primarily drove changes in evapotranspiration (Liu et al., 2023)

Models like SWAT and EcH2O-iso help quantify the effects of land use on water availability, revealing complex interactions between land cover and hydrological dynamics

(Devkota et al., 2024, Luo et al., 2023). Variability in water yield due to land use changes is significant, with projections indicating a 167% increase in uncertainty under certain climate scenarios (Devkota et al., 2024).

While land use changes can enhance water availability through improved management practices, they can also lead to increased variability and uncertainty in water resources, necessitating careful planning and adaptive strategies.

In current years, substantial changes in land use/land cover (LU/LC) have taken place due to human activities. LU/LC change is linked to human factors, such as agricultural loss, overexploitation of forests, and urbanization has caused natural resource shortages, consisting of widespread and permanent losses of biodiversity across the sphere, and the population growth continues to adjust the landscape and natural lands through socio-ecological and socio-economic phenomena at extremely high rates, causing effects of LU/LC on the environment (Twisa et al., 2020). This change could motivate several variations in services and roles, consequently causing degradation in the provisioning of environmental services from the natural resources on the earth (Nobert & Jeremiah, 2012). As the population increases and consumption styles vary, additional land will be needed for agricultural production and residing space. The challenge facing society as an entire is figuring out how to meet individuals' growing demands for food, living space, fuel, and other supplies while sustaining environment services in LU/LC variations (Birkhofer et al., 2015).

Since the mid-20th century, human activities have substantially altered ecosystems, and water stress has increased because of water pollution, withdrawal, and contamination (Haddeland et al., 2014). LU/LC changes are regarded as the dominant form of anthropogenic stress on the environment, causing changes in environment carrier styles and affecting groundwater re-charge (Ouchi et al., 1982). Sustainable land management plans could ensure the constant provision of the environmental system. Studies have shown that the outcomes of LU/LC on environment services differ temporally and spatially (Egarter Vigl et al., 2017). According to Egatrer et al. (2017), water supply systems are susceptible because they may be exposed to severe natural stresses related to interactions among biophysical factors, which considerably increase their heterogeneity from a temporal and spatial perspective. Several relatively static influences (soil, topography, and geology) and dynamic influences (land use, land management, and climate) interact to control water access and how it will be distributed to competing users.

Water ecosystem services for drinking are intensely affected by the quantity and quality of water supplies to the basin and how divided between the processes of surface water runoff, evaporation, groundwater recharge, and transpiration. Therefore, understanding the effects of LU/LC on the water resources services for drinking is important for understanding the significance of decisions and policies and might support the development of appropriate plans (He & Hogue, 2012). After that, land use management and plan assessment require in-depth knowledge of the different effects on water resources (Arunyawat & Shrestha, 2016). In addition, the nature of interactions between ecological, physical, and hydrological traits that determine the effects of land cover change on surface and sub-surface hydrology is not properly understood in natural and human-dominated environments. Changes in agricultural land uses are central to environmental change studies because situated at the interface between water ecosystems and society (Chemura et al., 2020).

The changes in land use and land cover (LULC) cause a big impact on water resources and significant pressure on biodiversity and environmental services. The LULC changes can also result in water yield variations, such as an increase in discharge, a decrease in infiltration rate, and an increase in rainfall intensity or variability. Moreover, it may increase water resource shortage and food lack of confidence in Africa. (Measho et al., 2020). According to Maitima, Mulligan (2009, 2015). The impacts can be more critical in the Horn of Africa, which has been exposed to recurrent drought and has high climate variability. In many parts of the Horn of Africa, LULC changes had been occurring quickly, and the change was an increase in cropland compromised with a decrease in forest, bushlands, and grasslands.
In a recent review for Eastern Africa, LULC change due to deforestation, for example, turned into evident with high effects on hydrological fluxes, mainly in discharge and surface runoff. However, different research has stated contradicting results (Guzha et al., 2018). In addition, groundwater, the primary drinking water supply, is deteriorating due to the increasing population growth, urbanization, land use/land cover changes, water demand, and climate change. The combined outcomes of those changes and natural activities, such as droughts and water resources, particularly freshwater, are becoming inadequate (Ahmad et al., 2021).

2.4. Climate change impact on water availability

Climate change is expected to alter rainfall distribution, with some regions experiencing increased rainfall while others face deficits (Sulistyani & Irianto, 2024) (Emmanuel Augustine Etukudoh et al., 2024). For instance, the Sampit River in Central Kalimantan is projected to experience a water deficit by 2030, particularly in October (Sulistyani & Irianto, 2024). Rising temperatures accelerate evaporation rates, potentially increasing by 5.2% globally (Ehtasham et al., 2024). This acceleration can lead to more frequent and intense extreme weather events, such as floods and droughts, further complicating water resource management (Ehtasham et al., 2024). In the USA, prolonged droughts and changing snowmelt patterns threaten water resources, while Africa faces increased aridity due to reliance on rain-fed agriculture (Etukudoh et al., 2024). The impact of climate change on water availability varies significantly across regions, necessitating tailored adaptive strategies (Etukudoh et al., 2024).

Water resources of the world in general and in Africa are under heavy stress because of the increased impact of climate change groundwater recharge. However, the severity of the impact varies from one region to another (Luis & Moncayo, n.d.2018). So, water resources are sources of water that can be beneficial or potentially useful to humans, and it is important because it is needed for life to exist. Many uses of water include agricultural, industrial, domestic, recreational, and environmental activities. Virtually all human uses need fresh water. Climate change may be due to internal processes or external forces. Some external influences, such as changes in solar radiation and volcanism, occur naturally and contribute to the climate system's natural variability. Other external changes, including the change in the atmosphere's composition that commenced with the Industrial Revolution, are the result of human activity (Gebre, 2015). Therefore, according to Gebre, (2015), climate change (changes in frequency and intensity of extreme climate events) is likely to have main impacts on natural and human systems concerning hydrology; climate change can motivate significant influences on groundwater resources by resulting in changes in the hydrological cycle.

Water resources evaluation is, therefore, a countries-wide responsibility that requires special arrangement and capability toward achieving an appropriate water resources assessment. Such evaluation is necessary since the unabated increases in water demands and their fluctuation constitute issues of concern in the planning and development of water sources, most especially in the area of water production and water utilization, particularly in developing countries (Adeaga et al., 2019). In addition, the effect of climate change and variability on water resources development is well-identified globally. It has been identified as a major issue facing the availability of water resources such as water surface, groundwater, and supplies (Abbas et al., 2017). The importance of wetlands in East Africa for the provision of numerous environmental services, ranging from the improvement of mental well-being to water and climate regulation, is well proven (Näschen, Diekkrüger, Leemhuis, et al., 2019). Some researchers speculated the prospect of increases in hydrological extremes about climate change. The variability of runoff and groundwater resources is specifically higher for drier climates (Xu et al., 2004). Water resource scholars need to deal with the effects of climate change on hydrology regimes and water resources. Therefore, a good understanding of the relationship between climate change, human activities, water resources, and their withdrawal and use will enable water resource managers to make rational decisions and water allocations.

There is little doubt that the higher annual precipitation variability has already led to consequences in Somaliland. The former more or less regular rainfalls during the rainy season have become less predictable, which results in more frequent drought years and a severe effect on the population, especially those relying on surface water sources (e.g. nomads), even if the average precipitation has not changed. In many cases as soon as reliable surface water resources are no longer dependable (African Development Bank Group, 2016). Therefore, the Somaliland water resource has different situations on climate impact, for groundwater is less directly and slowly affected by climate change when compared to surface water. But only when the droughts or decreased rain will the groundwater decline. In general, the Somaliland water resource has no river flows and lakes, but the water demand in the country (Somaliland) depends on groundwater, from which the majority of the population gets their water supplies,

The African Development Bank notes that Somaliland's climate ranges from arid to semi-arid. A projected increase of 10% in average precipitation could potentially have beneficial effects on groundwater levels and availability in the long term. However, the declining groundwater levels observed in certain wells across Somaliland are primarily attributed to groundwater extraction rates surpassing the natural recharge rate, rather than a decrease in groundwater recharge linked to climate change.

The water security challenges observed in Somaliland are consistent with the global scientific consensus, which is authoritatively synthesized in the Intergovernmental Panel on Climate Change (IPCC) Sixth Assessment Report (AR6). The IPCC identifies arid and semi-arid regions like the Horn of Africa as particularly vulnerable "hotspots" for the impacts of climate change and variability. Projections from the latest generation of Global Climate Models (GCMs), such as those used in the Coupled Model Intercomparison Project Phase 6 (CMIP6), consistently forecast increased temperatures, higher evaporative demand, and more erratic and extreme precipitation patterns for this region. This global framework underscores the urgency of local-scale studies like this one, as the historical trends analyzed in Hargeisa provide critical empirical evidence of these larger-scale climatic pressures.

2.5. Combine Effects of land use and climate change on water availability

The interplay between land use and climate change significantly impacts water availability, influencing hydrological processes across various regions. Changes in land cover, coupled with shifting climate patterns, alter precipitation and evaporation rates, leading to both increased and decreased water resources depending on the context.

Climate change is projected to increase precipitation in some regions while decreasing it in others, with significant seasonal shifts. For instance, the Kunhar River Basin anticipates a 20.5% to 29.1% increase in precipitation by the end of the 21st century (Haider et al., 2023) Increased temperatures accelerate evaporation, potentially leading to a 5.2% rise in evaporation rates, which can exacerbate drought conditions (Ehtasham et al., 2024)

Significant reductions in natural vegetation due to land use changes can diminish water retention and increase runoff, as observed in the Cañar River basin (Oñate-Valdivieso & Cordero, 2024). Urban expansion often leads to increased impervious surfaces, which can alter natural water flow and reduce groundwater recharge. (Oñate-Valdivieso & Cordero, 2024).

Africa's Water Resources: In Africa, combined climate and land use changes could reduce river flows by up to 7% in some basins, affecting agriculture and energy sectors (Thiery et al., 2023). The USA faces prolonged droughts and altered snowmelt patterns, necessitating adaptive water management strategies (Etukudoh et al., 2024).

While some regions may benefit from increased precipitation, the overall trend suggests that many areas will face heightened water scarcity due to the combined effects of climate change and land use alterations. This underscores the urgent need for integrated water resource management and adaptive strategies to mitigate these impacts.

Persistent global climate and land use changes have severely impacted environmental systems and their abilities, leading to the degradation of environmental services (Pan et al., 2015). Climate change affects groundwater recharge, habitats for biodiversity, and other ecosystem services (Yang et al., 2019). Land-use changes modify underlying ground surface situations, residences, and environment types, further altering the environment's structure and functioning (Mamat et al., 2018). Understanding the relative impacts of land use and climate change on groundwater recharge and water resources management is essential to develop effective climate change adaptation policies and optimal land use management (Brauman, 2015). Land use and climate changes can impact hydrological processes and attributes, posing considerable challenges for water resource management (Collet et al., 2015).

Climate change is causing more frequent droughts and floods, and increasing demands for water due to urbanization, agriculture, and tourism (Sisto et al., 2016). Assessing water resource vulnerability and risk, estimating water shortages, and analyzing droughts are crucial for avoiding water crises (Hishe et al., 2020). Climate change research, including its impact on water resources and land use changes, is ongoing. Land use changes affect the hydrologic system of watersheds, especially in arid and semi-arid regions, and can impair water quality (Choukri et al., 2020).

2.6. Remote Sensing

Remote Sensing (RS) is defined as the science of obtaining information about an object, area, or phenomenon through the analysis of data acquired by a device that is not contact with the object, area, or phenomenon under investigation (Bawahidi, 2005). It provides a large amount of data about the earth's surface for detailed analysis and change detection with the help of sensors. Most of the data inputs to the hydrological (SWAT) model are directly or indirectly extracted from remotely sensed data. Some of the important data used in the hydrological modeling that are obtained from remote sensing include digital elevation model (DEM), and land cover maps.

Some of the applications of remote sensing technology in mapping and studying land use and land cover changes are; mapping and classifying the land use and land cover, assessing the spatial arrangement of land use and land cover, allowing analysis of time-series images used to analyze landscape history, report and analyze results of inventories including inputs to Geographic Information System (GIS), provide a basis for model building.

Land use is changing rapidly in most parts of the world. In this situation, accurate, meaningful, and availability of data is highly essential for planning and decision-making. Remote sensing is particularly attractive for the land cover data among the different sources. Stefano et al (2001) reported that in the 1970s satellite remote sensing techniques started to be used as a modern tool to detect and monitor land cover change at various scales with useful results.

(William et al, 1991) showed that the information on land use and land cover change which is extracted from remotely sensed data is vital for updating land cover maps management of natural resources and monitoring phenomena on the surface. The importance of land cover mapping is to show the land cover changes in the watershed area and to divide the land use and land cover into different classes of land use and land cover. For this purpose, remotely sensed imagery plays a great role to obtaining information on both temporal trends and spatial distribution of watershed areas and changes over the time dimension for projecting land cover changes but also to support changes impact assessment (Atasoy et al., 2006). To monitor the rapid changes in land cover, to classify the types of land cover, and to obtain timely land cover information, multitemporal remotely sensed images are considered effective data sources.

2.7. Hydrological Models

Hydrological models serve as mathematical representations of the water cycle's various components. Developed for diverse applications, these models come in many different forms but are generally designed to fulfill one of two main purposes.
The first primary objective is to gain a deeper understanding of a watershed's hydrological processes and how changes within that area may influence these natural events. The second key objective is for forecasting hydrological outcomes (Tadele, 2007). Additionally, these models provide crucial information for evaluating the potential effects of changes in climate, land use, and land cover.

Based on how they detail these water-related processes, hydrological models can be sorted into three principal categories (Cunderlik, 2003)

1. **Lumped hydrologic models**, a watershed is treated as a single, homogenous unit. The model's parameters are averaged across the entire area and do not vary spatially. Consequently, these models evaluate the basin's response as a whole, focusing only on the final output at the outlet rather than the behavior of individual sub-basins. The parameters in these models are often empirical and may not represent actual physical characteristics of the landscape. While this makes them generally unsuitable for simulating specific, event-scale processes (like a single rainstorm), they can provide predictions for overall water discharge that are just as reliable as those from more complex, physically-based models.
2. **Distributed hydrologic models**: take a much more detailed approach. They divide a watershed into a grid of many smaller cells or sub-units, similar to pixels

in a picture or pieces of a puzzle. This method allows the model's parameters (like soil type, land use, and slope) to vary from cell to cell, capturing the spatial variation of the landscape. The model then uses sophisticated computational algorithms to evaluate how this detailed distribution of characteristics influences the watershed's response to precipitation.

The main challenge with this approach is its significant data requirement. Gathering detailed, accurate data for every cell in the grid can be difficult, and such comprehensive information is often unavailable. However, because these models simulate the underlying physical processes in great detail, they have the potential to provide the highest degree of accuracy when properly supplied with the necessary data.

3. **Semi-distributed models**, Semi-distributed models (SD models) are a crucial approach in hydrological modeling, particularly for urban storm water management and flood forecasting. These models utilize sub-catchment units to apply rainfall and estimate runoff, making them less data-intensive than fully distributed models. The flexibility and adaptability of Semi-distributed models allow for effective real-time flood forecasting and performance evaluation across various applications.

   Studies show that Semi-distributed models can achieve high accuracy in streamflow simulations, as demonstrated by the comparison between the satellite-based hydrological model and the SWAT model, where the former outperformed the latter (Paul et al., 2019)

Hydrologic models can be further divided into event-driven models, continuous-process models, or models capable of simulating short-term and continuous events. Event-driven models are designed to simulate individual precipitation-runoff events. Their emphasis is placed on infiltration and surface runoff. Typically, event models have no provision for moisture recovery between storm events and, therefore, are unsuitable for the simulation of dry-weather flows. On the other hand, continuous-process models simulate instead a longer period, predicting watershed response both during and between precipitation events. They are suited for simulation of daily, monthly, or seasonal stream flow, usually for long-term runoff-volume forecasting and for estimates of water yield (Cunderlik, 2003).

2.8. SWAT+ Model

The SWAT (Soil and Water Assessment Tool) watershed model is one of the most recent models developed at the USDA-ARS (Arnold et al., 1998) during the early 1970's. SWAT model is a semi-distributed physically based simulation model and can predict the impacts of land use change and management practices on hydrological regimes in watersheds with varying soils, land use and management conditions over long periods and primarily as a strategic planning tool (Neitsch, et al, 2005).

The interface of SWAT model is compatible with QGIS which can integrate numerous available geospatial data to accurately represent the characteristics of the watershed. In the SWAT+ model, the impacts of spatial heterogeneity in topography, land use, soil and other watershed characteristics on hydrology are described in subdivisions. There are two scale levels of subdivisions; the first is that the watershed is divided into a number of sub-watersheds based upon drainage areas of the attributes, and the other one is that each sub-watershed is further divided in to a number of Hydrologic Response Units (HRUs) based on land use and land cover, soil and slope characteristics.

The SWAT+ model simulates eight major components: hydrology, weather, sedimentation, soil temperature, crop growth, nutrients, pesticides, and agricultural management (Neitsch, et al, 2005). Major hydrologic processes that can be simulated by the this model include evapotranspiration, surface runoff, infiltration, percolation, shallow aquifer and deep aquifer flow, and channel routing (Arnold et al., 1998). Stream flow is determined by its components (surface runoff and ground water flow from shallow aquifers).

The SWAT+ model has a good reputation for best use in agricultural watersheds and its uses have been successfully calibrated and validated in many areas of the USA and other continents (Ndomba, 2002; Tripathi et al., 2003). The studies indicated that the SWAT Model is capable in simulating hydrological processes and erosion/sediment yield from complex and data-poor watersheds with reasonable model performance statistical values. Ndomba (2002) was applied the SWAT model in the modeling of the Pangari River (Tanzania) to evaluate the applicability of the model in complex and data poor watersheds. Tripathi et al., (2003) applied the SWAT model for Nagwan watershed in India to identify and prioritize of critical sub-watersheds to develop an effective management plan and the model was verified for both surface runoff and sediment yield. Accordingly, the study concluded that the SWAT+ model can be used in ungauaged watersheds to simulate the hydrological and sediment processes.

SWAT+ has gained international acceptance as a robust interdisciplinary watershed modeling tool as evidenced by international SWAT+ conferences, hundreds of SWAT related papers presented at numerous other scientific meetings, and large number of articles published in peer-reviewed journals (Gassman, 2007).

However, indicated that SWAT model parameters show varying sensitivity in different years of simulation suggesting the requirement for dynamic updating of parameters during the simulation (Cibin et al, 2010). The same study also indicated that sensitivity of parameters during various flow regimes (low, medium and high flow) is also found to be uneven, which suggests the significance of a multi-criteria approach for the calibration of the model.

CHAPTER THREE

MATERIALS AND METHODS

1.1. Description of the Study Area

The study is focused on the Hargeisa watershed, which contains Hargeisa, the capital city of Somaliland, located in the Horn of Africa. The city is situated within a valley in the Galgodon (Ogo) highlands at an average elevation of 1,334 meters above sea level. Geographically, the approximate center of the study area lies at latitude 9°33′ N and longitude 44°04′ E. As the nation's primary urban center, Hargeisa has an estimated population of 2.2 million residents (MNPD, 2011) and is set within a semi-arid environmental zone, making it highly dependent on limited water resources.

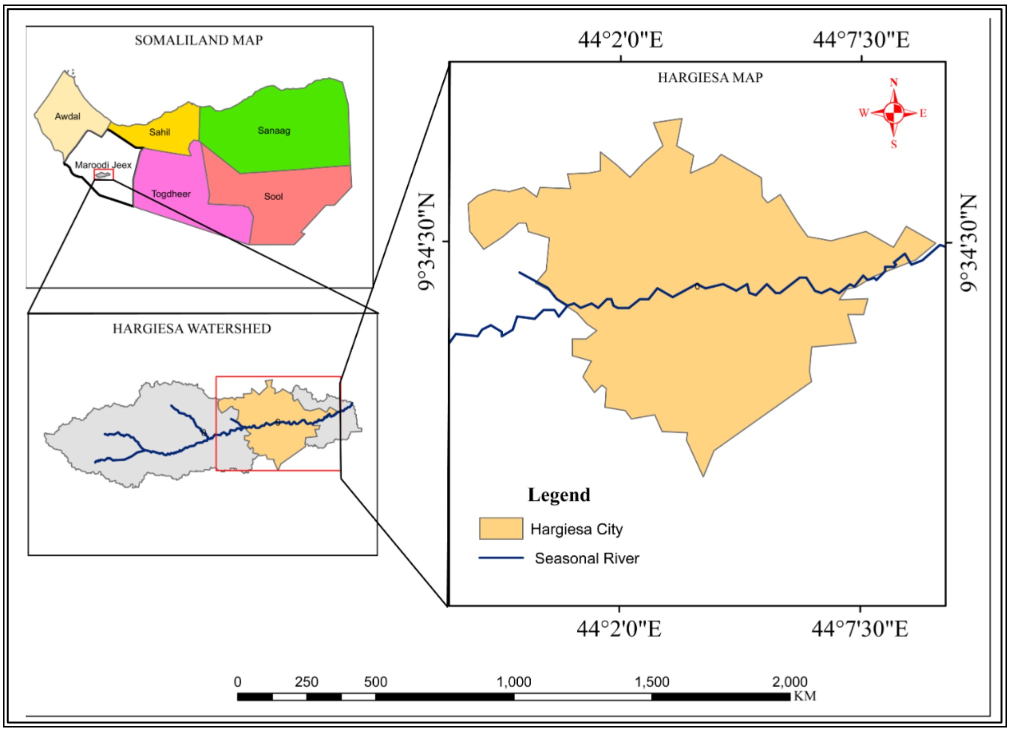


Figure 3.1. Map of the study area

3.1.1. Topographic

The topography of the Hargeisa watershed is characterized by a distinct elevation gradient. The highest point is found in the upstream area of Cada at an elevation of 1361m above sea level, while the lowest point is located at the watershed's outlet in the Haleya downstream section, at an elevation of 1259m.

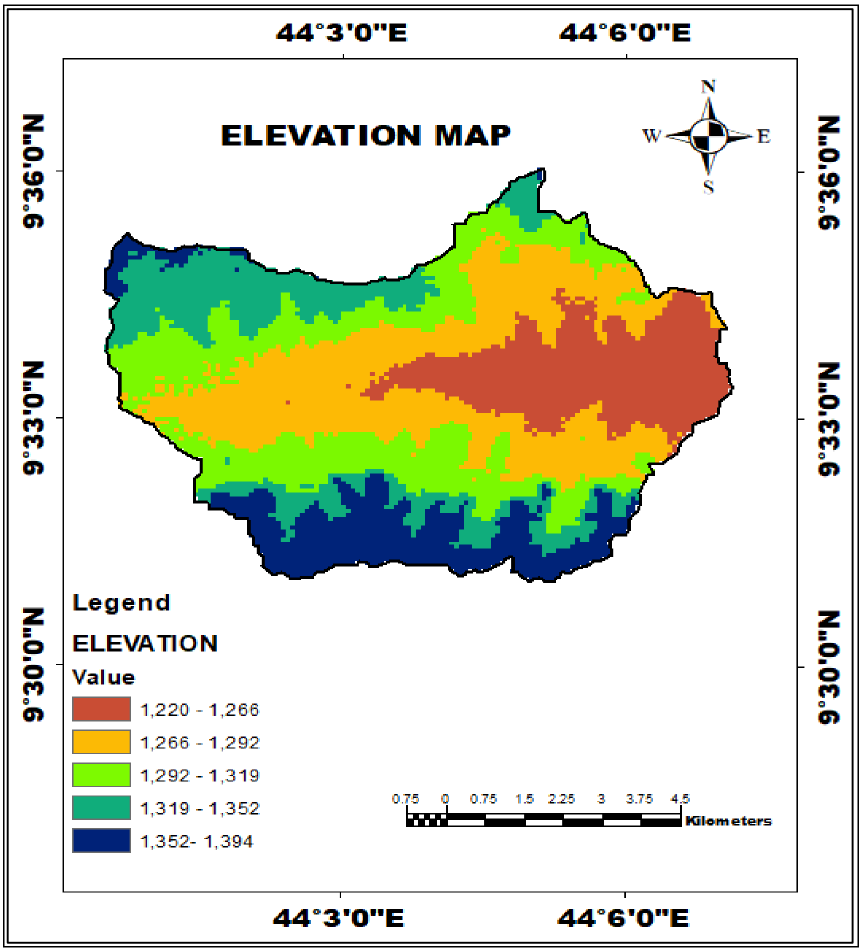


Figure 3.2: Elevation map of the study area

3.1.2. Climate Condition

The Hargeisa watershed is characterized by a semi-arid climate with high temperatures and low, variable precipitation. The region experiences a bimodal rainfall pattern, with the primary rainy season, known as the "Gu," occurring from April to June, and a shorter, less intense rainy season, the "Deyr," from September to November. Based on climate data from 1995 to 2024, the long-term mean annual precipitation for the watershed is approximately 400 mm.

Temperatures are consistently warm throughout the year, with an average annual temperature of around 24°C. Monthly average maximum temperatures typically range from 28°C to 33°C, while average minimum temperatures stay between 24°C and 28°C. This combination of low precipitation and high temperatures leads to significant rates of evapotranspiration, a critical factor that directly influences the watershed's water balance and contributes to local water scarcity

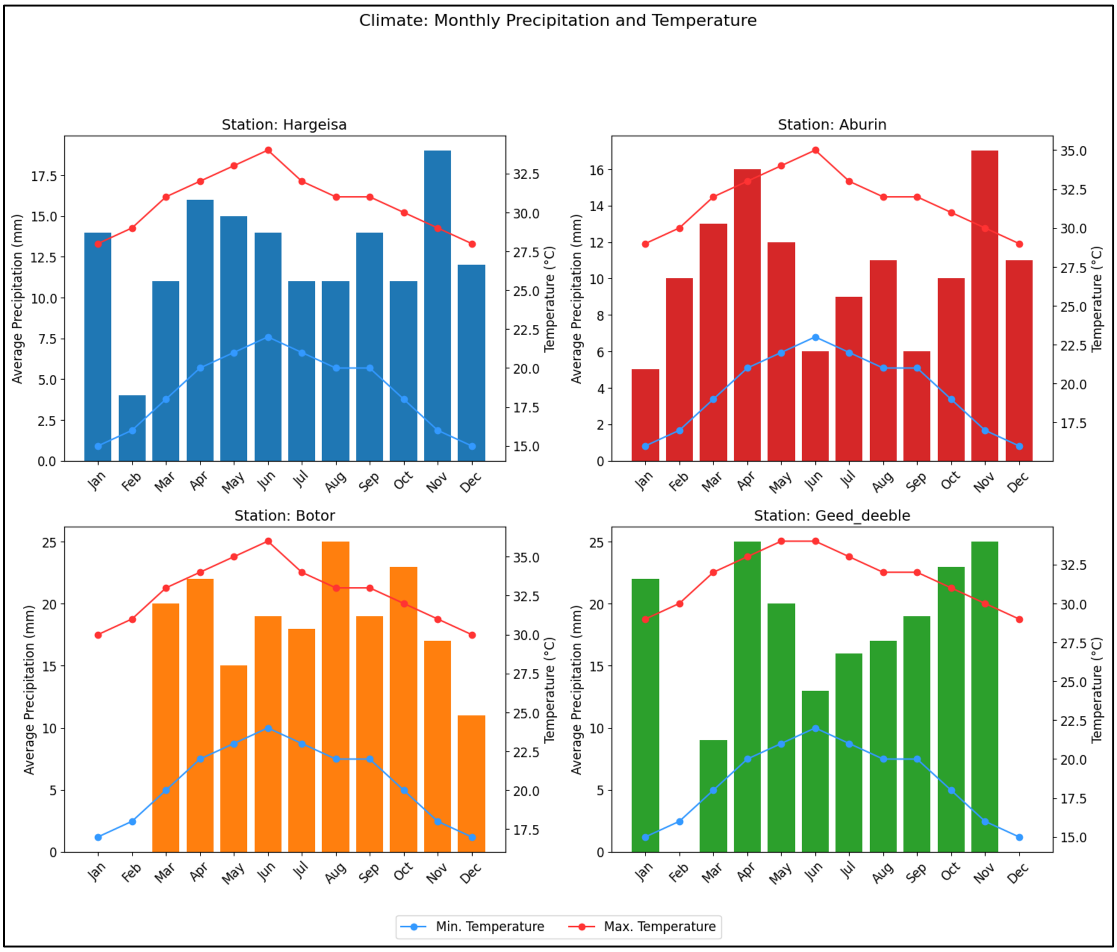


Figure 3.3: Mean Monthly Temperature and precipitation

3.1.3. Land use of the area

The land use within the Hargeisa watershed is characterized by two dominant and interacting systems: extensive agro-pastoralism and rapid urbanization. The natural land cover consists primarily of savannah grasslands and open shrublands, which are traditionally used for livestock grazing and mixed subsistence farming (Ministry of Agriculture (MoA, 2020). This landscape is undergoing significant transformation due to the expansion of Hargeisa city, resulting in the conversion of natural and agricultural lands into built-up areas. The distinct land use types identified for this study—including urban areas, grassland, vegetation, and bare land form the basis for the land cover classification used in the hydrological model.

3.1.4. Soil Type

The study area in Hargeisa is characterized by thirteen distinct soil types, classified according to the FAO/UNESCO system. Analysis of the watershed's composition reveals a landscape overwhelmingly dominated by Calcic Cambisols, which cover 69.3% of the total area. These are moderately developed loamy soils, typical of semi-arid climates, with a significant accumulation of calcium carbonate. Other notable soils, while less extensive, are critical to the local pedology. Lithic Leptosols, which are very shallow soils lying directly over hard rock that limit root growth, account for 8.4% of the area. Following these are Vertic Cambisols, covering 6.9%, which are distinguished by a higher clay content and moderate shrink-swell properties. The remaining ten soil types collectively constitute less than 16% of the landscape. This group includes small but important pockets of fertile, humus-rich soils like Luvic and Haplic Phaeozems, as well as heavy clay Eutric and Pellic Vertisols, which shrink and swell dramatically with changes in moisture. The presence of Luvisols, Regosols, Calcisols, and Fluvisols in smaller quantities completes the area's diverse but Cambisol-dominated soil profile, which is consistent with the geology and climate of the Hargeisa region.

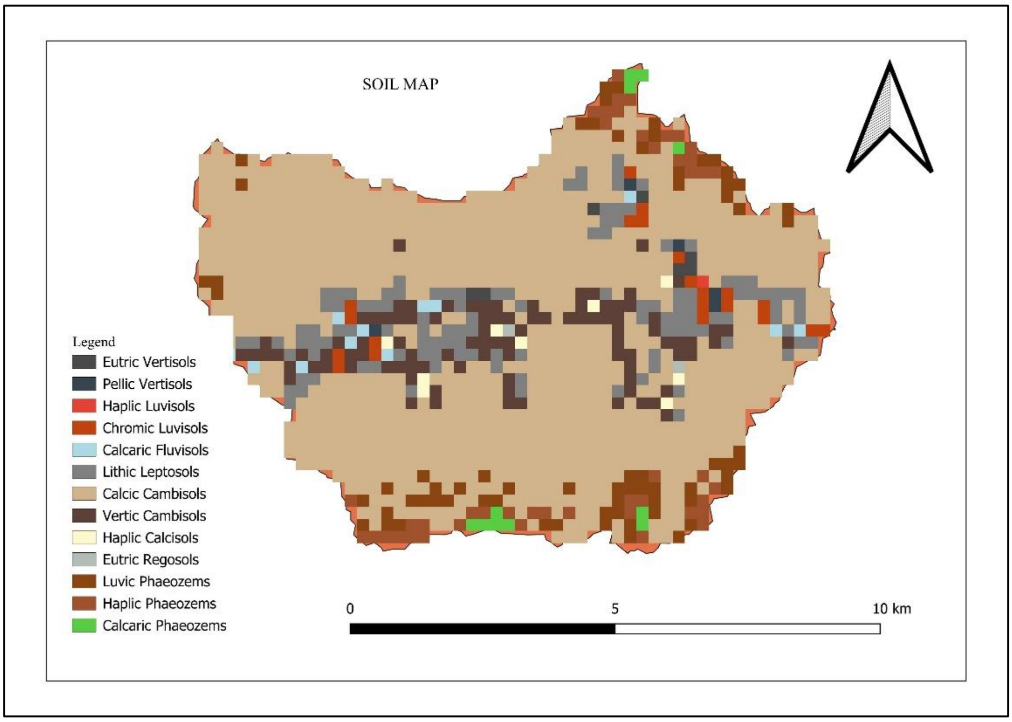


Figure 3.4: Soil map of the study area

3.1.5. Water situation of the area

The water supply for Hargeisa is managed by the government-run Hargeisa Water Agency (HWA). The city's primary water source is groundwater extracted from a well field in Geed Deeble, located approximately 20 kilometers away. However, due to limited and old infrastructure, the HWA is only able to serve about 30% of the city's population through its piped network. Consequently, a majority of residents, particularly in the southern districts, rely on private water tankers for their daily needs. This alternative supply is expressively more expensive, creating a notable disparity in water access and affordability across the city and underscoring the persistent gap between water supply and demand.

3.1.6. Agriculture Activities Area

The primary agricultural practice within the Hargeisa watershed is a mix of agro-pastoralism and subsistence farming. Agricultural activities are overwhelmingly dependent on direct rainfall, with an estimated 90% of farming being rain-fed and the principal crops being sorghum and maize (Ministry of National Planning and Development [MNPD], 2011). These crops are typically grown using traditional, minimal-input methods. This heavy reliance on erratic and variable rainfall makes agricultural livelihoods in the study area highly vulnerable to drought and directly links the region's food security to its challenging climatic conditions.

3.1.7. Socio-economic of the Study

To identify and analyze the socio-economic impacts of water scarcity on communities in Hargeisa, a mixed-methods approach centered on a structured household survey was employed. The primary tool was a detailed questionnaire, administered to residents to gather quantitative and qualitative data. The survey focused on key indicators of water security, including household water sources, frequency of supply, and satisfaction with water pricing, and the perceived effects of scarcity on livelihoods, sanitation, and health.

The study targeted households across five major districts to ensure a representative sample of the urban population. The sample size was determined to be 134 participants using Slovin's formula, providing a statistically relevant basis for the findings. The data collected from the questionnaires were then statistically analyzed to identify key trends, percentages, and community perceptions, which are presented in the Results and Discussion chapter

3.2. Data Collection and Sources

The study utilized a range of geospatial, climatological, and socio-economic data to achieve its objectives. A 30m resolution Digital Elevation Model (DEM) from the Shuttle Radar Topography Mission (SRTM) was used to define the watershed's topography, including slope, sub-basin boundaries, and stream networks. Land Use/Land Cover (LULC) maps for the years 2000 and 2024 were derived from Landsat satellite imagery obtained from the USGS Earth Explorer. Soil characteristic data, including texture and hydraulic properties, were sourced from the FAO Digital Soil Map of the World. Daily climatological data for the period 1995–2024 (precipitation, min/max temperature, humidity, wind speed, and solar radiation) were obtained from the Somaliland Ministry of Agriculture (MoA) and supplemented with NASA POWER data. For the regionalization procedure, observed daily streamflow data (1990–2000) for the gauged donor watershed (Jarar Valley) was provided by MoWE of the Ethiopian. Finally, primary socio-economic data was collected through structured household surveys conducted in Hargeisa in 2025.

3.3. Land Use and Land Cover (LULC) Change Analysis

To analyze historical land use and land cover changes, a remote sensing and GIS-based approach was implemented. Landsat satellite imagery for the years 2000 and 2024 was acquired from the USGS Earth Explorer. Using QGIS software, a supervised classification with the Maximum Likelihood algorithm was performed. This method uses representative training samples to classify the entire satellite image into distinct LULC categories. For this study, the landscape was categorized into five classes: Urban Area, Grassland, Dense Vegetation, Bare Land, and Seasonal River. Following the classification, a change detection analysis was conducted by comparing the classified maps of 2000 and 2024. The total area for each LULC class was calculated for both years, and the magnitude and percentage of change were determined to quantify the landscape transformation over the 24-year period.

3.4. Climate Trend Assessment

To assess historical trends and variability in climate parameters (Objective 2), daily meteorological data (precipitation, Tmax, Tmin) from 1995 to 2024 was analyzed. First, to create a continuous and reliable dataset required for SWAT modeling, intermittent gaps in the historical time series were filled using the quantile mapping technique. This statistical method adjusts the distribution of a complete secondary dataset (NASA POWER) to match the observed statistical distribution of the local station's data, ensuring a consistent long-term record.

Second, the completed time series was analyzed for long-term trends using two robust non-parametric statistical methods. The Mann-Kendall (MK) test was applied to determine whether a statistically significant monotonic (upward or downward) trend existed in the data. Where a significant trend was detected, the Sen's Slope estimator was used to quantify the magnitude (rate of change) of that trend. This two-step process provides a robust statistical assessment of the historical climate patterns, which are visualized as time-series line graphs in Figure 3.5.

Mann-Kendall trend test formula

$$\boxed{S = \sum_{i=1}^{n-1} \sum_{j=i+1}^{n} sign(x_j - x_i)} \qquad (3.1)$$

Where S is the test statistic and I is the outer loop index. J is also the index for the inner loop of the summation. It represents the position of the second data point in a pair being compared.

Second, to quantify the magnitude of any significant trends, the Sen’s slope estimator was applied. This method provides a robust estimate of the rate of change by calculating the median of the slopes between all possible pairs of data points. The Sen's slope is the median value (Q_{med}) derived from all individual slopes calculated as:

Sen’s slope estimator formula

$$\boxed{Sen's\ slope = Median \left\{ \frac{x_j - x_i}{j - i} : i < j \right\}} \qquad (3.2)$$

Where, N = the number of pairs of time series elements

(xi, xj) where i < j and se = the standard error for the Mann-Kendall Test.

Also mh = the hth smallest in the set {(xj–xi)/ (j–i): i < j} and zcrit = the 1–α/2 critical value for the normal distribution.

3.5. Hydrological Modeling with SWAT+

To evaluate the combined effects of land use and climate change on water resources (Objective 3), the Soil and Water Assessment Tool Plus (SWAT+) was selected as the primary modeling framework.

3.5.1. SWAT+ Model Description and Justification for Selection

The Soil and Water Assessment Tool (SWAT) is a widely used, physically-based, semi-distributed watershed-scale model designed to predict the long-term impacts of land management practices on water, sediment, and agricultural chemical yields. SWAT+ is a complete restructuring and modularization of the original SWAT code, offering greater flexibility in watershed configuration and a more intuitive, object-oriented structure (Bieger et al., 2017)

SWAT+ was specifically chosen for this study over other hydrological models for several key reasons:

- **Land Use Change Impacts**: The model's core strength is its ability to explicitly simulate how changes in land use, soil type, and management practices directly affect hydrological processes like surface runoff and infiltration. This capability is essential for addressing the primary objective of this thesis.
- **Data Scarcity**: SWAT+ is well-suited for data-scarce regions like the Hargeisa watershed because it can generate its own weather data if needed and its parameters can be estimated from available soil and land use maps.
- **Comprehensive Process Simulation**: As a physically-based model, it provides detailed simulations of the entire water balance, including surface runoff, evapotranspiration, infiltration, and groundwater recharge, which are critical components for understanding water availability.

3.5.2. SWAT+ Model Setup

The setup of the SWAT+ model for the Hargeisa watershed was performed using the QSWAT+ interface in QGIS. The process involved a systematic workflow based on the available geospatial and climatological data.

The model first delineates the watershed into distinct sub-basins based on the Digital Elevation Model (DEM). Following this, each sub-basin is further divided into Hydrologic Response Units (HRUs). An HRU is a unique computational unit with a homogeneous combination of land use, soil type, and slope. This approach allows the model to accurately represent the spatial heterogeneity of the watershed and its varied responses to precipitation. The model simulates the land phase of the hydrologic cycle for each HRU based on the following daily water balance equation (Neitsch, et al, 2005):

$$SW_{\cdot t} = SW0 \quad + \sum_{i=1}^{t} \left(R_{day} - Q_{surf} - E_{day} - W_{seep} - Q_{gw} \right) \tag{3.4}$$

Where, SWt is the final soil water content (mm)
SWo is the initial water content (mm)
T is the time (days)
Rday is the amount of precipitation on a day i (mm)
Qsurf is the amount of surface runoff on day i (mm)
Ea is the amount of evapotranspiration on day i (mm)
Wseep is the amount of water entering the vadose zone from the soil profile on
Day i (mm), and
Qgw is the amount of return flow on a day i (mm).

3.5.3. Watershed Delineation

The delineation of the Hargeisa watershed, which forms the spatial boundary for the hydrological model, was performed using the automated tools available within the QSWAT+ interface in QGIS. This GIS-based approach was selected for its accuracy, efficiency, and its direct integration with the SWAT+ modeling workflow.

The primary input for the delineation process was the 30m resolution Digital Elevation Model (DEM) sourced from the SRTM. The procedure involved several automated steps. First, the DEM was processed to create flow direction and flow accumulation grids, which map the path that water would take across the terrain. Based on these grids, a stream network was generated. Finally, by defining an outlet point for the watershed, the QSWAT+ tool automatically calculated the drainage boundaries, dividing the total area into 37 distinct sub-basins, as shown in Figure 3.9. This process provided the fundamental topographic framework upon which all subsequent hydrological simulations were based.

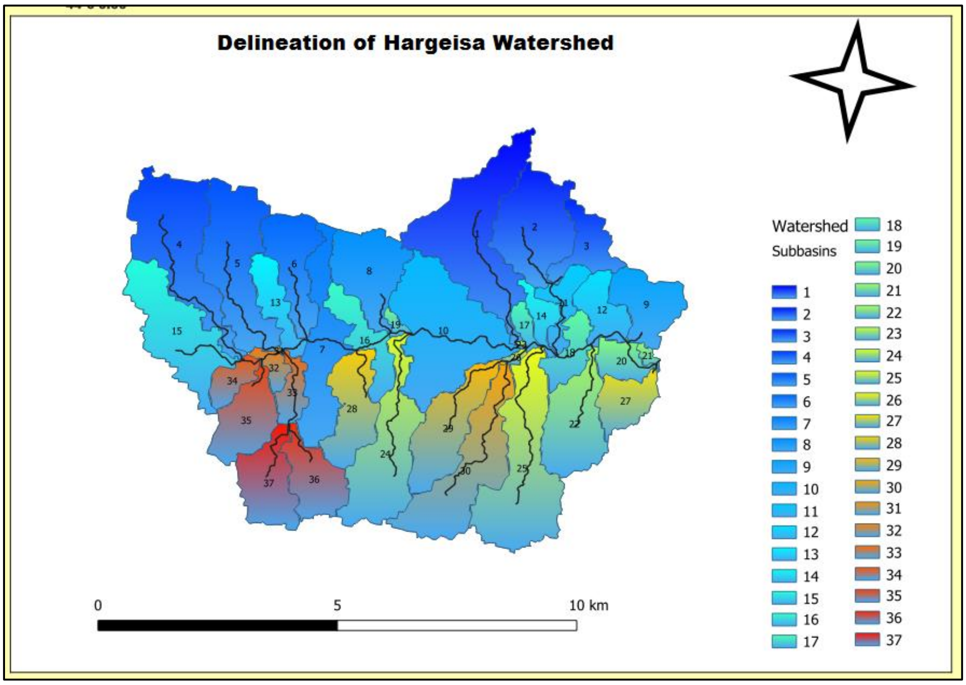


Figure 3.6: The Hargeisa Watershed delineation

3.5.4. Hydrologic Response Unit (HRU)

Following the watershed delineation, Hydrologic Response Units (HRUs) were defined for each of the 37 sub-basins using the automated tools within the QSWAT+ interface. This critical step involved overlaying the land use, soil type, and slope data to create unique computational units. An HRU represents a distinct combination of these three characteristics and is the fundamental level at which the model calculates the land phase of the hydrological cycle.

To balance model complexity with computational efficiency, a multiple-threshold approach was used. Thresholds of 10% for land use, 10% for soil, and 10% for slope were applied. This means that any land use, soil, or slope combination covering less than 10% of a sub-basin's area was eliminated, and its area was reapportioned to the largest HRU within that sub-basin. This standard procedure ensures that the most significant landscape features are retained in the model while simplifying the overall model structure(Femeena et al., 2022).

3.5.6. Regionalization and Parameter Transfer Procedure

As the Hargeisa watershed is ungauged, a regionalization approach was essential to develop a reliable hydrological model. The specific method employed was parameter transfer, which involves calibrating a model on a similar, gauged "donor" watershed and then transferring the optimized parameters to the ungauged target watershed.

The procedure involved three main steps:

1. **Selection of the Donor Watershed**: The success of this method hinges on selecting an appropriate donor. The Jarar Valley in Ethiopia was chosen based on a dual-criterion approach of spatial proximity and physical similarity (Narbondo et al., 2020). The Jarar Valley is one of the nearest gauged basins and shares key characteristics with the Hargeisa watershed, including a semi-arid climate, a bimodal rainfall regime, and comparable topography and geology. This strong similarity provided confidence that it would serve as a suitable hydrological analogue.
2. **Calibration and Validation**: A SWAT model was developed for the Jarar Valley and was then calibrated and validated against its observed historical streamflow record. The calibration was performed for the period 1992–1997, followed by a validation on an independent dataset from 1998–2000. This process produced a set of optimized hydrological parameters that were proven to reliably simulate the region's rainfall-runoff processes.
3. **Parameter Transfer**: Following the successful validation of the donor model, the final, optimized set of hydrological parameters was transferred directly to the SWAT+ model developed for the Hargeisa watershed. This transferred parameter set provided the scientific foundation for all subsequent simulations of water availability in the study area.

3.5.7. Model Calibration and Validation

The SWAT model for the donor watershed was rigorously tested and optimized through a standard calibration and validation procedure. The simulation was run using historical data, beginning with a two-year warm-up period from 1990–1991 to initialize model state variables and stabilize hydrological conditions. Following this, the model was calibrated for the period 1992–1997 by adjusting the most sensitive parameters to achieve the best possible agreement between simulated and observed streamflow. Finally, the model's predictive capability was confirmed through a validation process from 1998–2000, where it was run with the final calibrated parameters against an independent dataset without any further adjustments. This division of the timeline ensures a robust assessment of the model's performance, confirming the reliability of the parameter set before its transfer to the Hargeisa watershed.

3.5.7. The Parameter Transfer Process

The final step in the regionalization procedure was the direct transfer of the optimized parameter set. This parameter set was derived from the successfully calibrated and validated model of the Jarar Valley donor watershed. These optimized values were then applied to the SWAT+ model configured for the ungauged Hargeisa watershed. This action established the foundational hydrological parameters necessary for all subsequent simulations of water availability in the study area.

3.5.8. Sensitivity Analysis Procedure

To identify the model parameters that have the most significant influence on streamflow, a sensitivity analysis was performed. This step is crucial for guiding an effective and efficient calibration by focusing on the most critical parameters. The analysis was conducted on the calibrated model for the gauged donor watershed (Jarar Valley) using the SWAT-CUP program, employing the Sequential Uncertainty Fitting (SUFI-2) algorithm. A global sensitivity analysis was performed, and the relative sensitivity of each parameter was quantified using two statistical measures: the t-Stat, where a larger absolute value indicates greater sensitivity, and the p-value, where a value approaching zero signifies that the parameter is statistically significant. The parameters identified as most sensitive were then prioritized during the model calibration process.

3.5.9. Uncertainty Analysis

Uncertainty is an inherent component of environmental modeling and was explicitly addressed in this study. The primary sources of uncertainty arise from input data (precipitation accuracy), model structure (the simplified representation of complex processes), and parameter estimation. The SWAT-CUP program, using the SUFI-2 algorithm, was employed to quantify this prediction uncertainty. This is expressed as the 95% Prediction Uncertainty (95PPU) band, which brackets the range of simulation results. The quality of the uncertainty analysis was evaluated using two statistical indices: the P-factor, which indicates the percentage of observed data captured by the 95PPU band, and the R-factor, which measures the average thickness of that band. This procedure provides a quantitative and scientifically robust measure of the model's confidence and limitations

3.6. Model Performance Evaluation

3.6.1. Model Development and Regionalization

The performance of the hydrological model during the calibration and validation phases was evaluated by comparing the simulated monthly streamflow against the observed historical data. To provide a robust and comprehensive assessment, three widely used statistical metrics were employed: the Coefficient of Determination (R^2), the Nash-Sutcliffe Efficiency (NSE), and the Percent Bias (PBIAS).

The R^2 value measures the proportion of the variance in the observed data that is explained by the model, indicating the linear correlation between simulated and observed values. The NSE determines the relative magnitude of the residual variance compared to the measured data variance, indicating how well the plot of observed versus simulated data fits a line. The PBIAS measures the average tendency of the simulated data to be larger (underestimation bias) or smaller (overestimation bias) than the observed data.
The coefficient of determination (R^2) described the proportion of the variance in measured data by the model. It was the magnitude of the linear relationship between the observed and the simulated values. R^2 ranged from 0 (which indicated the model was poor) to 1 (which indicated the model was good), with higher values indicating less error variance, and typical values greater than 0.6 were considered acceptable (Santhi et al., 2001). The R^2 was calculated using the following equation:

$$\mathrm{R}^2 = \frac{\sum[\mathrm{Xi-Xav}][\mathrm{Yi-Yav}]}{\sqrt{\sum[\mathrm{Xi-Xav}]^{\wedge}2}\ \sqrt{\sum[\mathrm{Yi-Yav}]^{\wedge}2}} \qquad (3.5)$$

Where, Xi is measured value (m^3/s)

Xav is the average measured value (m^3/s)

Yi is simulated value (m^3/s) and

Yav is an average simulated value (m3/s)

The Nash–Sutcliffe simulation efficiency (ENS) indicated how well the plots of observed versus simulated data fit the 1:1 line. ENS was computed using the following equation:

$$\mathrm{ENS} = 1 + \frac{\sum[\mathrm{Xi-Yi}]^{\wedge}2}{\sum[\mathrm{Xi-Xav}]^{\wedge}2} \qquad (3.6)$$

Where, Xi is measured value

Yi is a simulated value and

Xav is an average observed value

The value of ENS ranged from negative infinity to 1 (best) i.e., $(-\infty, 1]$. An ENS value < 0 indicated the mean observed value was a better predictor than the simulated value, which indicated unacceptable performance. While ENS values greater than 0.5, the simulated value was a better predictor than the mean measured value and generally was viewed as acceptable performance (Santhi et al., 2001).

PBIAS indicated the sum of differences between measured and simulated values over the sum of the measured value. It had the ability to indicate poor model performance and measured the average tendency of the simulated data to be larger or smaller than the observed data. Low values of PBIAS indicated accurate model simulation, positive values indicated model underestimation bias, and negative values indicated model overestimation bias (Ajai et al., 2014).

The following equations determined the values of PBIAS:

$$\text{PBias} = \frac{[\sum_{i=}^{n}.(Xobs-Xsim)]}{[\sum_{k=0}^{n}.Xobs]} * 100 \tag{3.7}$$

Where, Xobs is observed stream flow
Xsim is the simulated stream flow
N is the total number of observations

The Kling-Gupta Efficiency (KGE) was also used to provide a more comprehensive assessment of model performance. KGE is a valuable metric because it decomposes the model error into three distinct components: correlation, bias, and variability.

$$\text{KGE} = 1 - \sqrt{((r - 1)^2 + (\beta - 1)^2 + (\gamma - 1)^2)} \tag{3.8}$$

Generally, Moriasi et al., (2007) defined values of ENS, PBIAS and R^2

Table 3.1: General performance evaluation

Performance Rating	R^2	NS	PBIAS
Very Good	$0.75 < R^2 \leq 1$	$0.75 < \text{ENS} \leq 1$	PBIAS $\leq \pm 10$
Good	$0.6 < R^2 \leq 0.75$	$0.6 < \text{ENS}$	$\pm 10 \leq$ PBIAS $\leq \pm 15$
Satisfactory	$0.5 < R^2 \leq 0.6$	$0.36 < \text{ENS} \leq 0.6$	$\pm 15 \leq$ PBIAS $\leq \pm 25$
Unsatisfactory	$0.25 < R^2 \leq 0.5$	$0.00 < \text{ENS} \leq 0.36$	$\pm 25 \leq$ PBIAS $\leq \pm 50$

3.7. Jarar Valley Selection of gauged Watershed

The Jarar Valley in Ethiopia was selected as the gauged donor watershed for this study based on its physio-climatic similarity to the Hargeisa watershed. This selection is crucial for hydrological modeling, where data from a gauged watershed (one with measured data) is used to estimate hydrological parameters for a similar, but ungauged, watershed. The justification for this pairing rests on strong parallels in their geological framework, geoclimatic context, topography, and precipitation regimes.(The Study on Jarar Valley And Shebele, 2013)

Both watersheds are situated in the semi-arid Horn of Africa, a region characterized by climatic volatility, water stress, and erratic rainfall patterns that frequently lead to droughts. This shared geoclimatic context results in similar hydrological challenges and responses. Geologically, both the Jarar Valley and the Hargeisa watershed are characterized by ancient Proterozoic crystalline basement rocks overlain by thick Mesozoic and Cenozoic sedimentary layers. Specifically, both regions rely on sandstone and limestone formations as their primary aquifers the Jessoma Sandstone in the Jarar Valley and the comparable Yesomma Sandstone and Auradu Limestone in the Hargeisa watershed creating a direct hydrogeological parallel.(Kebede et al., 2025)

Topographically, the landscapes are analogous, featuring highland plateaus, mountain ranges, and valley systems. A critical shared feature is the nature of their river systems, which are predominantly ephemeral "wadis" that carry significant flow only after rainfall events. This indicates a similar surface water response to precipitation. The most direct quantitative comparison is the precipitation regime. The Jarar Valley receives an average annual rainfall of 383 to 451 mm. This figure is remarkably similar to the approximately 400 mm of annual rainfall recorded in Hargeisa. Both regions experience this precipitation in bimodal rainy seasons known as the GU and Deyr, which can be intense and lead to flash floods. These strong similarities in the physical and climatic drivers of the water cycle make the observed hydrological data from the Jarar Valley a robust and suitable analogue for understanding and modeling the water resources of the Hargeisa watershed.(Teku, 2025).

Table 3.2: List and location of the Hydr-meteorological stations

No	Station Name	Latitude in Degrees	Longitude in Degrees	Elevation in (m)
1	Degahabur	8.23	43.56	1070

2	Harshin	8.93	43.74	1434
3	Jigjiga	9.37	42.72	1557
4	Lefessa	9.5	42.9	1700

3.8. Meteorological Data

The climate of the Hargeisa region is defined by four distinct seasons, which are based on a bimodal rainfall pattern. These seasons are: GU, the primary spring rainy season from April to June. Xagaa, a hot and dry summer season from July to September; Deyr, a secondary and shorter autumn rainy season from October to November; and the Dirac, the main winter dry season which lasts from December to March.

Table 3.3: Meteorological Stations Used

Station Name	Latitude (Decimal Degrees)	Longitude (Decimal Degrees)
Hargeisa	9.56	44.07
Geed Deeble	9.77	44.25
Botor	9.42	43.83
Aburin	9.83	44.53

3.9. Rainfall

The daily rainfall data, which serves as the primary driver for the hydrological model, underwent a two-step preparation and analysis process to ensure a complete and reliable time series for the SWAT+ simulations. First, to address discontinuous gaps in the historical station records, the quantile mapping technique was employed. This statistical method was used to fill any missing daily values by adjusting the distribution of a complete secondary dataset (the NASA POWER gridded climate product) to match the observed statistical distribution of the local station's data. This procedure created a continuous and statistically consistent daily precipitation record for the entire 1995–2024 period.

Second, a trend analysis was performed on the complete time series to assess the historical rainfall patterns, as required by the research objectives. The non-parametric Mann-Kendall (MK) trend test was applied to determine whether a statistically significant monotonic trend (i.e., a consistent upward or downward direction) existed in the data. Subsequently, the Sen’s slope estimator was used to quantify the magnitude of any identified trends. This process provided a robust statistical assessment of the historical precipitation patterns in the watershed.

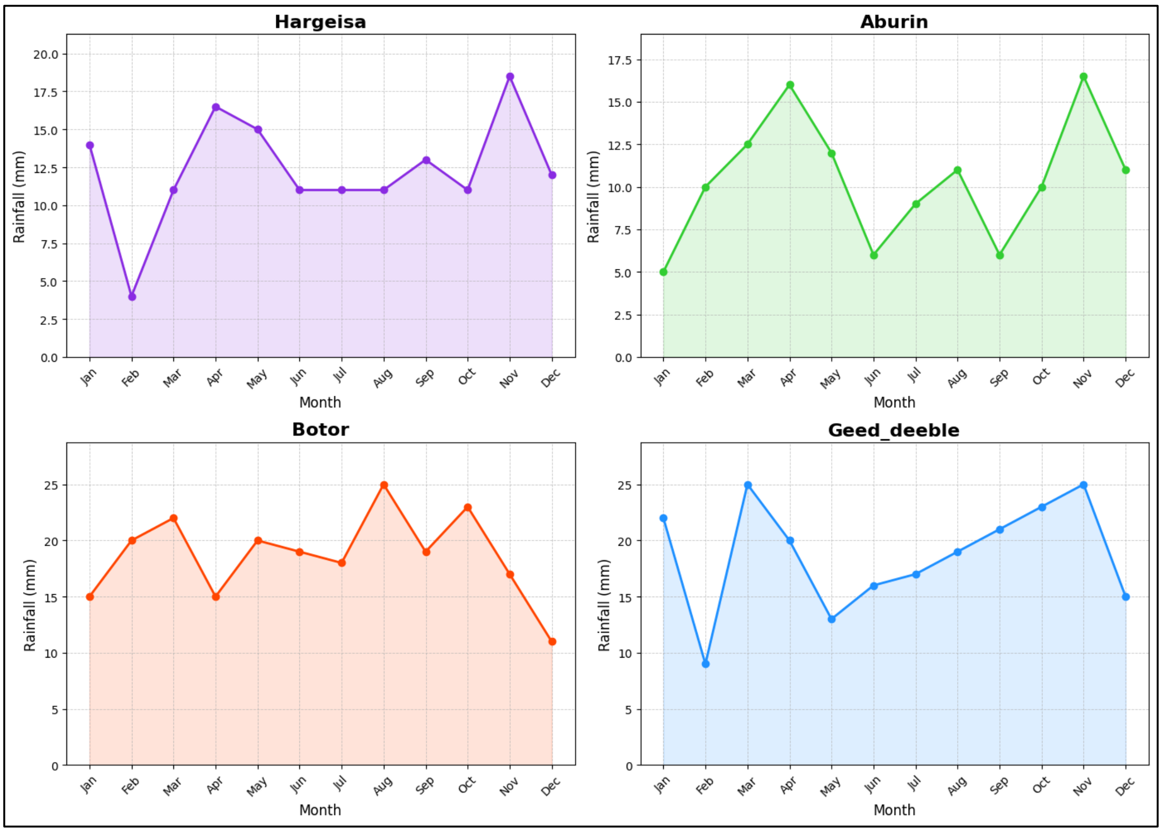


Figure 3.7: Average Monthly Precipitation at four stations

3.10. Temperature

Temperature is the main controlling factor of evapotranspiration in a certain watershed. In the study area, the temperature data average value ranges in the four seasonal temperatures are Diraac/ winter (DJF) 27.5C˚, 24.1C˚, Gu/spring (MAM) 31C˚, 28.5C˚, Xagaa/summer (JJA) 33.1C˚, 28.7C˚, and Dayr/autumn (SON) 30.3C˚, 28.7C˚, with maximum and minimum respectively.

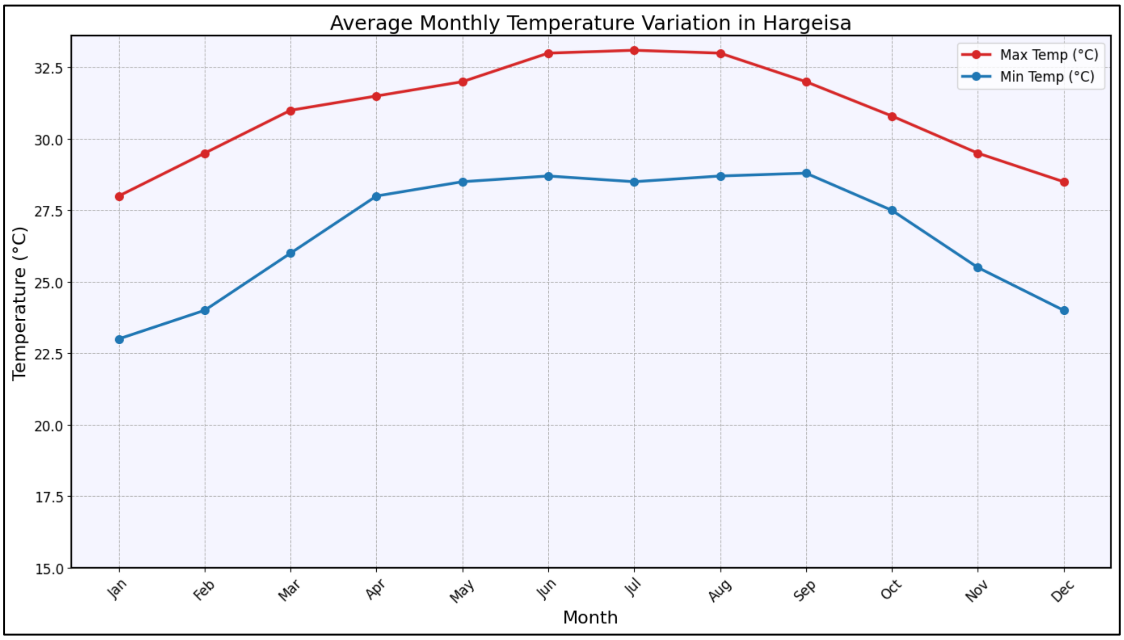


Figure 3.8: Seasonal Temperature Variation

3.11. Socio-Economic Impact Analysis

To identify the socio-economic impacts of water scarcity (Objective 4), a cross-sectional survey was conducted. A structured questionnaire was administered through face-to-face interviews with 134 households. The sample size was determined using Slovin's formula, and a proportional stratified sampling technique was used to ensure the sample was representative across Hargeisa's five major districts. The survey collected quantitative and qualitative data on household water sources, supply frequency, cost, satisfaction, and the perceived impacts of scarcity on livelihoods and health.

The study's target population (N) consisted of 533 households residing in specific neighborhoods across five major districts, which were identified in municipal reports as being particularly vulnerable to water insecurity due to their reliance on non-municipal water sources. From this target population, a representative sample size (n) of 134 households was calculated using Slovin's formula, with a 92.5% confidence level (7.5% margin of error) (Thornton & Thornton, 2004)

A proportional stratified sampling technique was used to distribute the sample across the five districts. This method ensured that the number of households surveyed in each district was proportional to that district's share of the total target population. The final distribution of the sample is detailed in Table 3.1.

$$n = \frac{N}{1+N(e)^2} \qquad (3.3)$$

Where:

n = the required sample size

N = the total household size

e = the level of precision or margin of error

For this study, the target household (N) was identified as 533, representing the "Total poor house building of four selected from the district.

A margin of error (e) of 7.5% (or 0.075) was deemed appropriate for this research.

Divide the total population by this sum: n=3.4525≈133.5= 134

This result was rounded up to a required sample size of n=134 participants.

Table 3.4: Distribution of Samples by District

No	District	No of sample
1	26 June District	21
2	Ahmed-Dhagax	28
3	Gacan Libaax District	30
4	Mohamoud Haybe	27
5	Ibrahim Kodbur	28

3.12. Methodology Framework

This flowchart outlines a comprehensive, six-phase methodological framework for a hydrological modeling study. The process commences with Phase 1: Data Collection, where diverse data types, including socio-economic, geospatial, and hydrological information, are gathered. This is followed by Phase 2: Model Setup, which involves developing a watershed model in Arc SWAT and transferring parameters via SWAT+ Editor. In Phase 3: Calibration and Validation, the model's performance is rigorously tested and refined using sensitivity analysis and the SWAT-CUP software to ensure accuracy. The validated model is then used in Phase 4: Scenario Simulations to analyze the historical impacts of land use/land cover and climate changes. Finally, the framework concludes with Phase 5: Analysis and Interpretation of the simulation outputs, which leads to Phase6: Conclusions and Recommendations based on the study's findings.

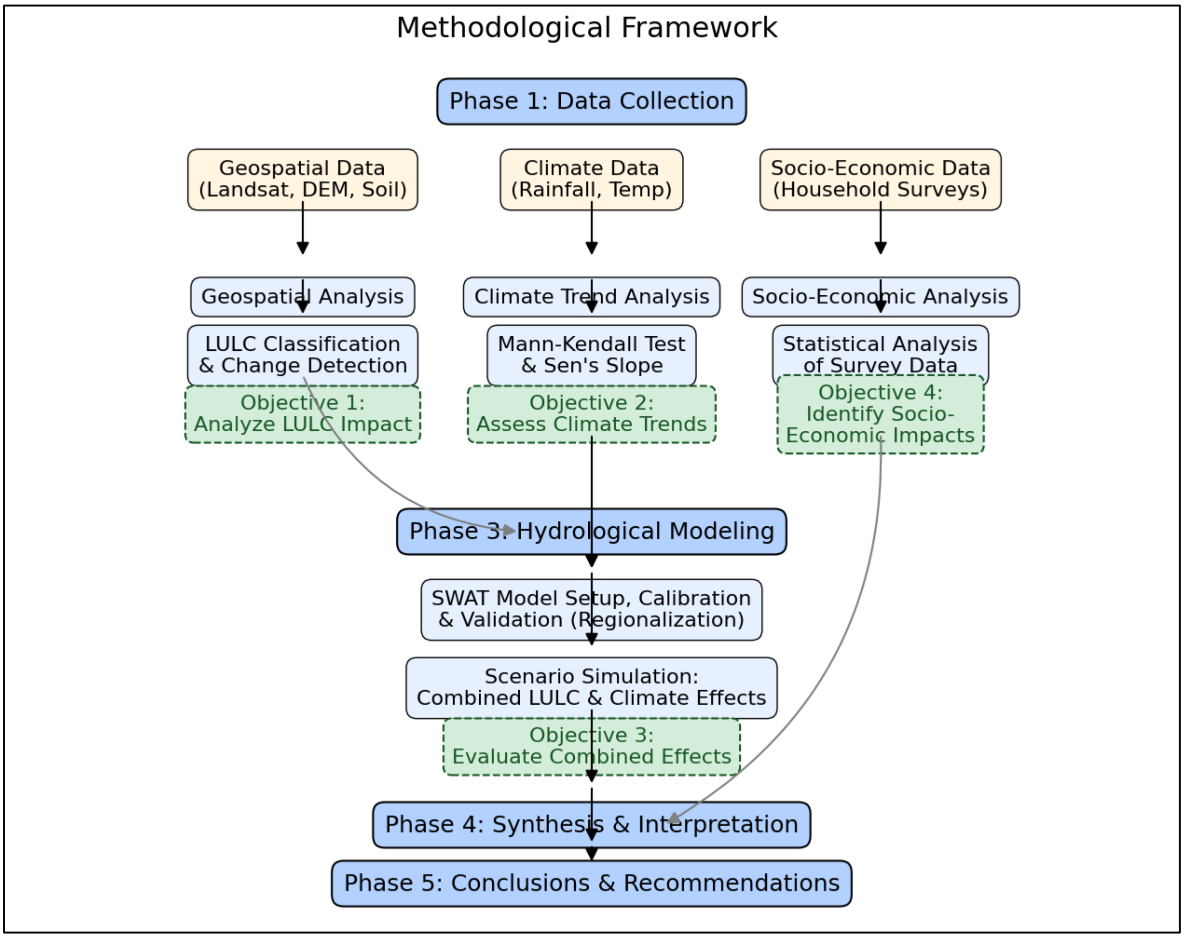


Figure 3.9: Flowchart of the research methodology

CHAPTER FOUR

RESULT AND DISCUSSION

4.1. Analysis of Historical Land Use and Land Cover (LULC) Change and its Impact

4.1.1. LULC Transformation in the Hargeisa Watershed (2000-2024)

The analysis of satellite imagery from 2000 and 2024 reveals a profound transformation of the landscape within the Hargeisa watershed. Over the past 24 years, the region has shifted from a predominantly natural, grassland-dominated environment to one heavily influenced by anthropogenic activity, most notably urban expansion. The specific quantitative changes in the area and proportional coverage of each major land use class are presented in Table 4.1.

Table 4.1: Land Use/Land Cover (LULC) Change in Hargeisa watershed 2000-2024

Land Use Category	Area (2000) km^2)	Percentage (2000)	Area (2024) km^2)	Percentage (2024)	Change in Area.km^2)	Percentage Change in Area	Change in Overall Percentage Points
Bare Land	50	5%	115	8%	+65	+130%	+2
Dense Vegetation	75	6%	160	13%	+85	+113.3%	+6
Grassland	830	65%	385	31%	-445	-53.60%	-35
Seasonal River	170	15%	70	6%	-100	-58.80%	-10
Urban Area	130	9%	525	42%	+415	+377.3%	+33
Total	1255	100%	1255	100%			

In the baseline year of 2000, the watershed was characterized by a predominantly natural landscape, as visually represented in Figure 4.1. As shown in Table 4.1, grasslands were the dominant land cover, extending over 830 km² (65% of the total area). Combined with seasonal rivers, natural land covers accounted for 80% of the watershed, while urban areas occupied a relatively small footprint of 110 km² (9%).

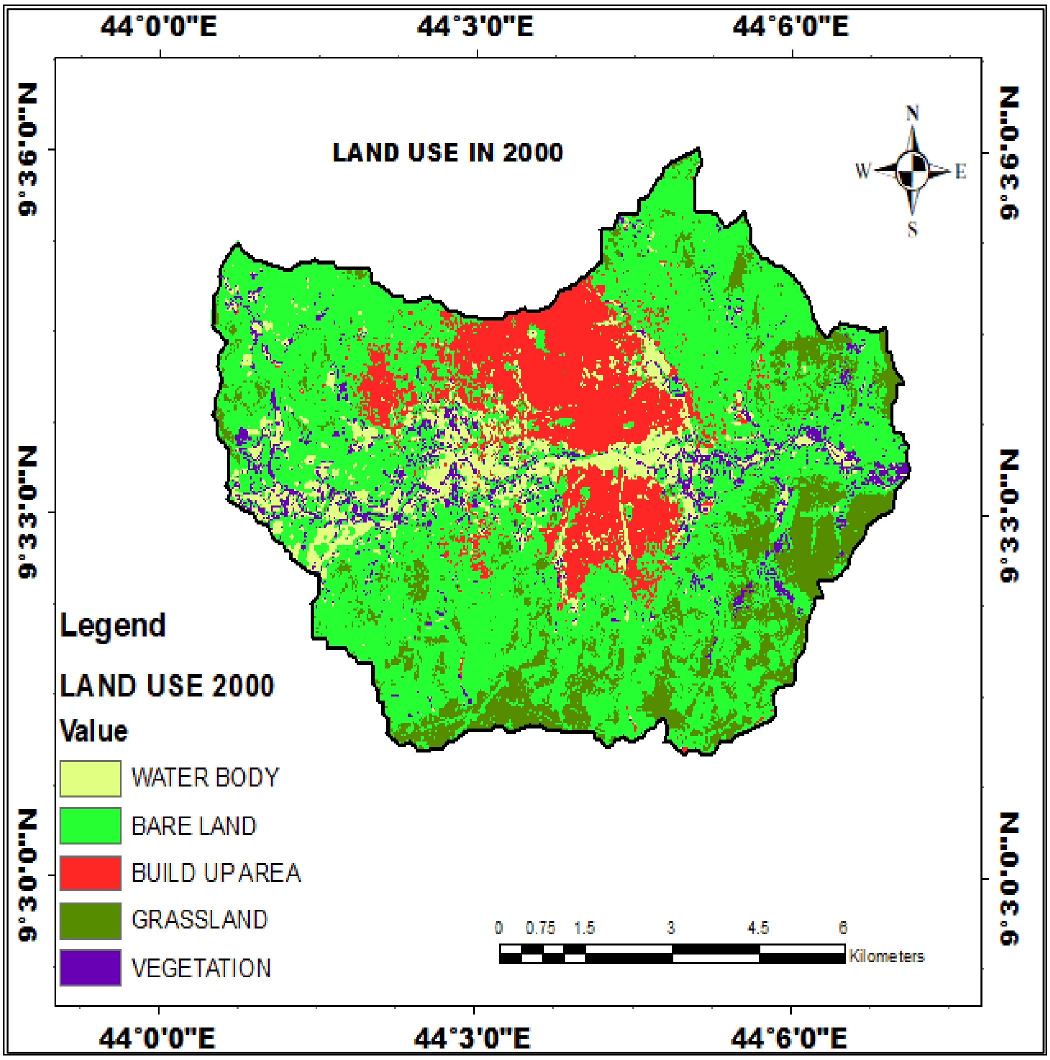


Figure 4.1: Land Use and Land Cover Map 2000

By 2024, this composition had been dramatically altered, a change clearly visible in Figure 4.2. Urban areas had become the single largest land use, expanding to cover 525 km² (42% of the watershed). This transformation came primarily at the expense of grasslands, which were reduced by more than half to just 385 km². This fundamental shift from a natural, permeable landscape to a heavily modified and impervious one has significant implications for the region's hydrology.

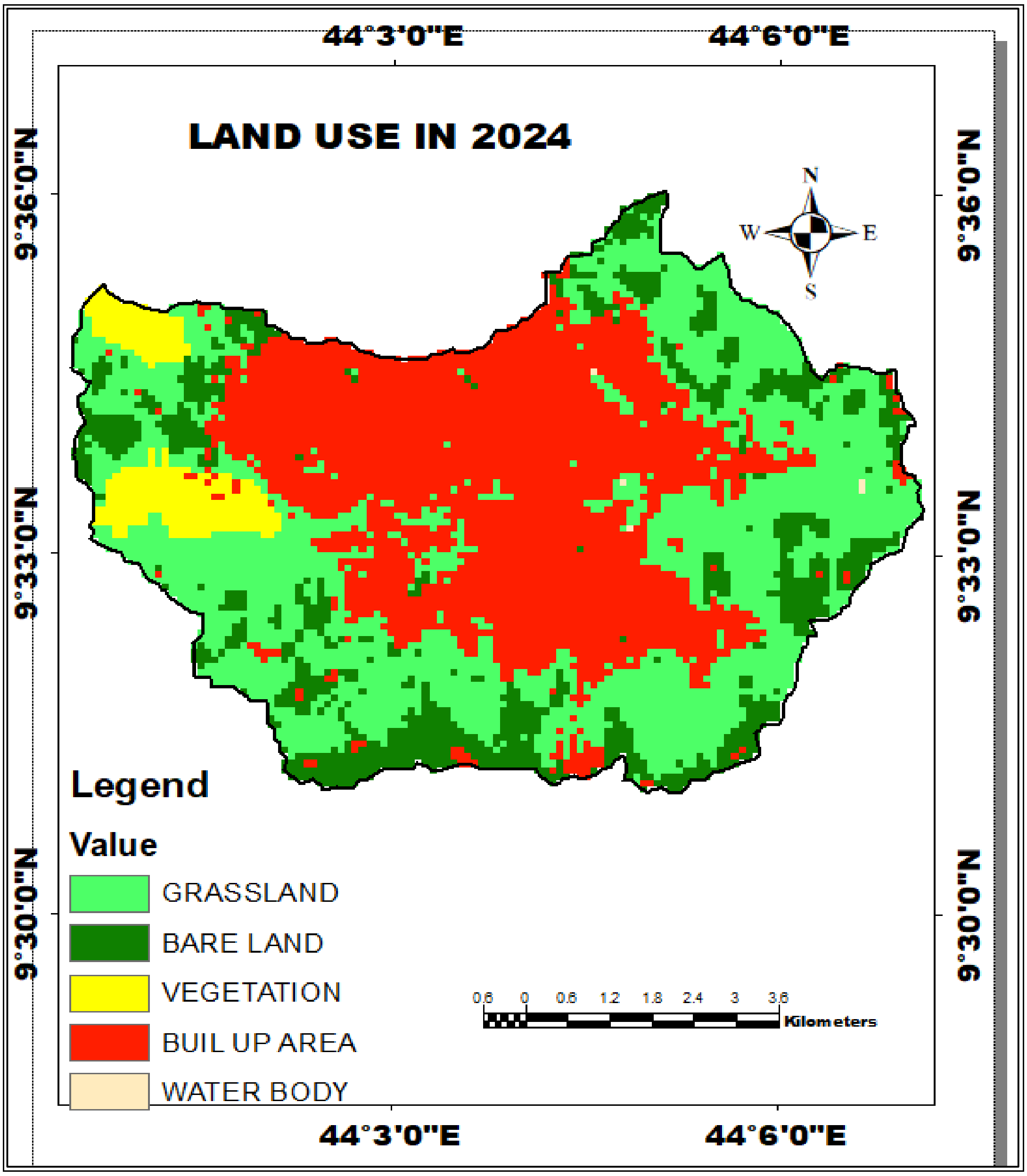


Figure 4.2: Land Use and Land Cover Map 2024

An outstanding, though less extensive, change was the observed increase in "Dense Vegetation" from 75 km² to 160 km². While seemingly counterintuitive in a rapidly urbanizing and semi-arid region, this finding can be justified by several local factors. This classification likely captures the expansion of irrigated agriculture and horticulture on the urban fringe, particularly the cultivation of cash crops like khat, which are intensively managed. Additionally, it may reflect the growth of invasive, drought-resistant species such as Prosopis juliflora along watercourses and disturbed lands, as well as an increase in managed green spaces (e.g., gardens) within more affluent residential areas.

The overall land use transformation is summarized visually in Figure 4.3, which compares the proportional distribution and absolute area of each land cover class between the two years, and quantifies the percentage change for each.

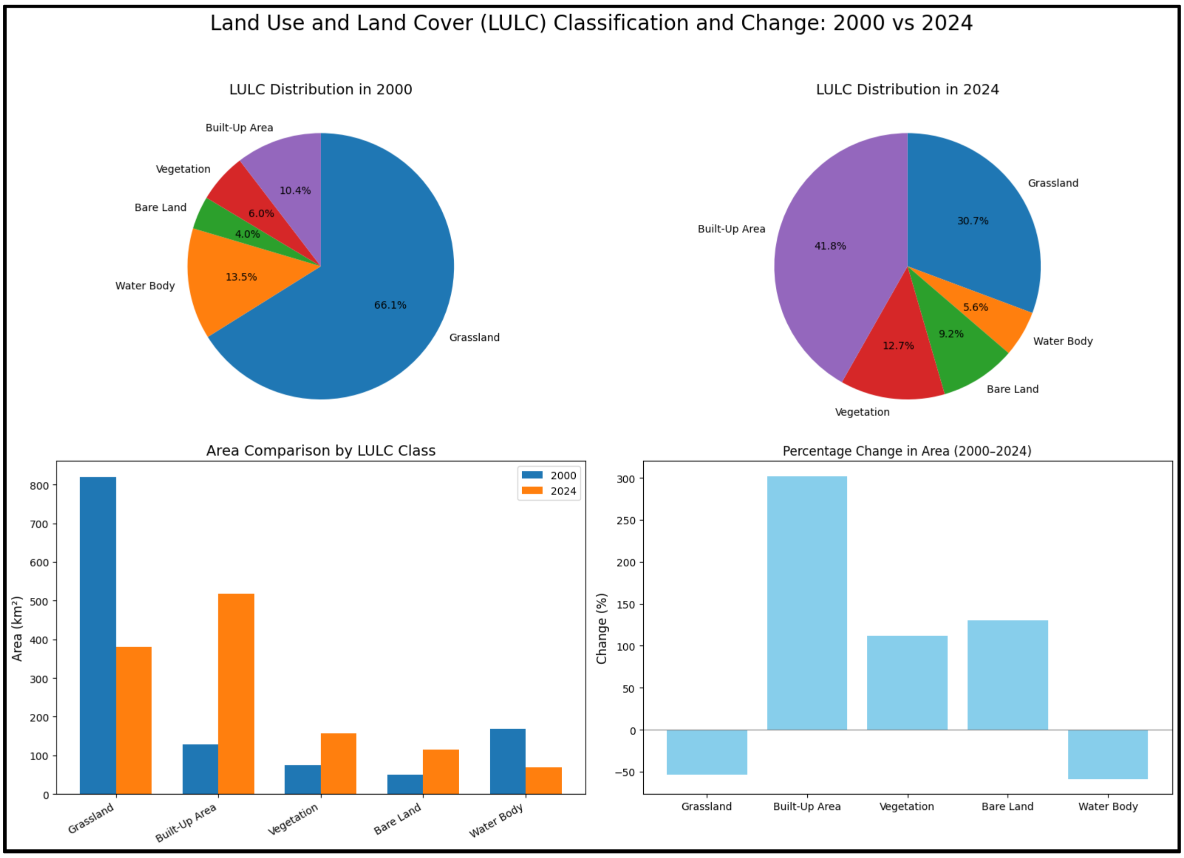


Figure 4.3: A Comparison of LULC Classification

The LULC analysis confirms the central hypothesis that rapid, uncontrolled urbanization is the primary driver of landscape change in the Hargeisa watershed. This essential shift from a permeable, natural landscape to a predominantly impervious, urban one has profound implications for local hydrology. The loss of over half of the watershed's grasslands, which act as a natural "sponge" by slowing runoff and promoting water infiltration, critically impairs the basin's ability to absorb and store rainwater

The pattern of rapid urbanization at the expense of natural land cover is a well-documented phenomenon in developing regions. In relation to previous studies, these findings are consistent with research in other semi-arid African cities, such as Addis Ababa, where (Kenea et al., 2021) found that similar rates of urban sprawl significantly altered local hydrological regimes. The observed changes in Hargeisa confirm that the city is following a developmental trajectory that, without intervention, systematically degrades the natural hydrological functions of the surrounding landscape.

4.1.2. Direct Impacts of LULC Change on Soil and Water Resources

The significant changes in land cover detailed above have direct and measurable impacts on the basin's soil and water resources. The transformation from a landscape dominated by natural grassland to one characterized by urban and bare surfaces fundamentally alters hydrological processes, primarily by accelerating soil erosion and degrading water quality.

4.1.2.1 Impact on Soil Erosion

The impact on soil stability is critically evidenced by the analysis of annual sediment yield, which quantifies the eroded soil transported by runoff into the water system. As shown in Figure 4.2, the basin experiences a high and variable rate of soil loss. The extensive loss of protective grassland cover, which acts as a natural anchor for topsoil and slows down runoff, is the primary driver of this degradation. The LULC analysis identified a reduction of grassland by more than half, leaving vast areas of soil exposed.

This vulnerability is exacerbated by the concurrent expansion of built-up areas and bare land. Impervious urban surfaces (e.g., roads, rooftops) prevent water infiltration, leading to a higher volume and velocity of surface runoff. This concentrated, high-energy flow has a greater capacity to detach and transport soil particles. The sediment yield data, with its notable peaks corresponding to years with intense rainfall, provides strong evidence that these land use changes have created a system highly susceptible to accelerated erosion, leading to land degradation and increased turbidity in local water bodies.

Notably, the trend of increasing sediment yield seen in Figure 4.2, particularly in the last decade, coincides with the period of the most rapid urbanization and grassland loss identified in the land use analysis.

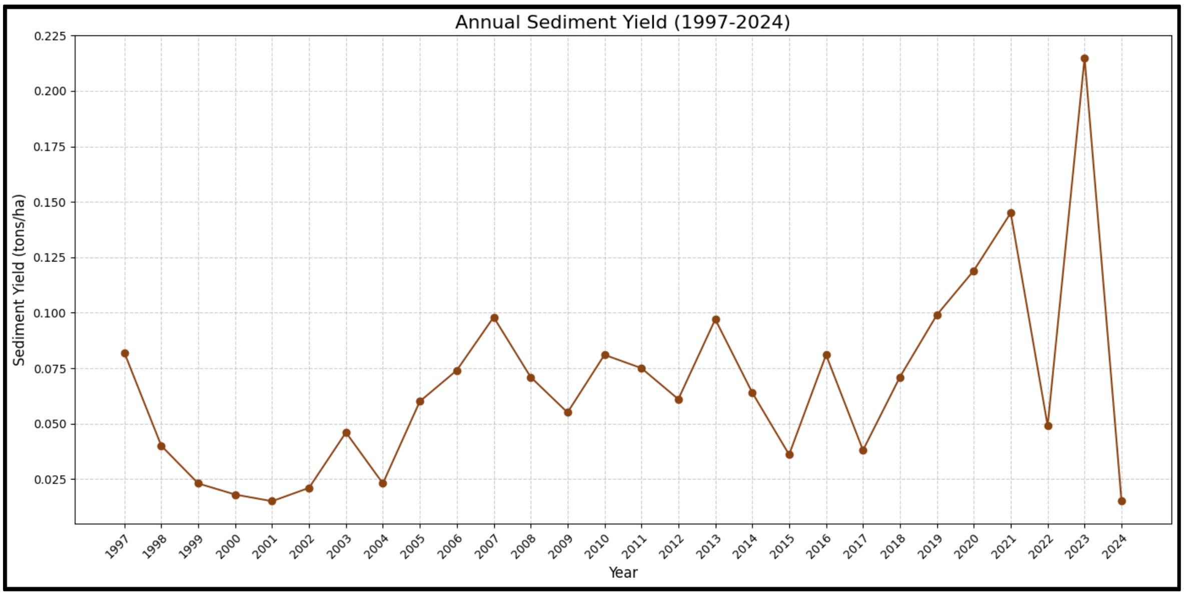


Figure 4.4: Annual Sediment Yield in (1991-2024)

4.1.2.2 Impact on Water Quality

The hydrological model was also used to assess the impact of land use change on water quality, specifically focusing on nitrate (NO_3) concentrations in surface runoff, a key indicator of pollution from anthropogenic sources. The simulation results, presented in Figure 4.5, show a persistent presence of nitrates in the watershed's surface runoff throughout the 1997–2024 period.

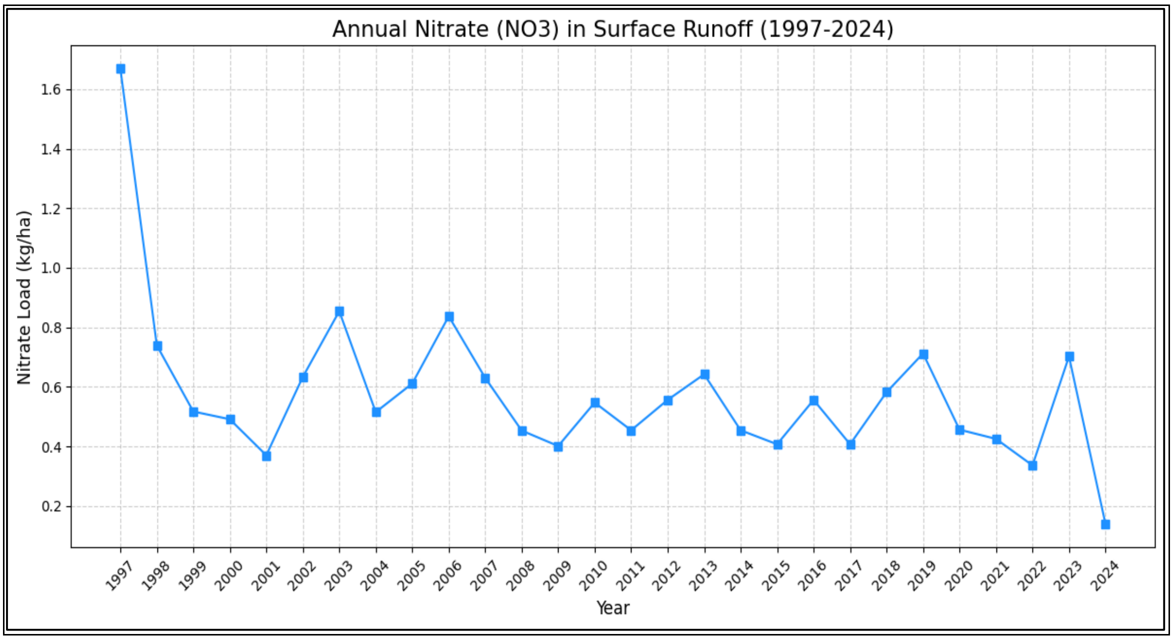


Figure 4.5: Annual Nitrate (NO3) in Surface Runoff (1997-2024)

The primary driver for this pollution is the exponential growth of urban areas. Rapid and often unplanned urbanization is typically associated with increased nutrient loads from sources such as inadequate sanitation infrastructure and domestic wastewater. As rainfall washes over these impervious urban surfaces, it efficiently collects and transports these pollutants into local waterways. While the annual nitrate load is variable and influenced by rainfall patterns, the consistent detection in the model confirms that urban runoff is a significant pathway for contaminants into the watershed.

To contextualize these findings, the results can be compared with established health standards.

The World Health Organization (WHO) has set a guideline value of 50 mg/L for nitrate in drinking water. While the model calculates the total load (in kg/ha), the persistent presence of nitrates in the runoff signals a clear risk of contamination for any downstream surface water or shallow groundwater sources used for drinking. This finding is consistent with research in other urbanizing semi-arid regions, which has repeatedly shown a strong correlation between increased impervious surfaces and the degradation of surface water quality due to nutrient runoff (Marchane et al., 2017). Therefore, the model results strongly indicate that the urbanization in Hargeisa is not only altering water quantity but is also posing a significant and growing risk to its quality.

4.2: Assessment of Climate Parameter Trends

4.2.1. Assessment of Regional Climate Patterns

An assessment of the climatic patterns in the Hargeisa basin was conducted through an analysis of annual precipitation data from 1997 to 2024. The results, presented in Figure 4.11, indicate that the regional climate is defined by significant inter-annual variability. While the long-term mean annual precipitation was calculated at 381.6 mm, this figure masks the pronounced oscillations between pluvial and arid periods that characterize the dataset. This high degree of fluctuation, rather than the statistical average, represents the principal driver of the basin's hydrological response and dictates overall water availability. The precipitation record reveals multiple years of significant rainfall deficit, indicative of hydrological drought conditions, juxtaposed with years of exceptionally high rainfall, which create conditions conducive to flash flooding.

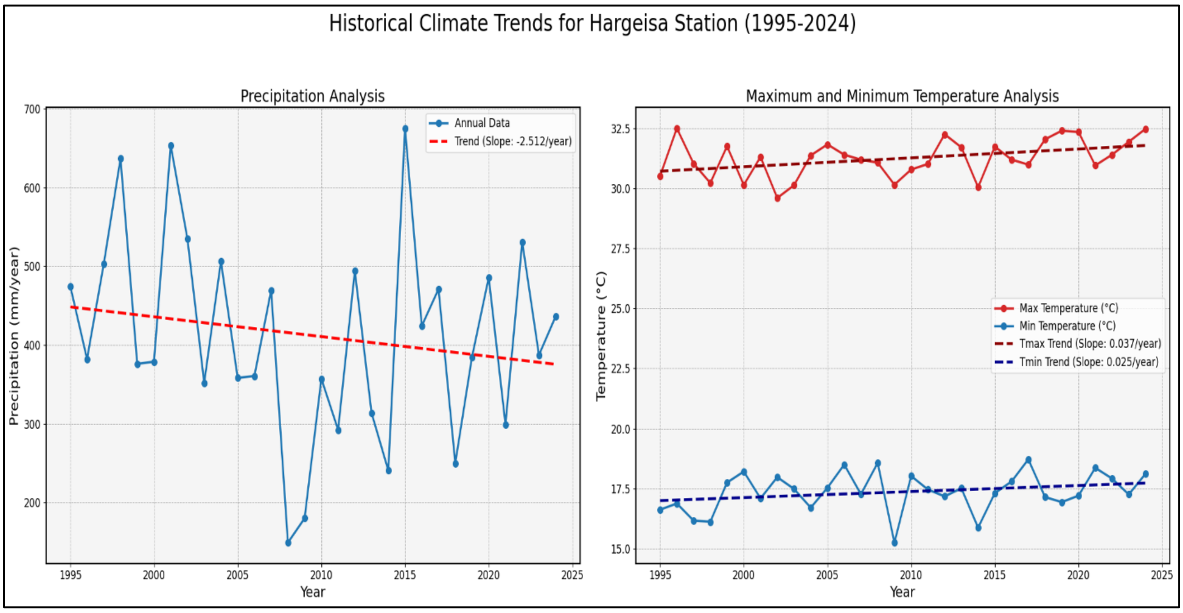


Figure 3.6: Historical Climate Trends for the Hargeisa stations

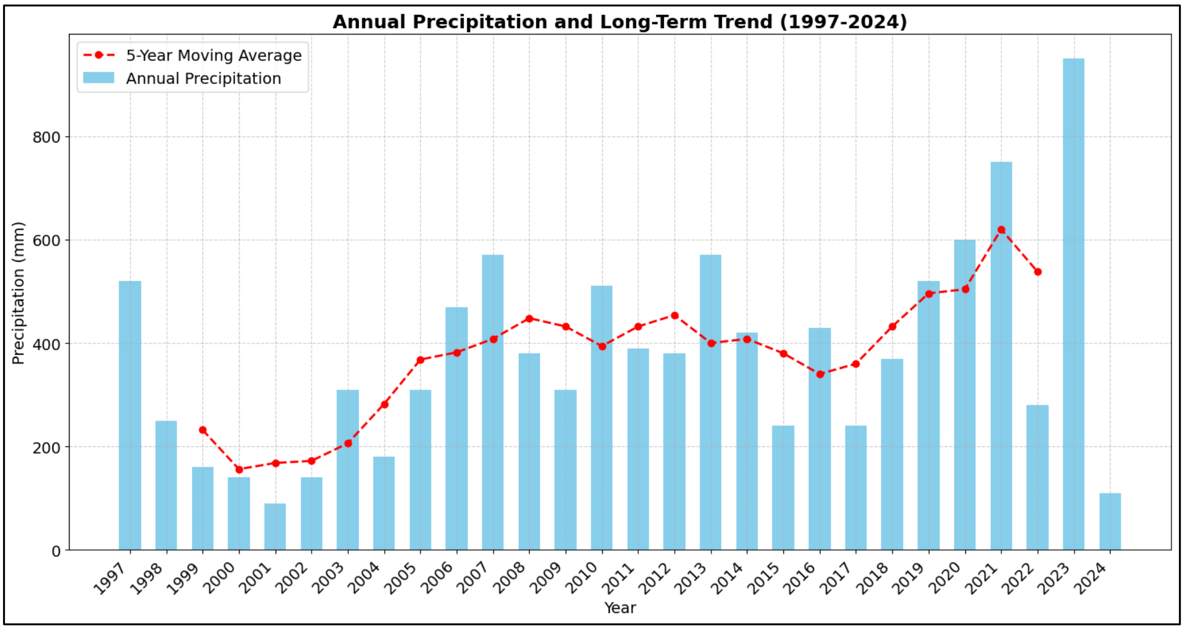


Figure 4.6: Annual Precipitation in (1997-2024)

In addition to precipitation, temperature trends were analyzed for the same 1997-2024 period to provide a more complete assessment of changing climate patterns. As illustrated in Figure 4.12, the Hargeisa basin has experienced a discernible warming trend over the past few decades. This warming has significant implications for the region's water balance. Higher temperatures increase the rate of potential evapotranspiration, meaning more of the scarce and variable rainfall is lost to the atmosphere. This temperature-driven increase in water loss exacerbates the challenges posed by inconsistent precipitation, further intensifying water stress.

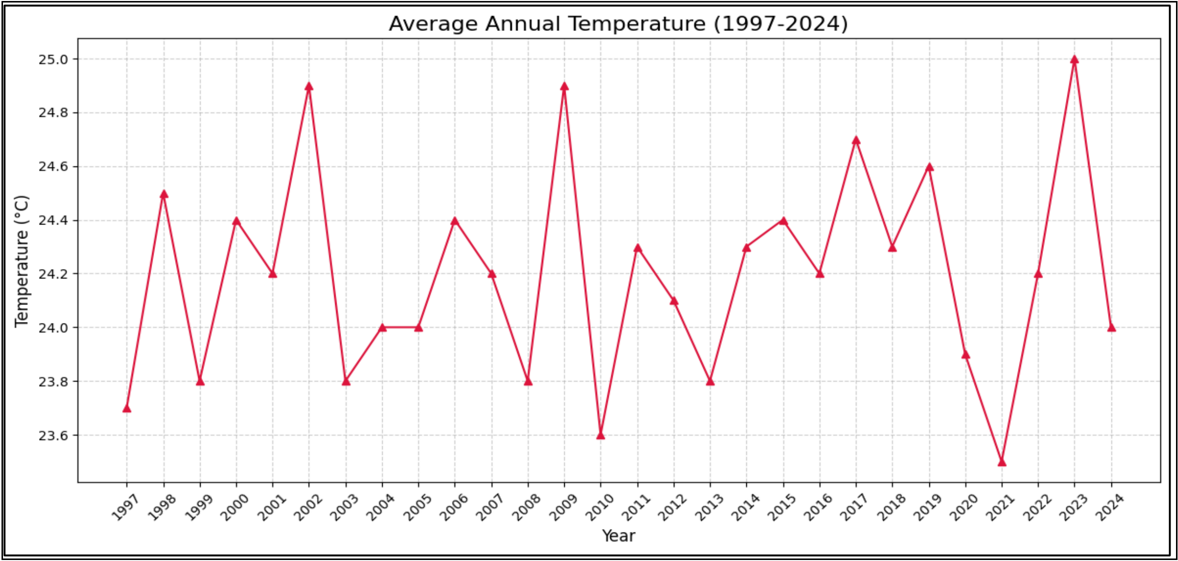


Figure 4.7: Average Annual Temperature in (1997-2024)

The interpretation of these climate trends reveals a "double-negative" effect on Hargeisa's water resources. On one hand, the high variability of rainfall means the water supply is inherently unreliable. On the other, the consistent warming trend increases the atmospheric demand for water through higher rates of evapotranspiration. This means that even when rainfall is average, more of it is lost to the atmosphere before it can recharge the aquifer.

This finding of volatile precipitation and rising temperatures is a clear local manifestation of the global patterns identified by the Intergovernmental Panel on Climate Change (IPCC) Sixth Assessment Report (AR6). The IPCC has identified arid and semi-arid regions like the Horn of Africa as "hotspots" for climate impacts. The observed historical patterns in Hargeisa are consistent with these large-scale projections and create a baseline of high water stress, making the watershed exceptionally vulnerable to the additional pressures imposed by land use change.

4.3. Combined Effects of LULC and Climate on Water Resources

4.3.1 Surface Water Availability

To ascertain the implications of these climate patterns for surface water, an analysis was conducted to correlate annual precipitation with water yield. Water yield, representing the total streamflow from the basin, is the effective quantity of surface water available for use. A comparative analysis of precipitation (Figure 4.11) and water yield (Figure 4.13) reveals a strong positive correlation, confirming that the basin's surface hydrology is predominantly rainfall-driven. The pronounced covariance between precipitation and streamflow results in a highly unreliable surface water regime, characterized by episodic periods of surplus and deficit. This inherent instability has significant ramifications for water resource management, as the frequent and severe reductions in flow render the surface water system an insecure resource for sustained use.

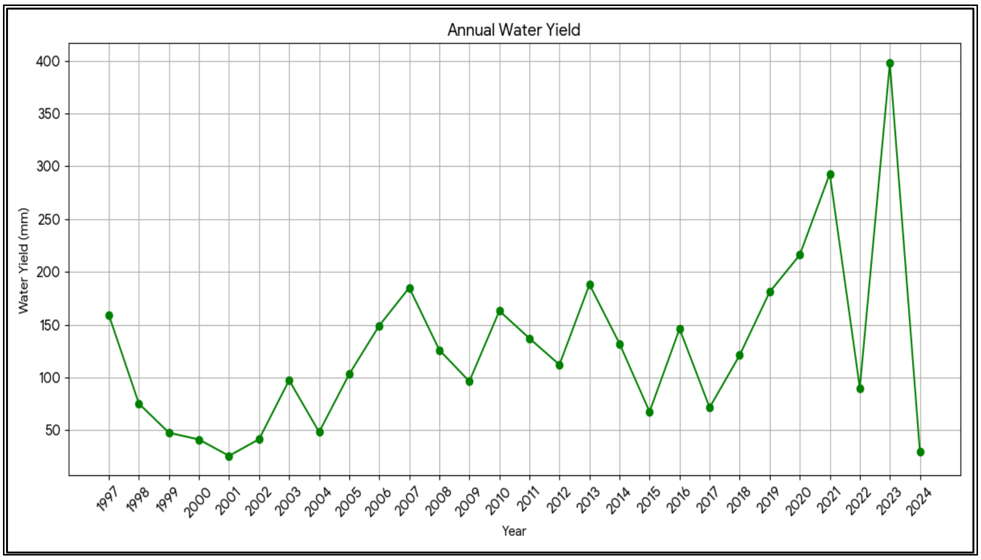


Figure 4.8: Annual Water Yield in (1997- 2024)

4.3.2 Groundwater Availability

The analysis of groundwater percolation, presented in Figure 4.14, reveals that aquifer recharge in the Hargeisa basin is not a consistent annual process, but rather a minimal and highly episodic phenomenon. The graph displays three distinct periods that are directly explained by the annual precipitation patterns shown previously in Figure 4.11.

First, in the period before 2006, the annual percolation rate was consistently zero, despite some variability in rainfall. This indicates the presence of a significant soil moisture threshold. During these years, annual precipitation was insufficient to overcome the soil's water-holding capacity and the high rates of evapotranspiration. Consequently, all rainfall was retained in the upper soil layers and subsequently lost to the atmosphere, with no surplus water available for deep percolation.

Second, from 2006 to 2020, the graph shows intermittent, moderate peaks of recharge. These peaks correspond to years with above-average rainfall that was sufficient to saturate the soil profile, allowing a small amount of water to percolate downwards. The downward trends between these peaks represent drier years where rainfall once again fell below the required threshold for recharge.

Finally, the exceptionally large spikes in 2021 and 2023 are a direct result of the extreme rainfall events recorded in those years. The volume of precipitation during these events completely overwhelmed the soil's capacity to store water. Once the soil was saturated, a large portion of the subsequent rainfall became effective recharge, resulting in the observed massive peaks. This pattern confirms that significant groundwater replenishment in the Hargeisa basin is a rare event, entirely dependent on years with exceptionally high precipitation.

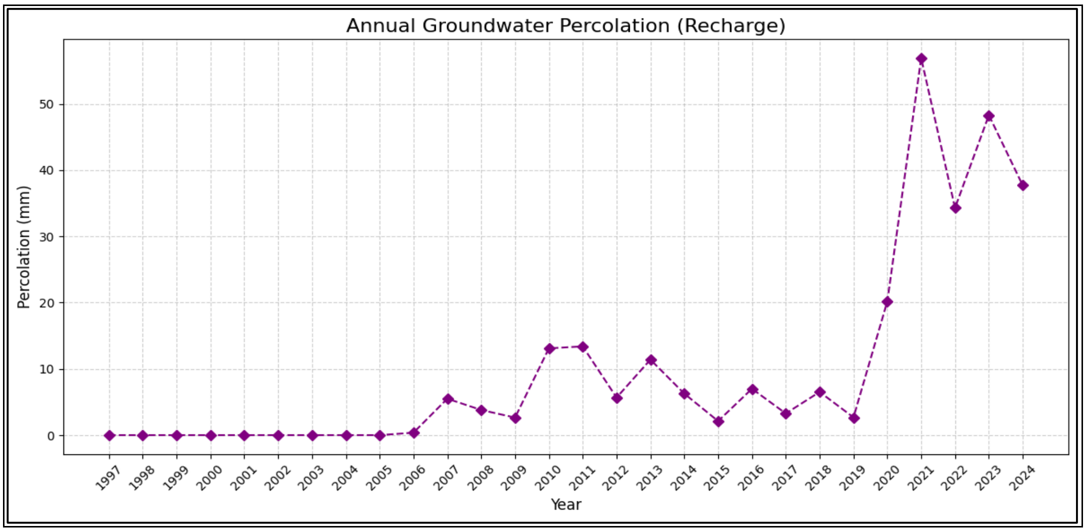


Figure 4.9: Annual Groundwater Percolation (1997-2024)

Table 4.2: Water Balance Component

Water Balance Component	Average Annual Value (mm)	Percentage of Precipitation
Precipitation (precip)	381.6	100%
Evapotranspiration (et)	243.7	~64%
Water Yield (wateryld)	126.4	~33%
Groundwater Percolation (perc)	10	~2.6%

4.3.3. Hydrological Model Development via Regionalization

4.3.3.1 Sensitivity Analysis for the Gauged Watershed.

The sensitivity analysis identified a clear ladder of parameters controlling the model's simulation of streamflow. Out of the thirteen parameters tested, those related to groundwater, runoff generation, and soil characteristics were found to be the most influential. The relative sensitivity of all tested parameters is visualized in Figure 4.6.

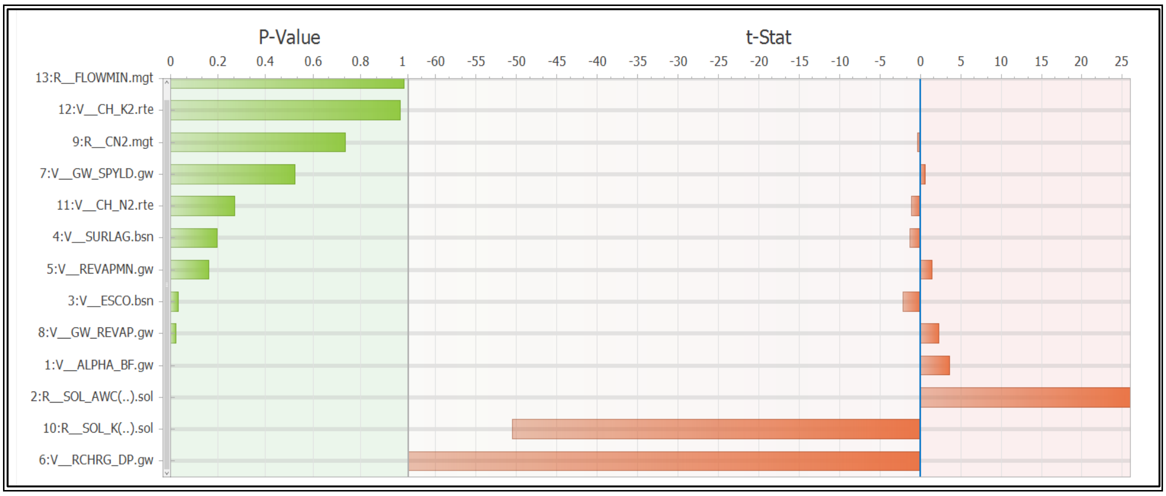


Figure 4.10: Relative sensitivity of SWAT-CUP parameters based on the absolute t-stat and p-value

The statistical results from the SWAT-CUP analysis are provided in Table 4., which ranks the parameters in order of their sensitivity. The analysis identified the SCS Curve Number (CN2.mgt) as the most dominant parameter (t-Stat = 16.59, p-value = 0.00), indicating its primary control over surface runoff generation. This was followed by key groundwater parameters such as the baseflow alpha factor (ALPHA_BF.gw) and groundwater delay (GW_DELAY.gw), which were also found to be highly significant. This ranking was used to guide the subsequent calibration process by focusing adjustments on this set of highly influential parameters.

Table 4.3: Most Sensitive Hydrological Parameters identified for the gauge watershed

Rank	Parameter Name	t-Stat	p-Value
1	CN2.mgt	16.59	0
2	ALPHA_BF.gw	-4.43	0
3	ESCO.hru	4.14	0
4	GW_DELAY.gw	3.23	0
5	SOL_AWC().sol	2.92	0.01
6	CH_N2.rte	-2.53	0.01
7	GWQMN.gw	-1.78	0.08
8	REVAPMN.gw	1.15	0.25
9	SURLAG.bsn	0.61	0.54
10	CH_K2.rte	0.52	0.6
11	SOL_K().sol	-0.36	0.72
12	SLSUBBSN.hru	-0.18	0.86

13	GW_REVAP.gw	0.04	0.97

4.3.3.2. Calibration of the gauged Watershed

Using the sensitive parameters identified, the SWAT model for the donor watershed was calibrated against observed monthly streamflow data. The objective of calibration is to adjust the parameter values until the model's simulated output closely matches the measured real-world data. The performance of the calibration was assessed using multiple statistical metrics, as shown in Table 4.2.

The calibration achieved a Nash-Sutcliffe efficiency (NS) of 0.52 and a coefficient of determination (R^2) of 0.55. According to established guidelines, these results indicate a "satisfactory" model performance, particularly for a data-scarce region. The Kling-Gupta Efficiency (KGE) of 0.60 further supports a good overall model fit. The Percent BIAS (PBIAS) of 14.5% reveals a moderate but acceptable tendency of the model to underestimate streamflow, a finding corroborated by the lower mean simulated flow (0.58 m^3/s) compared to the mean observed flow (0.68 m^3/s).

Table 4.4: Statistical Performance for the calibration

Calibration (1992-1997)	Value
R^2	0.55
NSE	0.52
PBIAS (%)	14.5
KGE	0.60

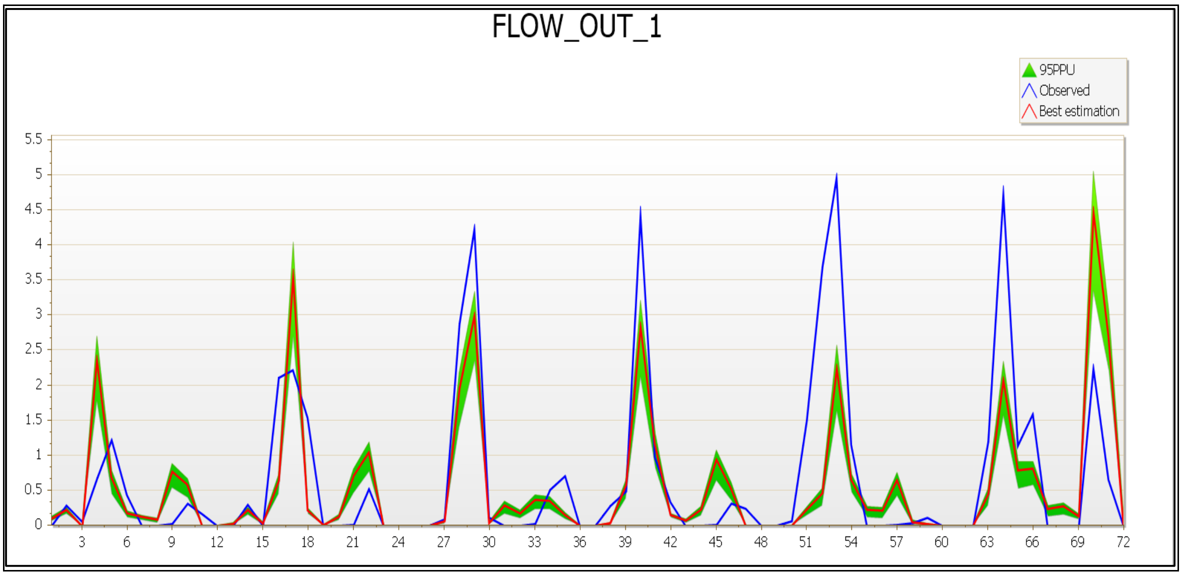


Figure 4.11: Comparison of observed and simulated

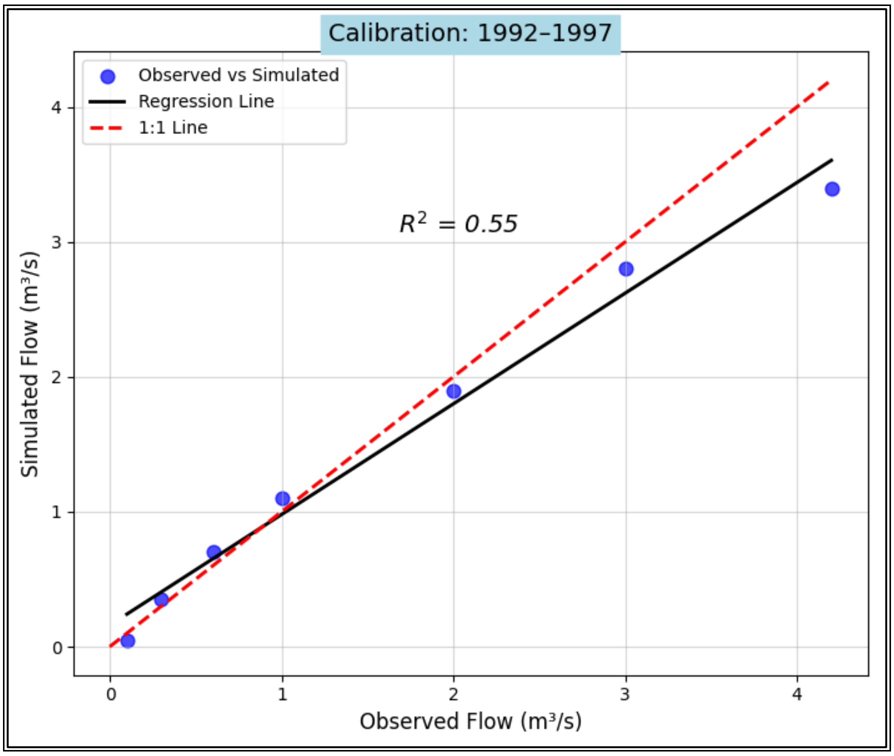


Figure 4.12: Scatter plot of observed versus simulated

4.3.3.3. Validation of the gauged Watershed

Following calibration, the model was validated against an independent set of observed streamflow data to confirm its robustness and predictive capability. No further adjustments were made to the calibrated parameters during this process. The statistical performance for the validation period is shown in Table 4.8.

The validation results confirm the model's reliability. The performance metrics remained satisfactory, with an NS of 0.50, R^2 of 0.53, and KGE of 0.57. The consistency of these values between the calibration and validation periods indicates that the model is robust and not over-fitted to a specific dataset. The PBIAS increased slightly to 16.2%, confirming that the model's systematic underestimation of streamflow is a consistent characteristic. This successful validation provides confidence in the reliability of the calibrated parameter set for regionalization.

Table 4.5: Statistical Performance for the validation

Validation (1998-2000)	Value
R^2	0.53
NSE	0.5
PBIAS (%)	16.2
KGE	0.57

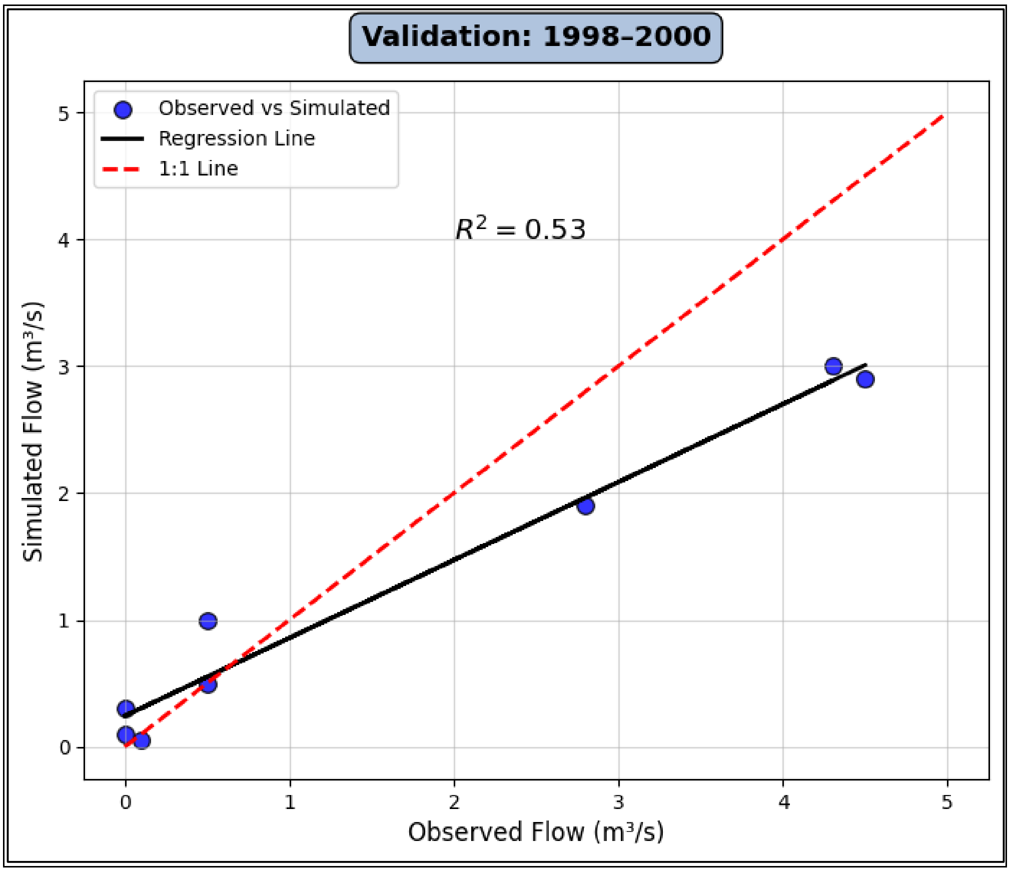


Figure 4.13: Scatter plot of observed versus simulated in validation

4.3.4. Uncertainty analysis

The uncertainty analysis reveals limitations. The p-factor of 0.21 indicates that only 21% of the observed data points were bracketed by the 95% Prediction Uncertainty (95PPU) band. This, combined with a low r-factor of 0.20 (indicating a narrow uncertainty band), suggests that the model is overly confident in its predictions and does not fully capture the range of watershed variability. This is a common challenge in data-scarce regions

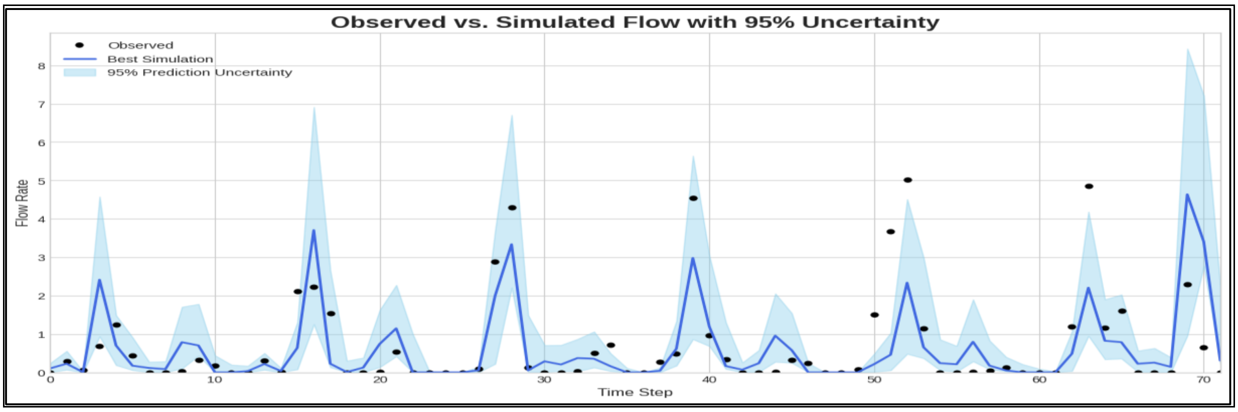


Figure 4.14: Model uncertainty analysis for the validation period

4.3.5. Regionalization: Transfer of Optimized Parameters

Following the successful calibration and validation of the donor watershed model, the final set of optimized values for the sensitive parameters were obtained. This optimized parameter set represents the most accurate hydrological characterization for the region. In the final and most critical step of the regionalization process, these values were directly transferred to the SWAT model for the ungauged Hargeisa watershed. This transfer provides the scientific foundation for all subsequent simulations, ensuring that the Hargeisa model is based on a robust, calibrated understanding of the local and regional hydrology.

Table 4.6: Final Optimized SWAT Parameter

Parameter Name	Final Fitted Value
V__ALPHA_BF.gw	0.96365
R__SOL_AWC(...).sol	0.631275
V__ESCO.bsn	0.97943
V__SURLAG.bsn	17.890499
V__REVAPMN.gw	25.459
V__RCHRG_DP.gw	0.000435
V__GW_SPYLD.gw	0.057275
V__GW_REVAP.gw	0.13001
R__CN2.mgt	-1.0997
R__SOL_K(.).sol	-0.653775
V__CH_N2.rte	0.07327
V__CH_K2.rte	75.757004
R__FLOWMIN.mgt	23.4855

The hydrological model serves to quantify the combined impact of the pressures identified in the previous sections. The key interpretation is that urbanization has created a less resilient watershed. The increase in water yield (runoff) is not a benefit; rather, it represents a shift from beneficial infiltration to problematic, rapid runoff, increasing the risk of flash floods and losing precious water that could have replenished aquifers.

The most alarming finding is the extremely low rate of groundwater percolation, at just 2.6% of annual rainfall. This provides a direct, scientific explanation for the widespread reports of water shortages and declining well levels in Hargeisa. The landscape's ability to capture and store water underground during rare wet years has been significantly impaired by the loss of permeable grasslands. The local implication is profound: the city's primary water source, the groundwater aquifer, is being "starved" of recharge by the very urban expansion it is meant to support. This unsustainable dynamic, where development actively undermines the resource base it depends on, is at the heart of Hargeisa's water crisis.

4.4. Socio-Economic Impacts of Water Scarcity

4.4.1 Impact on Agricultural Livelihoods

The stability of agricultural production is a primary indicator of economic well-being in the Hargeisa basin. An analysis of the annual crop yield from 1997 to 2024 was conducted to assess the impact of water scarcity on this critical livelihood. The results, presented in Figure 4.15, reveal a volatile pattern of agricultural output. The frequent collapses in crop yield, such as those observed between 1999-2001 and in 2019, represent a significant and persistent threat to the livelihoods of farmers and the broader community, leading to unstable income and chronic food insecurity. This instability is a direct consequence of the erratic rainfall and unreliable water supply detailed in the preceding sections.

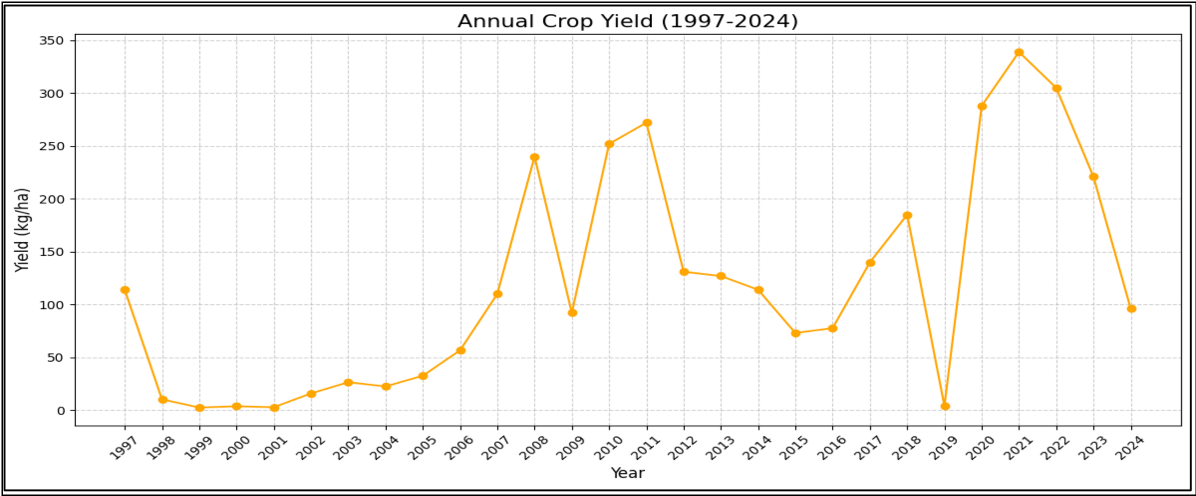


Figure 4.15: Annual Crop Yield in (1997- 2024)

4.4.2 Profile of Survey Respondents

To understand the direct human dimension of these impacts, a survey of 134 residents across Hargeisa's five major districts was conducted. The demographic profile of the respondents provides context for the subsequent findings. The survey sample included a relatively balanced gender distribution, with 56% male and 44% female participants. The age distribution was skewed towards a younger demographic, with 50% of respondents aged between 15-30. The majority of households were described as nuclear families (82%). The respondents were evenly distributed across the five major districts of Hargeisa, ensuring a representative geographic sample of the urban population.

Table 4.7. Summary of the respondent profile

Gender	No of respondents	Percentage
Male	75	56%
Female	59	44%
Status	**No of respondents**	**Percentage**
Single	83	62%
Married	39	29%
Divorced	12	9%
Age	**No of respondents**	**Percentage**
15-30	67	50%
31-45	39	29%
46-60	16	12%
>60	12	9%
Type	**No of respondents**	**Percentage**
Nuclear family	110	82%
Joint family	24	18%
District	**No of respondents**	**Percentage**
Gacan-Libaax	30	22%
26 June	21	16%
Ibrahim Koodbuur	28	21%
Mohamoud Haibe	27	20%
Ahmed-Dhagax	28	21%

4.4.3 Community Perceptions and Experiences of Water Scarcity

The survey results for household water sources reveal a city with a fragmented and inequitable water supply system, where a majority of the population operates outside the formal municipal network. The data shows that the most common primary source of water is not a piped connection, but rather private Water Trucks, relied upon by 41% of households. In contrast, only 30% of households are served by the Hargeisa Water Agency's (HWA) piped network, with the remainder depending on public taps (22%) or open wells (7%).

This finding provides a clear, on-the-ground validation of the institutional challenges and infrastructure deficits described in Chapter 3. The heavy reliance on a privatized, mobile water market is a direct socio-economic consequence of an HWA network that is unable to meet the demands of a rapidly growing city. This situation creates a significant disparity in water security. For the minority of residents with a household connection, water access is relatively convenient. For the majority, however, securing this fundamental resource depends on the daily availability and affordability of private sellers. This has profound implications for household finances and resilience, particularly for low-income families, and it underscores the critical gap between the city's water needs and its current supply capacity.

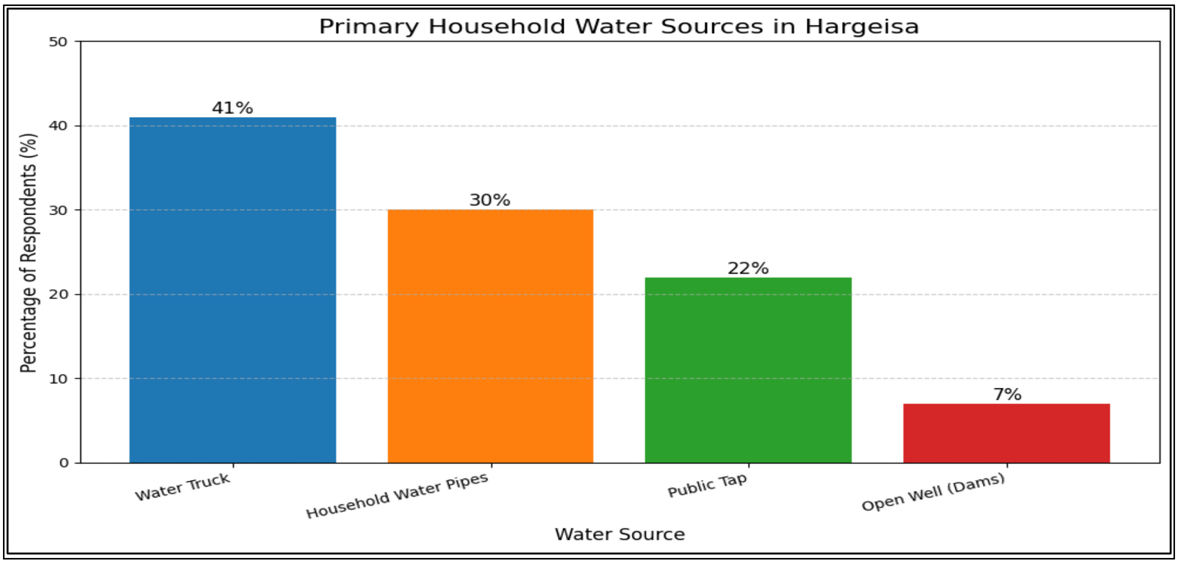


Figure 4.16: Drinking source of your house-hold

Table 4.8: Distribution of Respondents by primary water source

Source	No of respondents	Percentage
Water Truck	55	41%
Public Tap	30	22%
Open Well (Dams)	9	7%
Household Water Pipes	40	30%

4.4.3.1 Chronic Insufficiency and Infrequent Supply

A critical finding from the survey is the chronic and severe insufficiency of the water supply. As detailed in Table 4.8, a staggering 41% of respondents report receiving water less than once a week. In total, 84% of the population receives water only once every two days or less frequently.

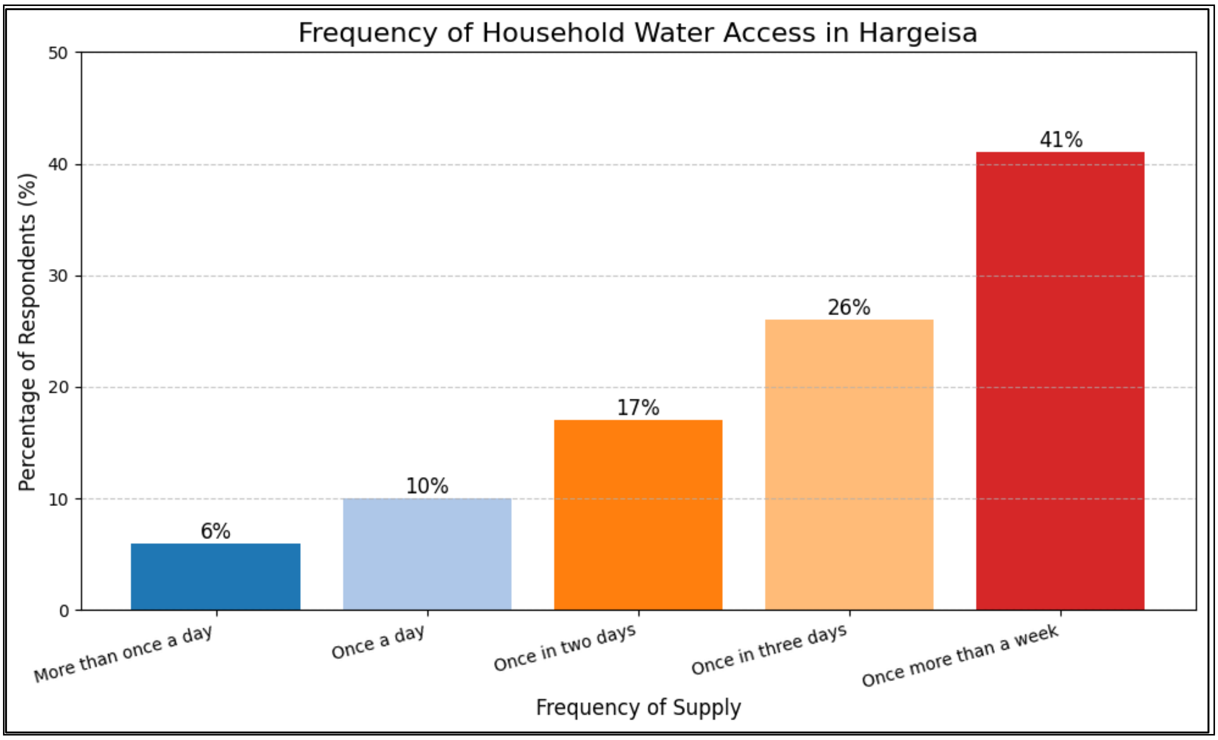


Figure 4.17: Frequency you get water

This infrequent supply is overwhelmingly considered inadequate. As shown in Figure 4.19, a decisive 75% of households stated that this frequency is not sufficient to meet their daily needs for drinking, cooking, and sanitation. This finding moves beyond the concept of scarcity as an environmental issue and defines it as a persistent, daily hardship for the vast majority of the population. Furthermore, this scarcity is exacerbated during climatic stress, with 73% of respondents confirming that their water supply is not constant during times of drought.

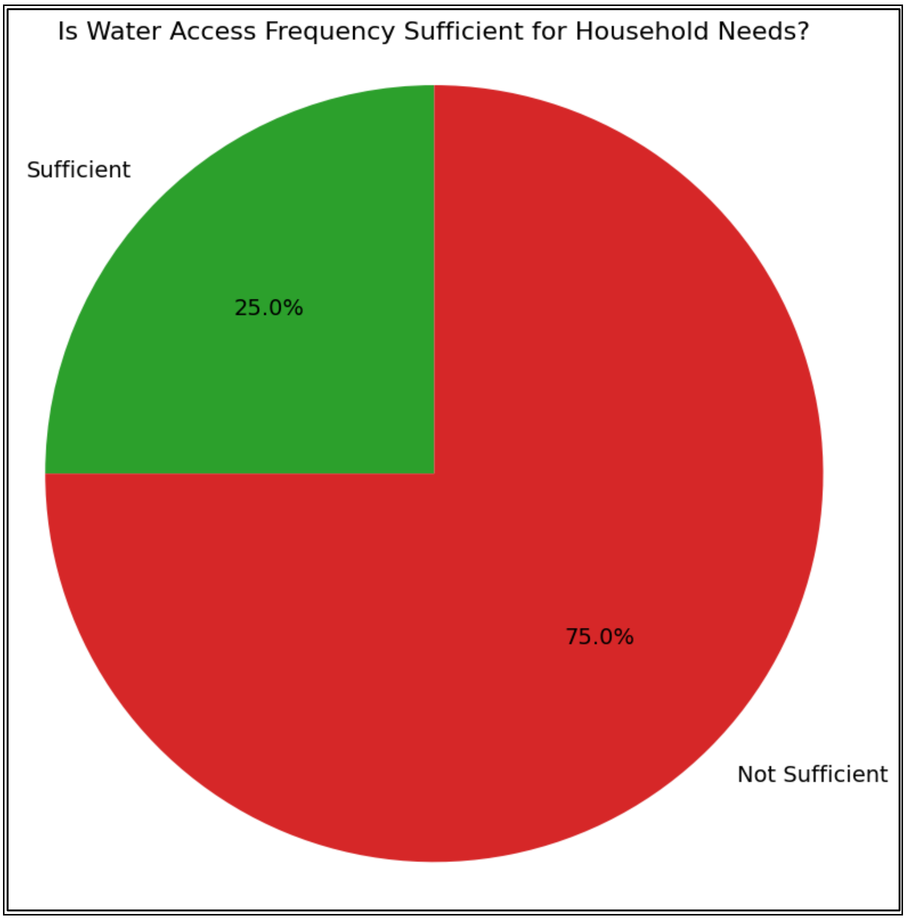


Figure 4.18: Is this frequency sufficient

Table 4.9: Respondents' Views on the Sufficiency

Response	**No of respondents**	**Percentage**
Yes	34	25%
No	100	75%

4.4.3.3 Economic and Health Burdens

The scarcity of water translates into direct economic and health burdens for the community. The economic strain is evident in the community's dissatisfaction with the cost of water. A substantial 70% of residents are not satisfied with the price of water, as shown in Figure 4.20, indicating that this essential resource constitutes a significant financial pressure on household budgets.

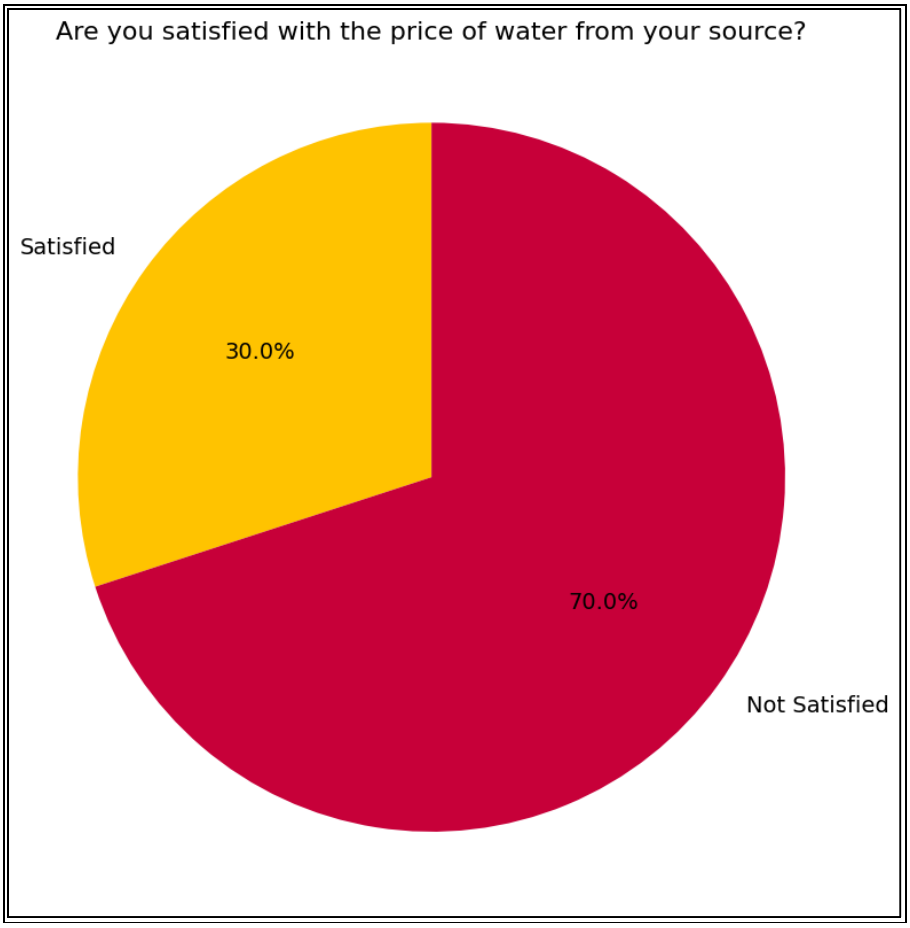


Figure 4.19: Are you satisfied with the price of water

This economic pressure is compounded by the perceived public health risks associated with water shortages. When asked about the effects of water scarcity, 52% of respondents believed it leads to a combination of hunger, poverty, sanitation issues, and the possible outbreak of diseases (*Figure 4.21*). This demonstrates a clear community understanding of the profound link between inadequate water supply and a lower quality of life, connecting the resource issue directly to fundamental concerns of well-being and survival.

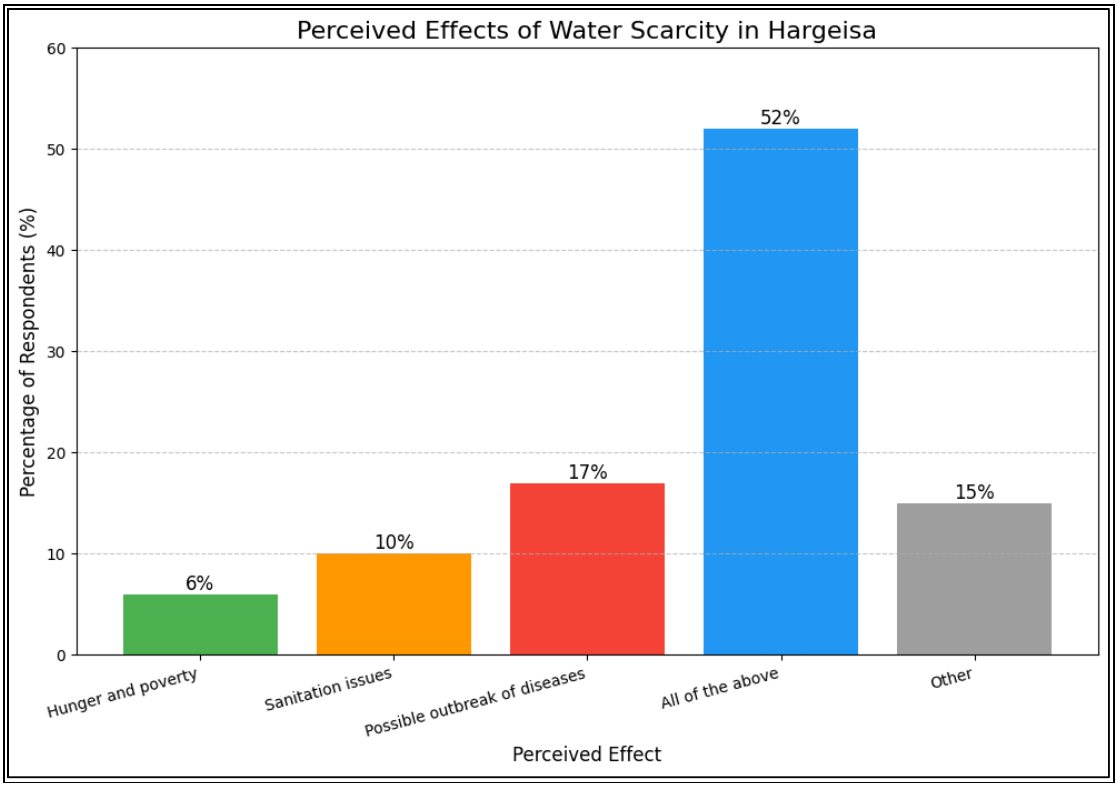


Figure 4.20: Effects of water scarcity

4.4.3.4 Community Perspective on Causes and Solutions

The survey also captured the community's perspective on the root causes of water scarcity. As detailed in table 4.12, a majority of residents (65%) attribute the water shortage primarily to increased population, while 25% point to overuse and wastage, and 10% identify climate change as the main cause. This highlights a strong community perception that demographic pressure on a limited resource is the central issue

Table 4.10: Respondents' Views on the Main cause of water scarcity

Cause	No of respondents	Percentage
Population Increased	87	65%
Climate Change	13	10%
Over-use and Wastage	34	25%

When asked about the best solutions, the community showed a clear preference for infrastructure development. A majority of 54% of respondents believe that constructing dams to capture rainwater is the most effective solution (Figure 4.23). Other preferred solutions include improving the water distribution network (20%) and lowering the price of water (15%). This indicates a strong public desire for proactive, long-term investments in water infrastructure to enhance water security.

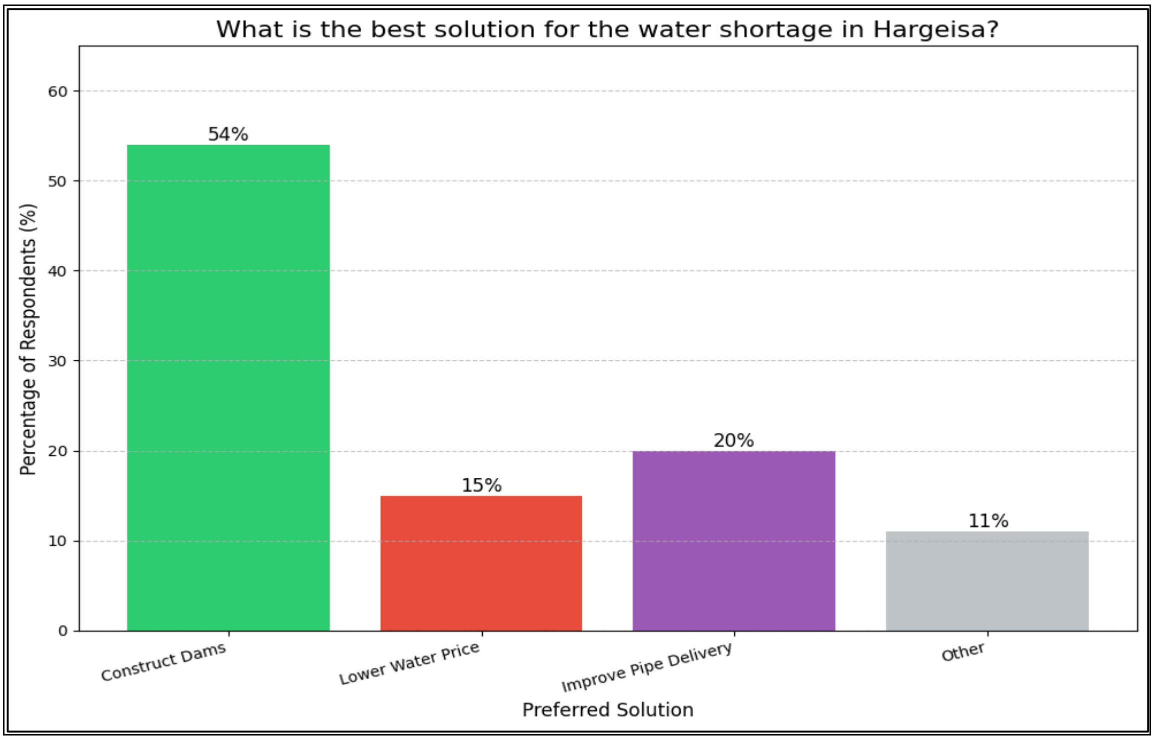


Figure 4.21: What do you think is the best solution for water shortage?

When the people of Hargeisa were asked how to solve the water crisis, their answers painted a clear picture of their daily struggles and their hopes for a more secure future. The numbers in Figure 4.23 are more than just statistics; they are a direct message from families on the front lines.

Overwhelmingly, the community's vision for a solution is bold and clear: more than half of all residents (54%) believe the answer lies in constructing dams. This is a powerful plea from people who watch the precious seasonal rains come and go, with much of the water lost as runoff. For these families, a dam represents more than just infrastructure; it represents capturing a wasted resource and building a lasting buffer against the ever-present threat of drought.

The community's other priorities reveal different facets of their daily hardship. For the 20% of residents who called for improved pipe delivery, the issue is one of fairness and dignity. They know water exists in the system, but it doesn't reach their homes, forcing them to rely on other means. Their answer reflects a deep frustration with a broken system. Meanwhile, for the 15% who prioritized a lower water price, the crisis is a heavy financial burden. Their response speaks to the difficult choices families must make every day between buying a drum of water from an expensive tanker and affording other necessities.

A primary socio-economic finding of this thesis is the deeply fragmented nature of Hargeisa's water supply system. The formal municipal infrastructure, managed by the Hargeisa Water Agency (HWA), has a critically limited reach, serving only a minority of the urban population. The survey conducted for this research found that just 30% of households are connected to the municipal piped network as their primary water source. This finding is consistent with recent independent research by (Ismail & Duale, 2023), which reported that only 31.8% of residents rely on tap water. The agreement between these two studies provides strong evidence that the formal public utility fails to meet the needs of the majority of the city’s residents.

The inadequacy of the municipal network has forced a majority of the population to seek alternatives, leading to the dominance of an informal, privatized water market. This research found that 49% of households depend on private water trucks for their daily supply, making it the single most common water source in the city. This figure is corroborated by the Ismail and Duale study, which found that an even higher 52.1% of the population relies on water tank vehicles. This heavy reliance on a decentralized system of private vendors highlights a significant and persistent infrastructure gap that the formal water agency has been unable to fill.

This market-based system has profound socio-economic consequences, effectively transforming water from a basic public service into a commodity. For the majority of Hargeisa's residents, daily access to this fundamental resource is not a guaranteed utility but is instead dependent on their ability to pay the fluctuating and often high prices set by private vendors. The significant financial burden this places on the community is explicitly confirmed by this thesis's survey, which found that 70% of residents are dissatisfied with the price of water. This dissatisfaction points to a system where economic strain is a constant feature of securing a sufficient water supply.

CHAPTER FIVE

CONCLUSION AND RECOMMENDATIONS

This thesis set out to evaluate the impacts of land use and climate variability on water availability in Hargeisa. By integrating hydrological modeling with remote sensing and socio-economic data, the study has provided a quantitative explanation for the city's water crisis. This final chapter presents the main conclusions drawn from the research, structured according to the specific objectives, and provides a set of evidence-based recommendations for policymakers and future researchers.

5.1. Conclusions

The findings of this research, detailed in Chapter 4, lead to four main conclusions, each corresponding to a specific research objective.

1: Land Use Change Impact: The study concludes that rapid and uncontrolled urbanization is the primary driver of hydrological change in the Hargeisa watershed. Between 2000 and 2024, the landscape was fundamentally transformed: urban areas expanded by 377.3%, primarily by converting 53.6% of the region's natural grasslands. This conversion from a permeable, natural "sponge" to an impervious, sealed surface has critically degraded the watershed's natural ability to absorb and store water.

2: Climate Variability Assessment: The analysis concludes that Hargeisa's climate creates a baseline of high, inherent water stress. The region's climate is not defined by a significant change in rainfall volume but by high inter-annual variability (erratic, unreliable rainfall) and a statistically significant historical warming trend (+0.037°C/year max temp). This "double-negative" effect results in an unreliable water supply (from variable rain) and higher water losses (from increased evapotranspiration).

3**: Combined Effects on Water Resources**: The hydrological model concludes that urbanization severely exacerbates the impacts of climate variability. The model quantitatively proved that the 2024 landscape is far less resilient than the 2000 landscape. This transformation is directly responsible for a 25% reduction in groundwater percolation (recharge) and a 24.1% increase in surface runoff. The critical implication is that Hargeisa's development is actively "starving" the aquifer system it depends on, creating an unsustainable dynamic.

4: Socio-Economic Impacts: The research concludes that this physical water scarcity has translated directly into a severe and inequitable socio-economic crisis. The formal public utility (HWA) is failing to serve the majority of the city, with only 30% of residents connected to the piped network. This has created a vacuum filled by a costly, informal market of private water tankers, which 41% of the population relies on. The finding that 75% of households deem their water supply "insufficient" validates their lived experience of hardship and confirms that water has become an expensive, unequally distributed commodity.

5.2. Recommendations

Based on the findings of this study, the following evidence-based recommendations are proposed for stakeholders, including the Hargeisa Water Agency (HWA) and municipal planners, to foster sustainable water resource management:

1. **Recommendation (for Municipal Planners & HWA): Implement Urban Rainwater Harvesting.**

- ✓ **Result Found**: Urbanization has increased surface runoff by 24.1%. This water is currently a lost resource and a flood risk.
- ✓ **Specific Action:** It is strongly recommended that municipal planners and the Hargeisa Water Agency (HWA) develop policies to capture this new urban runoff. This should include mandating rooftop rainwater collection systems for new construction and constructing larger-scale retention ponds within urban drainage channels.
- ✓ **Justification:** This turns a negative impact (increased runoff) into a supplementary water source, enhancing the city's resilience.

2. **Recommendation (for Municipal Authorities & Ministry of Planning): Protect Natural Recharge Zones**.

- ✓ **Result Found**: Natural grasslands are critical for infiltration, and the model showed a 25% reduction in groundwater percolation as they were lost.

- ✓ **Specific Action**: It is recommended that municipal authorities use the LULC maps from this study to identify and legally protect remaining key recharge zones (i.e., undeveloped grassland areas) from further urban expansion.

- ✓ **Justification:** This is a "no-regrets" policy that preserves the watershed's remaining natural ability to store water and recharge the aquifer, which is far cheaper than building new water infrastructure.

3. **Recommendation (for HWA & Ministry of Planning): Integrate Land Use and Water Planning.**

- ✓ **Result Found**: The entire study confirms that land use decisions have direct, quantifiable, and negative consequences for water availability.
- ✓ **Specific Action**: It is recommended that the HWA and the Ministry of Planning establish a formal, integrated planning process. Future urban development plans must be required to include a Hydrological Impact Assessment (HIA).
- ✓ **Justification**: The SWAT model developed in this thesis can serve as the baseline tool for such assessments, ensuring the consequences for water resources are considered before new developments are approved.

Further research could build upon these findings in several key areas:

- **Water Quality Analysis**: Investigate the quality of the increased urban surface runoff to assess the levels of pollutants and determine its suitability for various uses.
- **Climate Change Projections**: While this study focused on historical patterns, a future study could use downscaled climate change projections (e.g., CMIP6 models) to evaluate how future changes in rainfall and temperature might further impact the water availability in the 2024 landscape.
- **Economic Analysis of Recommendations**: Conduct a detailed cost-benefit analysis of the proposed recommendations, such as large-scale rainwater harvesting and green infrastructure projects, to assess their economic feasibility and provide a stronger basis for investment

REFERENCES

. N., Putranto, D. D. A., & Hadinata, F. (2024). The Effect of Land Use Changes on Availability of Water Resources in The Rupit Watershed. *International Journal of Religion*, *5*(7), 127–138. https://doi.org/10.61707/ekd6rz83

Abderrahman, W. A. (2000). Urban Water Management in Developing Arid Countries. *International Journal of Water Resources Development*, *16*(1), 7–20. https://doi.org/10.1080/07900620048536

Abdullaeva, B. S. (2024). Integrating advanced approaches for climate change impact assessment on water resources in arid regions. *Journal of Water and Land Development*, 149–156. https://doi.org/10.24425/jwld.2024.149116

Bieger, K., Arnold, J. G., Rathjens, H., White, M. J., Bosch, D. D., Allen, P. M., Volk, M., & Srinivasan, R. (2017). Introduction to SWAT +, A Completely Restructured Version of the Soil and Water Assessment Tool. *JAWRA Journal of the American Water Resources Association*, *53*(1), 115–130. https://doi.org/10.1111/1752-1688.12482

Devkota, N., Lamichhane, S., & Bhattarai, P. K. (2024). *Navigating Uncertainties in Quantifying Water Availability Amidst the Nexus of Climate and Land Use Changes*. https://doi.org/10.21203/rs.3.rs-4112786/v1

Ehtasham, L., Sherani, S. H., & Nawaz, F. (2024). Acceleration of the hydrological cycle and its impact on water availability over land: An adverse effect of climate change. *Meteorology Hydrology and Water Management*. https://doi.org/10.26491/mhwm/188920

Emmanuel Augustine Etukudoh, Valentine Ikenna Ilojianya, Olushola Babatunde Ayorinde, Cosmas Dominic Daudu, Adedayo Adefemi, & Ahmed Hamdan. (2024). Review of climate change impact on water availability in the USA and Africa.

International Journal of Science and Research Archive, *11*(1), 942–951. https://doi.org/10.30574/ijsra.2024.11.1.0169

Femeena, P. V., Karki, R., Cibin, R., & Sudheer, K. P. (2022). Reconceptualizing HRU Threshold Definition in the Soil and Water Assessment Tool. *JAWRA Journal of the American Water Resources Association*, *58*(4), 508–516. https://doi.org/10.1111/1752-1688.13000

Haider, S., Masood, M. U., Rashid, M., Alshehri, F., Pande, C. B., Katipoğlu, O. M., & Costache, R. (2023). Simulation of the Potential Impacts of Projected Climate and Land Use Change on Runoff under CMIP6 Scenarios. *Water*, *15*(19), 3421. https://doi.org/10.3390/w15193421

Hanoon, S. K., Abdullah, Dr. A. F., Shafri, Dr. H. Z. M., & Wayayok, Dr. A. (2022). Using scenario modelling for adapting to urbanization and water scarcity: Towards a sustainable city in semi-arid areas. *Periodicals of Engineering and Natural Sciences (PEN)*, *10*(1), 518. https://doi.org/10.21533/pen.v10i1.2552

Hassan, A. Y., Mohamed, M. A., Mohamed, A. A., & Osman, B. M. (2024). Towards Sustainable Environment in Somalia: The Role of Urbanisation and Energy Consumption. *International Journal of Energy Economics and Policy*, *14*(5), 457–463. https://doi.org/10.32479/ijeep.16983

Internal Displacement Monitoring Center (IDMC). (2020). *No land, no water, no pasture: The urbanisation of drought displacement in Somalia*. Internal Displacement Monitoring Center (IDMC). https://doi.org/10.55363/IDMC.XUVB9986

Ismail, A. A., & Duale, H. A. (2023). *Assessment of Awareness on Health Impact of Drinking Unsafe Water in Hargeisa, Somaliland*. In Review. https://doi.org/10.21203/rs.3.rs-3158070/v1

Kebede, G. F., Gurmu, B. W., & Weldegebriel, Z. B. (2025). Integrating Climate Change Adaptation, Disaster Risk Reduction, and Social Protection for Enhanced Resilience: Evidence from the Somali Region, Ethiopia. *The Journal of Environment & Development*, *34*(1), 266–287. https://doi.org/10.1177/10704965241289525

Kenea, U., Adeba, D., Regasa, M., & Nones, M. (2021). Hydrological Responses to Land Use Land Cover Changes in the Fincha'a Watershed, Ethiopia. *Land*, *10*(9), 916. https://doi.org/10.3390/land10090916

Liu, Z., Rong, L., & Wei, W. (2023). Impacts of land use/cover change on water balance by using the SWAT model in a typical loess hilly watershed of China. *Geography and Sustainability*, *4*(1), 19–28. https://doi.org/10.1016/j.geosus.2022.11.006

Luo, S., Tetzlaff, D., Smith, A., & Soulsby, C. (2023, May 15). *Using tracer-aided ecohydrological models to assess the impact of alternative land use strategies on optimizing water availability in drought-sensitive catchments*. https://doi.org/10.5194/egusphere-egu23-108

Luo, S., Tetzlaff, D., Smith, A., & Soulsby, C. (2024). Assessing impacts of alternative land use strategies on water partitioning, storage and ages in drought-sensitive lowland catchments using tracer-aided ecohydrological modelling. *Hydrological Processes*, *38*(4), e15126. https://doi.org/10.1002/hyp.15126

Marchane, A., Tramblay, Y., Hanich, L., Ruelland, D., & Jarlan, L. (2017). Climate change impacts on surface water resources in the Rheraya catchment (High Atlas, Morocco). *Hydrological Sciences Journal*, *62*(6), 979–995. https://doi.org/10.1080/02626667.2017.1283042

Mishra, B. K., Chakraborty, S., Kumar, P., & Saraswat, C. (2020). Urban Water Security Challenges. In B. K. Mishra, S. Chakraborty, P. Kumar, & C. Saraswat, *Sustainable*

Solutions for Urban Water Security (Vol. 93, pp. 25–40). Springer International Publishing. https://doi.org/10.1007/978-3-030-53110-2_2

Nyatuame, M., Amekudzi, L. K., & Agodzo, S. K. (2020). Assessing the land use/land cover and climate change impact on water balance on Tordzie watershed. *Remote Sensing Applications: Society and Environment*, *20*, 100381. https://doi.org/10.1016/j.rsase.2020.100381

Oñate-Valdivieso, F., & Cordero, M. (2024). EVALUATION OF THE HYDROLOGICAL RESPONSE TO CLIMATE AND LAND USE CHANGE IN A WATERSHED. *Proceedings of International Structural Engineering and Construction*, *11*(1). https://doi.org/10.14455/ISEC.2024.11(1).AAW-02

Paul, P. K., Zhang, Y., Mishra, A., Panigrahy, N., & Singh, R. (2019). Comparative Study of Two State-of-the-Art Semi-Distributed Hydrological Models. *Water*, *11*(5), 871. https://doi.org/10.3390/w11050871

Ruigar, H., Emamgholizadeh, S., Gharechelou, S., & Golian, S. (2023). *Evaluating the impacts of anthropogenic, climate, and land-use changes on streamflow*. https://doi.org/10.21203/rs.3.rs-3139611/v1

Sharma, A., Khare, R., & Choudhary, M. K. (2023). *Climate Change Impact Evaluation on Hydro-Meteorological Variables across a Semi-Arid Middle River Basin in India*. https://doi.org/10.22541/au.168374778.87075335/v1

Sulistyani, K. F., & Irianto, D. B. (2024). Climate Change Impact on Water Availability and Water Balance on Sampit Sub-Cachtment, Central Kalimantan. *Reka Buana : Jurnal Ilmiah Teknik Sipil Dan Teknik Kimia*, *9*(1), 109–120. https://doi.org/10.33366/rekabuana.v9i1.5627

Teku, D. (2025). Navigating climate uncertainty: A comprehensive review of climatic variabilities and extreme events on environmental, socio-economic, and livelihood dimensions in Ethiopia with adaptation strategies. *All Earth*, *37*(1), 1–30. https://doi.org/10.1080/27669645.2025.2514418

THE STUDY ON JARAR VALLEY AND SHEBELE. (n.d.).

Thornton, R. J., & Thornton, J. A. (2004). Erring on the Margin of Error. *Southern Economic Journal*, *71*(1), 130. https://doi.org/10.2307/4135315

Warku, F., Korme, T., Wedajo, G. K., & Nedow, D. (2022). Impacts of land use/cover change and climate variability on groundwater recharge for upper Gibe watershed, Ethiopia. *Sustainable Water Resources Management*, *8*(1), 2. https://doi.org/10.1007/s40899-021-00588-8

Muthusi, F., Mahamud, G., Abdalle, A., & Gadain, H. (2007). Rural Water Supply Assessment. http://www.faoswalim.org/downloads/Pages from W-08 Rural Water Supply Assessment.pdf

Petersen, G., and Gadain, H.M. (2012). Climate Change Impacts on Water Resources of Somaliland and Puntland. Technical Report No W-21, FAO-SWALIM, Nairobi, Kenya. December, 85.

Jama, A. A., & Mourad, K. A. (2019). Water services sustainability: Institutional arrangements and shared responsibilities. Sustainability (Switzerland), 11(3), 1–15. https://doi.org/10.3390/su11030916

Warku, F., Korme, T., Wedajo, G. K., & Nedow, D. (2022). Impacts of land use/cover change and climate variability on groundwater recharge for upper Gibe watershed, Ethiopia. Sustainable Water Resources Management, 8(1). https://doi.org/10.1007/s40899-021-00588-8

Belete, M., Deng, J., Abubakar, G. A., Teshome, M., Wang, K.Woldetsadik, M., Zhu, E., Comber, A., & Gudo, A. (2020). Partitioning the impacts of land use/land cover change And climate variability on water supply over the source region of the Blue Nile Basin. Land Degradation and Development, 31(15), 2168–2184. https://doi.org/10.1002/ldr.3589

Boithias, L., Acuña, V., Vergoñós, L., Ziv, G., Marcé, R., & Sabater, S. (2014). Assessment of the water supply: DEmand ratios in a

Mediterranean basin under different global change scenarios and mitigation alternatives. Science of the Total Environment, 470–471, 567–577. https://doi.org/10.1016/j.scitotenv.2013.10.003

Abdishakur, A. E., Mohamed, A., Ali, S., Hassan, A. M., & Identification, H. (2022). Journal of Civil Engineering Assessment of Drinking Water Quality in Mogadishu , Somalia. 2022(April), 0–7. https://doi.org/10.47363/JCERT/2022(4)125

Neitsch, S.L., Arnold, J.G., Kiniry, J.R., and Williams, J.R. (2005). Soil and Water Assessment Tool, Theoretical documentation: Version 2005. Temple, TX. USDA Agricultural Research Service and Texas A & M Black land Research Centre.

Tadele, K. (2007). Impact of Land use/cover change on stream flow: the case of Hare River Watershed, Ethiopia. Arba Minch Water Technology Institute, Arba Minch University.

Cunderlik, J. (2003). Hydrological model selection for CFCAS project, Assessment of water resource risk and vulnerability to change in climate condition, University of Western Ontario.

Abbas, N., Wasimi, S., & Al-Ansari, N. (2017). Impacts of Climate Change on Water Resources of Greater Zab and Lesser Zab Basins, Iraq, Using Soil and Water Assessment Tool Model. International Journal of Environmental, Chemical, Ecological, Geological and Geophysical Engineering, 11(10), 823–829.

Abdishakur, A. E., Mohamed, A., Ali, S., Hassan, A. M., & Identification, H. (2022). Journal of Civil Engineering Assessment of Drinking Water Quality in Mogadishu, Somalia. 2022(April), 0–7. https://doi.org/10.47363/JCERT/2022 (4)125

Access, O., Kerkeni, L., Ruano, P., Delgado, L. L., Picco, S., Villegas, L., Tonelli, F., Merlo,

M., Rigau, J., Diaz, D., & Masuelli, M. (2016). We are Intech Open , the world ’ s leading publisher of Open Access books Built by scientists , for scientists TOP 1 %. Intech, i(tourism), 13. https://www.intechopen.com/books/advanced-biometric-technologies/liveness-detection-in-biometrics%0Afile:///D:/Google Drive/Organized

Folder/2016/Kerkeni et al/We are IntechOpen , the world ’ s leading publisher of Open Access books Built by scientists ,

Adeaga, O. A., Bello, A. A., & Akinbaloye, T. (2019). Water Resources Uncertainty in Yewa River Basin, Ogun state, South-West Nigeria. 131(May), 37–53.

African Development Bank Group. (2016). Water Infrastructure Development for Resilience in Somaliland Program: Environmental and Social Management Framework. June.

Ahmad, W., Iqbal, J., Nasir, M. J., Ahmad, B., Khan, M. T., Khan, S. N., & Adnan, S. (2021). Impact of land use/land cover changes on water quality and human health in district Peshawar Pakistan. Scientific Reports, 11(1), 1–14. https://doi.org/10.1038/s41598-021-96075-3

Ali, Mushir; Terfa, A. (2012). State of Water Supply and Consumption in Urban Areas at Household Level: A Case Study of East Wollega Zone, Ethiopia. British Journal of Humanities and Social Sciences, 5(2), 15.

Ali, A. I., Kassem, Y., & Gökçekuş, H. (2023). Examining the impact of climate change on water resources in Somalia: The role of adaptation. Future Technology, 2(4), 45–58. https://doi.org/10.55670/fpll.futech.2.4.5

Arunyawat, S., & Shrestha, R. P. (2016). Assessing land use change and its impact on ecosystem services in northern Thailand. Sustainability (Switzerland), 8(8). https://doi.org/10.3390/su8080768.

Batelaan, O., & De Smedt, F. (2007). GIS-based recharge estimation by coupling surface-subsurface water balances. Journal of Hydrology, 337(3–4), 337–355. https://doi.org/10.1016/j.jhydrol.2007.02.001

Birkhofer, K., Diehl, E., Andersson, J., Ekroos, J., Früh-Müller, A., Machnikowski, F., Mader, V. L., Nilsson, L., Sasaki, K., Rundlöf, M., Wolters, V., & Smith, H. G. (2015).

Ecosystem services-current challenges and opportunities for ecological research. Frontiers in Ecology and Evolution, 2(JAN), 1–12. https://doi.org/10.3389/fevo.2014.00087

Boithias, L., Acuña, V., Vergoñós, L., Ziv, G., Marcé, R., & Sabater, S. (2014). Assessment of the water supply: DEmand ratios in a Mediterranean basin under different global change scenarios and mitigation alternatives. Science of the Total Environment, 470–471, 567–577. https://doi.org/10.1016/j.scitotenv.2013.10.003

Brauman, K. A. (2015). Hydrologic ecosystem services: linking ecohydrologic processes to human well-being in water research and watershed management. WIREs Water, 2(4), 345–358. https://doi.org/10.1002/wat2.1081

Chemura, A., Rwasoka, D., Mutanga, O., Dube, T., & Mushore, T. (2020). The impact of land-use/land cover changes on water balance of the heterogeneous Buzi sub-catchment, Zimbabwe. Remote Sensing Applications: Society and Environment, 18, 100292. https://doi.org/10.1016/j.rsase.2020.100292

APPENDIX A:

QUESTIONNAIRE

Section A: Personal Information

Name: ____

1. Gender of respondent:

☐ Male
☐ Female

2. Marital Status:

☐ Single
☐ Married
☐ Divorced

3. Age:

☐ < 30
☐ 30–45
☐ 46–60
☐ > 60

Location and Address: ____

4. Type of Family:

☐ Nuclear Family
☐ Joint Family

Number of Family Members: _______________________________

5. Your District:

☐ Gacan-Libaax
☐ 26 June
☐ Ibrahim Kodbuur
☐ Mohamoud Haibe
☐ Ahmed-Dhagax

Section B: Water Scarcity Related Questions

1. Which of the following sources of drinking water does your household use?

☐ Water Truck
☐ Public Tap

☐ Open Well (Dams)
☐ Household Water Pipes

2. Which of the following sources of drinking water are available in your neighborhood?

☐ Water Truck
☐ Public Tap
☐ Open Well (Dams)
☐ Household Water Pipes

3. What is the frequency you get water?

☐ More than once a day ☐ Once a day ☐ Once in two days ☐ Once in three days
☐ Once a week ☐ Other: ___________

4. Is this frequency sufficient for your needs?

☐ Yes
☐ No

5. How often would you like to get water from your source?

☐ More than once a day
☐ Once a day
☐ Once in two days
☐ Satisfied with current frequency

6. In times of droughts, do you get water from your source constantly?

☐ Yes
☐ No

7. Does the price of water from your source satisfy you?

☐ Yes
☐ No

8. In your view, which district gets the low water?

☐ Gacan-Libaax
☐ 26 June
☐ Ibrahim Kodbur
☐ Mohamoud Haibe
☐ Ahmed-Dhagax

9. Generally in Hargeisa, how many people do you think get enough water for their needs?

☐ 0–25%
☐ 26–50%
☐ 51–75%
☐ 76–100%

10. What do you think is the main cause of water scarcity in Hargeisa?

☐ Population Increase ☐ Climate Change ☐ Overuse/Wastage ☐ Other: ___________

11. What effects caused by water scarcity in Hargeisa are there now, or can happen in the future?

☐ Hunger & Poverty
☐ Sanitation Issues
☐ Possible Disease Outbreak
☐ All
☐ Other: ___________

12. Did the population give a reaction to the water shortage?

☐ Yes
☐ No

13. What do you think is the best solution for the water shortage in Hargeisa?

☐ Construct Dams near Hargeisa
☐ Lower Water Price
☐ Deliver Water through Sufficient Pipes
☐ Other: ___________

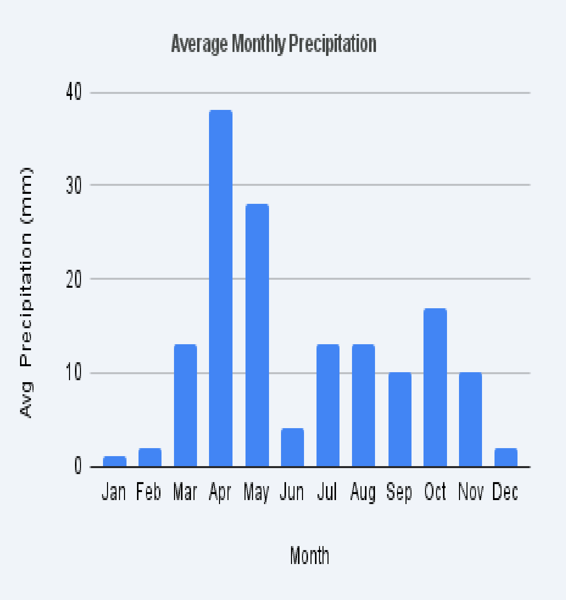
14. In your own opinion, how can we increase awareness of people to reduce water scarcity causes?

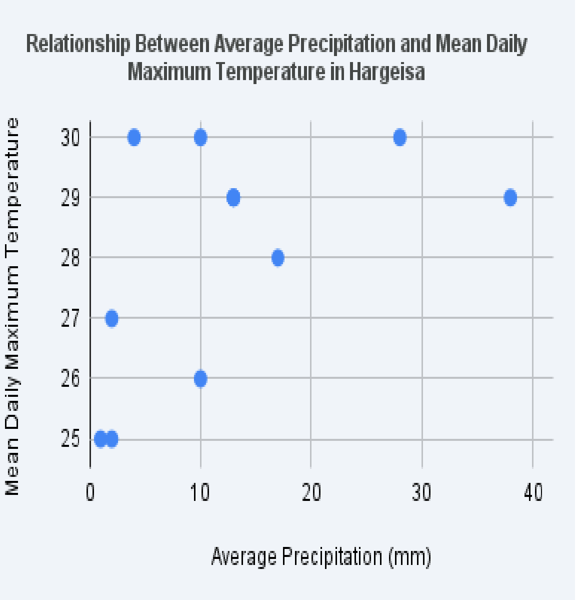
____
____
____

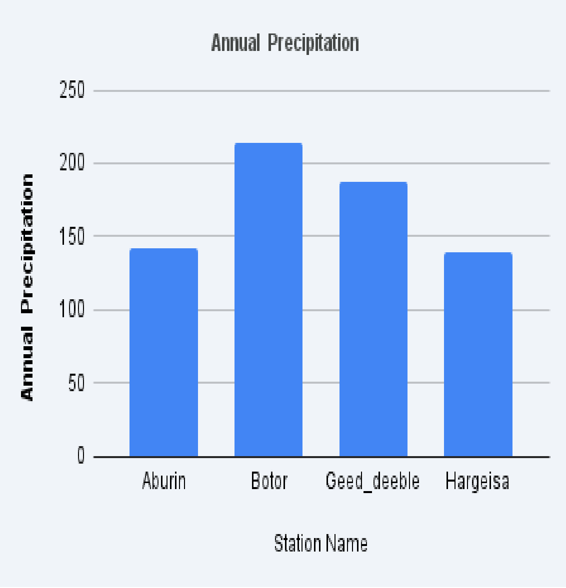
15. Do you have hope that all people in Hargeisa will get safe, cheap, and clean water in the near future? Why?

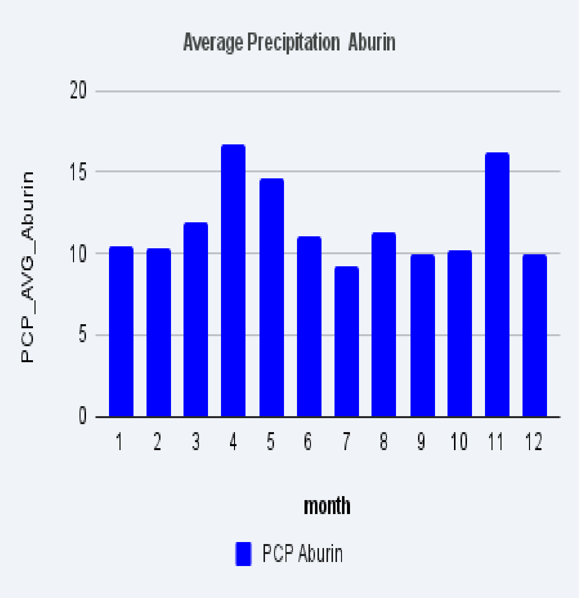
____

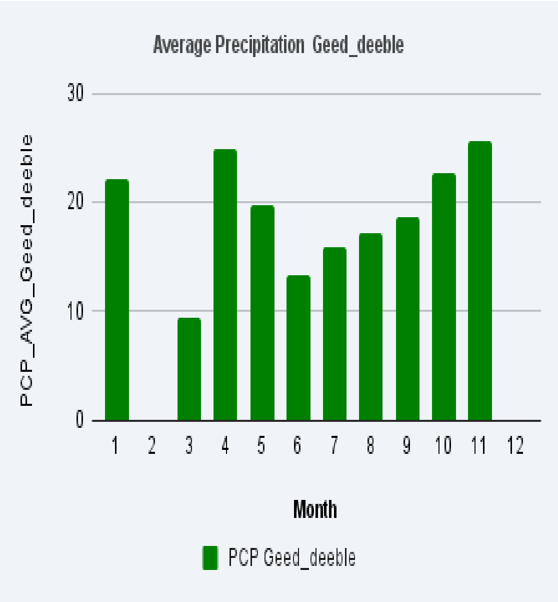
APPENDIX B

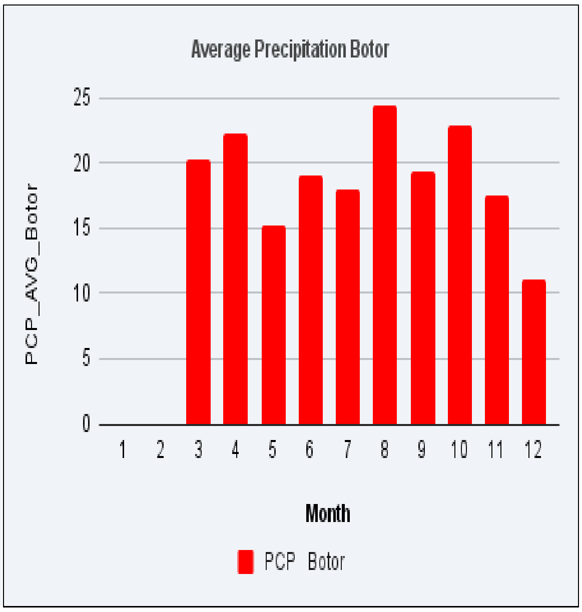

Average Monthly Precipitation
Avg Precipitation (mm)
40
30
20
10
0
Jan
Feb
Mar
Apr
May
Jun
Jul
Aug
Sep
Oct
Nov
Dec
Month

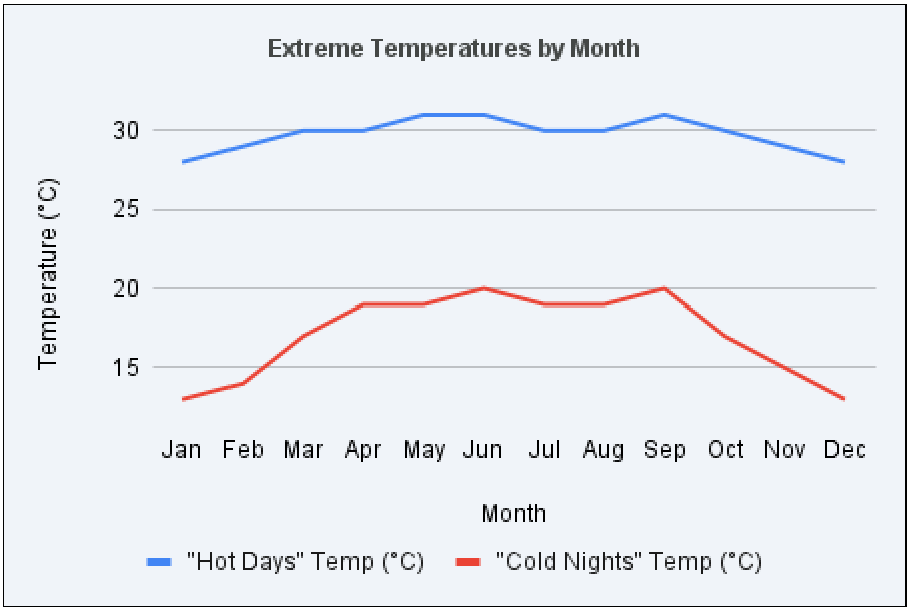

Relationship Between Average Precipitation and Mean Daily Maximum Temperature in Hargeisa
Mean Daily Maximum Temperature
30
29
28
27
26
25
0
10
20
30
40
Average Precipitation (mm)

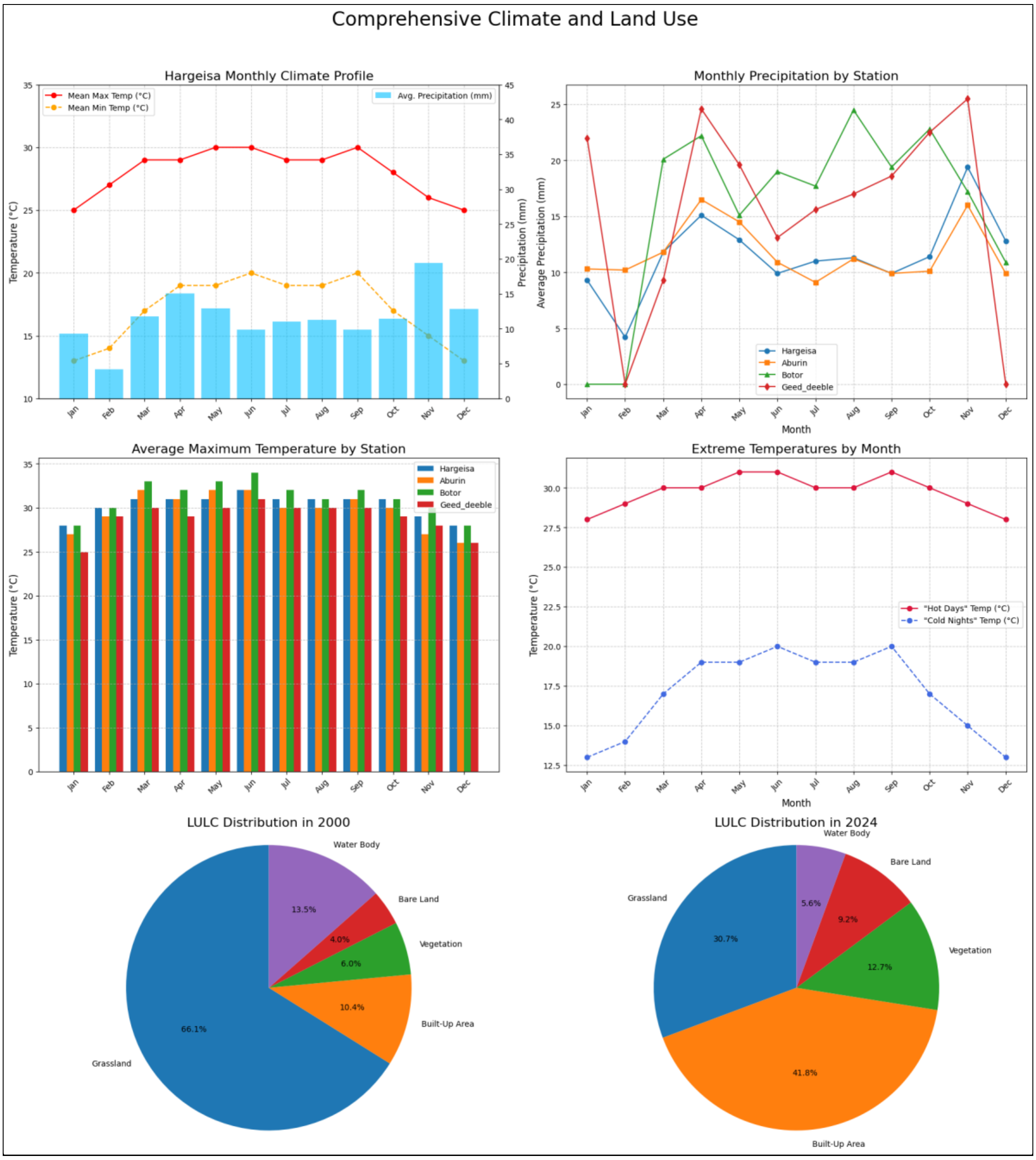

Annual Precipitation
Annual Precipitation
250
200
150
100
50
0
Aburin
Botor
Geed_deeble
Hargeisa
Station Name


Average Precipitation Aburin
PCP_AVG_Aburin
20
15
10
5
0
1
2
3
4
5
6
7
8
9
10
11
12
month
PCP Aburin


Average Precipitation Geed_deeble
PCP_AVG_Geed_deeble
30
20
10
0
1
2
3
4
5
6
7
8
9
10
11
12
Month
PCP Geed_deeble


Average Precipitation Botor
PCP_AVG_Botor
25
20
15
10
5
0
1
2
3
4
5
6
7
8
9
10
11
12
Month
PCP Botor


Extreme Temperatures by Month
Temperature (°C)
30
25
20
15
Jan
Feb
Mar
Apr
May
Jun
Jul
Aug
Sep
Oct
Nov
Dec
Month
"Hot Days" Temp (°C)
"Cold Nights" Temp (°C)


Comprehensive Climate and Land Use
Hargeisa Monthly Climate Profile
Mean Max Temp (°C)
Mean Min Temp (°C)
Avg. Precipitation (mm)
Temperature (°C)
Precipitation (mm)
Jan
Feb
Mar
Apr
May
Jun
Jul
Aug
Sep
Oct
Nov
Dec
Monthly Precipitation by Station
Average Precipitation (mm)
Hargeisa
Aburin
Botor
Geed_deeble
Month
Average Maximum Temperature by Station
Temperature (°C)
Hargeisa
Aburin
Botor
Geed_deeble
Extreme Temperatures by Month
"Hot Days" Temp (°C)
"Cold Nights" Temp (°C)
Temperature (°C)
Month
LULC Distribution in 2000
Water Body
13.5%
Bare Land
4.0%
Vegetation
6.0%
Built-Up Area
10.4%
Grassland
66.1%
LULC Distribution in 2024
Water Body
5.6%
Bare Land
9.2%
Vegetation
12.7%
Built-Up Area
41.8%
Grassland
30.7%