EVALUATING IMPACTS OF CLIMATE CHANGE ON WATER AVAILABILITY: THE CASE OF HARGEISA WATERSHED IN SOMALILAND

IBRAHIM AHMED SHIRE

A THESIS SUBMITTED TO THE DEPARTMENT OF WATER RESOURCES ENGINEERING, COLLEGE OF CIVIL ENGINEERING AND ARCHITECTURE

PRESENTED IN PARTIAL FULFILLMENT OF THE REQUIREMENT FOR THE DEGREE OF MASTER'S IN WATER RESOURCES ENGINEERING (HYDROLOGY AND WATER RESOURCES MANAGEMENT)

OFFICE OF GRADUATE STUDIES
ADAMA SCIENCE AND TECHNOLOGY UNIVERSITY

September, 2025
Adama, Ethiopia

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DECLARATION

I hereby declare that this Master's Thesis entitled "Evaluating Impacts of climate change on water availability: the case of Hargeisa watershed in 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

Ibrahim Ahmed Shire	__________	______________
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 impacts of climate change on water availability: the case of Hargeisa watershed in Somaliland”, prepared under my guidance by Ibrahim Ahmed Shire.

Therefore, I recommend the submission of the thesis to the department for further review and evaluation.

Dr. Abdulkerim Bedewi (PhD)

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Major Advisor	Signature	Date

APPROVAL SHEET

I hereby certify that the recommendations and suggestions given by the thesis review committee are appropriately incorporated into the final thesis entitled "evaluating impacts of climate change on water availability: the case of Hargeisa watershed in Somaliland" by Ibrahim Ahmed Shire.

Major Advisor	Signature	Date

We, the undersigned, members of the Board of Examiners of the thesis by Ibrahim Ahmed Shire have read and evaluated the thesis entitled "evaluating impacts of climate change on water availability: the case of Hargeisa watershed in 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

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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
College Dean	Signature	Date
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LIST OF ACRONYMS AND ABBREVIATIONS

DEMs	Digital Elevation Models
ESMs	Earth System Models
GCM	General Circulation Model
GIS	Geographic Information System
GPM	Global Precipitation Measurement
GSA	Global Sensitivity Analysis
HRU	Hydrological Response Unit
SWAT+	Soil and Water Assessment Tool plus
IAMs	Integrated Assessment Models
IPCC	Intergovernmental Panel on Climate Change
ITA	Innovative Trend Analysis
MAE	Mean Absolute Error
MK	Mann-Kendall
MLR	Multiple Linear Regression
NSE	Nash-Sutcliffe Efficiency
RCM	Regional Climate Model
RCPs	Representative Concentration Pathways
RMSE	Root-Mean-Square Error
SSPs	Shared Socio-economic Pathways
WRF	Weather Research and Forecasting
UNICEF	United Nations Children's Fund
SWALIM	Somalia Water and Land Information Management

ABSTRACT

The Hargeisa watershed is the lifeline water basin located in the Marodi-jeh region of Somaliland, which includes the capital city of Hargeisa. However, as a semi-arid and groundwater-dependent system, the watershed is highly vulnerable to the impacts of climate change. This study quantifies these impacts using the Soil and Water Assessment Tool plus (SWAT+) model, driven by downscaled data from three coupled model inter-comparison project phase six (CMIP6) of Global Circulation Models (CanESM5, NorESM2-MM, GFDL-ESM4) under SSP2-4.5 and SSP5-8.5 scenarios. A regionalization approach using data from the gauged Dagahbur catchment was employed to overcome local data scarcity. Historical analysis (1995-2024) exposed a significant increasing trend in annual precipitation (up to 13.19 mm/year) alongside regional warming. Future projections indicate a complex hydrological response to accelerating warming, which could exceed +6.8°C by the end of the century under SSP5-8.5. Evapotranspiration is projected to increase substantially across all scenarios (+46.0% to +184.2%). Critically, despite this, groundwater recharge shows a consistent and significant increase, ranging from +4.1% to as high as +781.0%. Completely different, projections for surface runoff are highly uncertain, ranging from a decrease of -32.7% to an increase of +135.8%. This study concludes that while the Hargeisa watershed may see improved groundwater security, it faces a dual risk of increased droughts and heightened flood potential. These findings provide a quantitative basis for developing adaptive water management strategies to ensure the region's long-term water security.

Keywords: SWAT+, GCM, CMIP6, Regionalization, Water availability, Hargeisa watershed in Somaliland.

1. INTRODUCTION

1.1. Background

Climate change is a significant global challenge, really affecting the hydrological cycle and impacting the availability of fresh water (Zulfa & Septiana, 2024). Rising temperatures and shifting precipitation patterns disrupt historical water balances, affecting both the timing and quantity of resources (Sarangi, 2023). These changes have a critical effect on groundwater recharge, as less water may infiltrate the ground, which worsens water scarcity in regions that are heavily dependent on groundwater, like Somaliland (Maliva, 2021). While this is a worldwide issue, its effects are particularly severe across Africa. The continent faces an acute water crisis due to pre-existing scarcity, which is compounded by the impacts of climate change on river flows and rainfall patterns (Mperejekumana et al., 2024). The Intergovernmental Panel on Climate Change (IPCC) has projected that East Africa will experience significant variations in rainfall, with some areas becoming drier while others may face increased flooding. These changes threaten not only the availability of freshwater but also the lives of millions who depend on consistent and reliable water sources for agriculture, drinking, and sanitation (Oriol et al., 2024).

Though climate change is a global concern, Somaliland is facing critical challenges. Previous studies have highlighted alarming future trends that demand more detailed investigation. Projections indicate that annual mean temperatures in the region are expected to rise by 2.5°C to 3.0°C (Petersen & Gadain, 2012). More critically for this groundwater-dependent area, a study by Khalif projected a consistent decline in rainfall during the crucial spring recharge season, with decreases ranging from -4.71% to -14.91%, even if total annual rainfall increases (Khalif, 2023). These findings underscore the urgent need to project future climate variables using the latest generation of climate models to fully understand the scope of potential changes.

To quantify these complex impacts, scientists rely on hydrological models, which are essential tools for simulating the water cycle and assessing how it responds to climatic shifts. A hydrological model is needed to analyze the changes in water availability due to the effects of the climate and simulate the water cycle, which includes precipitation, evaporation, runoff, and groundwater flow (Narwade & Ukarande, 2023). Given these significant threats to the region's water resources, a detailed, quantitative assessment for the Hargeisa watershed is urgently needed. Therefore, this research filling that gap and the general objective of this study is to evaluate the specific impacts of climate change on its water availability. This will be achieved through the main methodology of applying the Soil and Water Assessment Tool plus (SWAT+) model, driven by a set of modern CMIP6 climate projections. This approach will allow for a process-based simulation of the watershed's future hydrology.

1.2. Statement of the Problem

Water scarcity in semi-arid regions is increasingly worsened by climate change, leading to significant socio-economic and environmental challenges (Hassan et al., 2025). East Africa, in particular, is one of the world's most vulnerable regions, where authoritative assessments, including the IPCC Sixth Assessment Report, forecast that rising temperatures and more erratic rainfall will intensify aridity. This trend poses a direct threat to the water security and socio-economic stability of millions of people (Muse, 2024). The Hargeisa watershed in Somaliland is a good example of this regional crisis. It serves as the essential lifeline for the capital city, yet it is already under severe water stress that creates significant practical challenges for its population. Currently, this watershed struggles to meet daily water demands, resulting in chronic shortages and forcing a heavy reliance on expensive private water tankers (Institute for Peace and Conflict Studies et al., 2023). This existing scarcity directly threatens public health, limits economic development, and impacts the overall stability of the watershed.

Despite this recognized threat, a critical research gap exists. While general climate trends for East Africa are known, there is a lack of specific, quantitative assessments detailing how these changes will affect the individual Water Balance of the Hargeisa watershed's (surface runoff, evapotranspiration, Net water yield and groundwater recharge). The originality of this research is that it directly fills this gap. It is the first study to apply the advanced, physically-based SWAT+ model to the Hargeisa watershed, driven by an ensemble of the latest CMIP6 climate projections under multiple scenarios (SSP2-4.5 and SSP5-8.5). This combination provides a more sophisticated and up-to-date assessment of future water availability than has been previously available for this specific region.

The findings will produce the necessary scientific foundation for policymakers and water managers to develop targeted, data-driven adaptation strategies to enhance the region's resilience and ensure its long-term water security.

1.3. Objectives

1.3.1. General objective

The general objective of the research is to assess the impacts of climate change on water availability of the Hargeisa watershed by using the Soil and Water Assessment Tool Plus (SWAT+) model.

1.3.2. Specific objectives

1. To analyze the spatiotemporal variability and trend of rainfall and temperatures over the Hargeisa Watershed in Somaliland
2. To project future climate variables on rainfall and temperatures in this watershed
3. To evaluate climate change impacts on water availability in the Hargeisa Watershed

1.4. Research Questions

1. How does the spatiotemporal variability and trend of historical precipitation and temperatures manifest over the Hargeisa Watershed in Somaliland?

2. What are the projected future changes in rainfall and temperatures for this watershed under different climate scenarios?

3. How will climate change affect water availability in the Hargeisa Watershed?

1.5. Significance of the Study

Understanding the hydrological impacts of climate change is crucial for ensuring water and food security worldwide especially in East Africa that is a region highly vulnerable to climatic shifts, where water management policies are often hampered by a lack of specific, quantitative data (Onyutha, 2024). On a local and national level, this study's primary significance is that it provides the first detailed, process-based quantitative assessment of climate change impacts for the Hargeisa watershed, offering data directly relevant to Somaliland's water resource policies. Specifically, the findings can inform policies related to sustainable groundwater management, the design of climate-resilient infrastructure to handle the dual risks of both droughts and floods, and the development of robust water allocation strategies. Furthermore, this study holds significant methodological importance. By successfully applying a regionalization approach, this research demonstrates a robust framework for analysis in a severely data-scarce environment. This approach is particularly significant as the complete absence of a permanent streamflow gauging station in the Hargeisa watershed makes direct model calibration impossible. The combination of this technique with the advanced SWAT+ model and the latest CMIP6 climate data provides a valuable and replicable blueprint for researchers seeking to conduct similar impact assessments in other ungauged basins across the Horn of Africa.

The Hargeisa watershed, which is vital to Somaliland's capital and its surrounding communities, faces increasing water stress due to a combination of existing shortages and the projected impacts of climate change (Khalif, 2023). While the general impacts of climate change on water resources in East Africa are recognized, a critical knowledge gap exists regarding the specific effects on the Hargeisa watershed's water balance. This study directly addresses this gap by utilizing the Soil and Water Assessment Tool Plus (SWAT+) model to quantify the impacts of projected climate change on key hydrological processes, including surface runoff, evapotranspiration, and groundwater recharge, which is crucial given the region's reliance on the Geed Deeble aquifer. The results give important information that can help make specific plans for dealing with changes and keeping water use sustainable. This will help keep enough water for the Hargeisa area for a long time. The way used in this study can also be used to look at other areas that do not have much data.

1.6. Scope of the Study

Geographically, this research is bounded to the Hargeisa Watershed in Somaliland, East Africa, serving as the critical hydrological catchment for the capital city. Temporally, the study covers a historical baseline period (1995–2024) using observed hydro-meteorological data and extends to future climate projections for the Mid-Century (2031–2060) and End-of-Century (2071–2100). The technical scope of the study centers on the application of the Soil and Water Assessment Tool plus (SWAT+) model to simulate the watershed’s hydrological response to climate change. In the context of this research, "water availability" is operationally defined not as total precipitation, but specifically as the aggregate of Groundwater Recharge and Total Water Yield (surface runoff available for harvesting). This distinction is critical for the scope of this study because, in this semi-arid environment, high evapotranspiration rates consume the vast majority of rainfall. Therefore, the study focuses strictly on the remaining fractions of the water balance that effectively replenish the Geed Deeble aquifer or generate streamflow. Although these components represent a small percentage of the total water balance, they constitute the sole renewable water sources for the region's population and are the primary indicators of water security. Methodologically, the scope addresses the challenge of data scarcity by employing a regionalization approach. This involves calibrating the model on the hydrologically similar Dagahbur catchment in Ethiopia and transferring the optimized parameters to the ungauged Hargeisa watershed. The study concludes by evaluating the dual risks of flood and drought to inform adaptation strategies.

2. LITERATURE REVIEW

2.1. Conceptual Framework for Hydrological Impact Assessment

This section outlines the conceptual framework used in this study to assess the impacts of climate change on the water Availability of the Hargeisa watershed. It provides a brief overview of the key components of this framework, beginning with the use of General Circulation Models, (GCMs), downscaling methods, Climate scenarios like Shared Socioeconomic Pathways (SSPs) to understand future climate scenarios. The discussion then covers the application of hydrological models, like SWAT+, to simulate the on-the-ground impacts on the water balance as well as Impact of Climate change on water resources. Together, these elements form the scientifically robust methodology required to translate large-scale climate data into actionable, watershed-specific information.

2.2. General Circulation Model (GCM)

GCMs represent the basic tools in the simulation and forecasting of atmospheric and climatic processes. (Kochkov et al., 2024). GCMs are fundamental to water resource studies because their projections of key climate variables, such as future precipitation and temperature, serve as the primary inputs for hydrological models (Illangasingha et al., 2023). By driving models like SWAT+ with GCM outputs, researchers can simulate how climate change may alter critical water balance components, including streamflow, evapotranspiration, and groundwater recharge (Narwade & Ukarande, 2023). However, a major challenge in applying GCMs to watershed-scale analysis is their coarse spatial resolution, where a single grid cell can span thousands of square kilometers. This scale mismatch makes it impossible to accurately represent the local topography and climate of a specific basin (Han et al., 2023). Therefore, the direct outputs from GCMs cannot be used for hydrological impact studies without first undergoing a downscaling process to refine them to a much higher local resolution.

2.3. Downscaling Methods

Downscaling methods are very significant in enhancing spatial resolution, as all precipitation and other environmental data are identified using remote sensing. Downscaling has been essential as a means of mitigating their shortcomings with low-resolution data, especially amidst heterogeneous terrains and varying climatic conditions (Wang et al., 2024). A critical challenge in climate change impact studies is the scale mismatch between the outputs of General Circulation Models (GCMs) and the requirements of watershed-scale hydrological models (Chang et al., 2023). GCMs operate at a coarse spatial resolution, often hundreds of kilometers per grid cell, which is unsuitable for representing the local climate and topography of a specific basin like the Hargeisa watershed. Therefore, downscaling is the process of translating these coarse GCM outputs to a finer, local scale. Generally, downscaling methods are divided into two main categories: statistical, which uses observed historical relationships between large-scale climate patterns and local weather and dynamical, which uses computationally intensive regional climate models (Li et al., 2024).

2.3.1. Statistically downscaling approach

Statistical downscaling methods are essential for transforming low-resolution climate model outputs into high-resolution data suitable for local applications. These methods leverage statistical relationships between large-scale atmospheric variables and local climate phenomena, enhancing the precision of climate forecasts (Harder et al., 2023). Statistical downscaling helps localize climate model predictions by 'downscaling' coarse-resolution predictions to finer spatial predictions. Key methods of statistical downscaling include Bias Correction and Spatial Disaggregation (BCSD), egression methods, weather typing/analog methods, stochastic weather generators, and threshold-downscaling techniques (George & P, 2023).

For hydrological impact studies, Bias Correction and Spatial Disaggregation (BCSD) is one of the most commonly used methods (Kornelsen et al., 2015). These two techniques aim at correcting two major shortcomings: the systematic statistical bias and the coarse spatial resolution of the GCM output (Chandel et al., 2024). The methodology is largely divided into two parts. The first part is the Bias Correction followed by Spatial Disaggregation. Bias Correction is the monthly output associated with GCM to statistically match the historical data of a given baseline period. In most cases, it is made through quantile mapping, meaning the GCM's whole distribution from mean to extreme values has to correspond sufficiently with the record of the observed climate. The Spatial Disaggregation step elevates the corrected biases into a higher resolution. The second part is downscaling the bias-corrected data on a finer grid by systematically merging the coarse-scale monthly GCM projections with a high-resolution observed climatology (Maraun et al., 2017). This technique, in particular, is good at retaining the more realistic patterns of local spatial structure especially patterns caused by topography and surfaces, the climate change signal shaped by the GCM. The BCSD technique has been essential in creating ready-for-analysis datasets such as the NASA Earth Exchange Global Daily Downscaled Projections (NEX-GDDP-CMIP6), which provides the high-resolution daily data required for driving regional impact models like SWAT+ (Chandel et al., 2024). Given its suitability for hydrological impact studies, the Bias Correction and Spatial Disaggregation (BCSD) method was selected for this research).

2.4. Climate Scenario

Climate scenarios, including Shared Socioeconomic Pathways (SSPs), Special Report on Emissions Scenarios (SRES), and Representative Concentration Pathways (RCPs), are mostly commonly used and they are essential for understanding future climate change dynamics. These frameworks help assess the interplay between socio-economic factors and greenhouse gas emissions, guiding climate policy and research (Strandsbjerg Tristan Pedersen et al., 2021). These scenarios are crucial inputs for driving General Circulation Models (GCMs), providing the basis for projecting future changes in temperature, precipitation, and other climate variables (Cointe, 2022). For this study, it used the Shared Socioeconomic Pathways (SSPs).

2.4.1 Shared Socioeconomic Pathways (SSPs)

The Shared Socioeconomic Pathways (SSPs) are a set of scenarios developed for the IPCC's Sixth Assessment Report to explore how future global socio-economic developments could influence climate change (Qin et al., 2023). This framework consists of five distinct narratives (SSP1-SSP5) that describe possible futures, ranging from sustainable development to regional rivalry and rapid, fossil-fueled growth. To create the full scenarios used in GCMs, these narratives are combined with specific climate outcomes measured in radiative forcing by the year 2100 (Nazarenko et al., 2022).

This study employs two contrasting scenarios, SSP2-4.5 and SSP5-8.5, to assess a wide range of potential impacts on water availability in Hargeisa watershed. The SSP2-4.5 "middle-of-the-road" scenario represents a future with moderate emissions and projects significant but varied changes; for example, while general water scarcity may increase, some areas like Ethiopia's Kessie Watershed could see a 5% increase in precipitation (Amognehegn et al., 2023). In stark contrast, the high-emissions SSP5-8.5 scenario poses more severe challenges, with projections of tripling energy demand leading to a potential 300% increase in water consumption, alongside reductions in major river flows of up to 18% (Pappis et al., 2020). By comparing the outcomes of the plausible, moderate-change

SSP2-4.5 with the high-impact, worst-case SSP5-8.5, this research provides a comprehensive assessment of the potential risks and opportunities for the Hargeisa watershed.

2.5. Trend Analysis of Hydro-Meteorological Data

Trend analysis is a crucial first step in climate impact studies, used to statistically identify and quantify long-term changes in historical data like precipitation and temperature. This process is essential for understanding the baseline climate of a region and for detecting existing shifts before projecting future impacts (Yilmaz & BiRdal, 2024). A standard and widely used method for this purpose is the non-parametric Mann-Kendall (MK) test. The MK test is used to determine if a monotonic (consistent upward or downward) trend exists within a time series and to assess whether that trend is statistically significant (Rasooly & Azimi, 2024). While the Mann-Kendall test effectively identifies the presence and significance of a trend, it does not quantify the magnitude or rate of that change. To accomplish this, the MK test is commonly paired with the Sen's Slope estimator. This is a robust non-parametric method that calculates the median of all slopes between data points in a time series (Hamid, 2023). The result is a single value representing the rate of change over time (e.g., mm/year for precipitation or °C/year for temperature). The combination of the MK test and the Sen's Slope estimator provides a comprehensive assessment of historical climatic trends (Ali & Abdul Ghani, 2024).

2.6. Hydrological Modelling

Hydrological models are the primary scientific tools used to translate climate data into on-the-ground impacts on a watershed's water balance. They simulate key processes of the water cycle, such as precipitation, runoff, and groundwater flow, allowing researchers to assess how water availability might change under different future climate scenarios (Dal Molin & Fenicia, 2023). However, the reliability of any hydrological model is fundamentally dependent on the quality of its input data and a robust calibration and validation process to minimize uncertainty in its predictions. One of the most popular tools of Hydrological models is a Soil and Water Assessment Tool plus (SWAT+).

2.6.1. Soil and Water Assessment Tool plus (SWAT+)

SWAT is a semi-distributed hydrological model that was established in the early 1990s. It is one of the most popular tools for simulating water quality and quantity (Tapas, Etheridge, Tran, Le, et al., 2024). Since the original model was built, technology has improved, allowing for more comprehensive hydrological modeling and making the model more complex (Tumsa et al., 2022). SWAT+ is an advanced version of SWAT with respect to data management, data analysis, data visualization, and process interaction at a watershed and sub-watershed level (Tapas, Etheridge, Tran, Finlay, et al., 2024). SWAT+ divides the watershed into sub-watersheds, sub-watersheds into landscape units, and landscape units into HRUs. An HRU is the smallest spatial unit in the SWAT+ i.e., there is at least one HRU per sub-basin. SWAT+ considers land cover, soil, and slope data for creating the HRUs. Although the basic equations for calculating flow in SWAT+ , such as the water balance equation, Manning's equation for channel flow, and the SCS curve number method for runoff estimation, have not been changed, significant changes have been made in the code and the formatting of the input files (Tapas, Etheridge, Tran, Finlay, et al., 2024). Due to these advanced capabilities, SWAT+ was chosen as the core tool for quantifying the climate changes in the Hargeisa watershed's water balance.

2.7. Impact of Climate change on Temperature and Precipitation

Climate change is significantly altering global temperature and precipitation patterns, leading to widespread environmental and socio-economic challenges. Projections forecast a potential global temperature rise ranging from 1.1°C to 5.4°C by the end of the 21st century under various emission scenarios (Al-Muhyi, 2022). These warming trends are already being observed, with consistent temperature increases recorded in regions like the Caspian Sea to Iraq (Hoseini et al., 2024). These shifts in climate are expected to lead to more frequent and intense extreme weather events, such as floods and droughts, posing significant challenges for climate adaptation efforts worldwide (Thomas & Cheung, 2024). These effects are particularly severe across Africa, which faces a range of ecological and socio-economic consequences. Projections for the continent show significant increases in both minimum and maximum temperatures, with some scenarios showing minimum temperatures rising by 2.94°C to 3.59°C and maximum temperatures by 2.61°C to 3.36°C (Abegaz, 2020). This warming, combined with projected declines in rainfall in some regions, has a harmful effect on agricultural productivity. The resulting decline in agricultural output often exacerbates food insecurity, particularly among vulnerable populations (Onyeaka et al., 2024).

Within East Africa, especially Ethiopia has already witnessed distinct changes. Studies have documented statistically significant increases in both minimum and maximum temperatures across the country (Gebrechorkos et al., 2019). While overall precipitation patterns show non-significant changes, the seasonal variability is a major concern. Rainfall has been observed to increase during some seasons but decrease during the critical Belg season, creating significant challenges for the nation's agriculture and water resource management (Abegaz, 2020).

The impacts of climate change are especially severe in Somaliland, where they directly affect agriculture and livelihoods. Over the past three decades, some regions has experienced notable trends of declining rainfall and warming temperatures, posing direct challenges to rain-fed agriculture and food security. Yearly temperature increases have been recorded, while annual rainfall has been observed to decrease by 1.5 mm/year to 2 mm/year in key agricultural regions. (Sharmake et al., 2022). This combination of reduced rainfall and rising temperatures has led to crop failures and heightened food insecurity, creating an urgent need for adaptation strategies for that regions. (Omer, 2024)

Therefore, while general trends of some regions are known, there is a clear need to re-evaluate the impacts of climate change in Somaliland using the latest generation of climate models. This study addresses this need by utilizing downscaled climate data from the Coupled Model Inter-comparison Project Phase Six (CMIP6). The CMIP6 models represent a significant advancement over previous generations, with improved representations of climate processes and a new, more advanced set of socio-economic scenarios (the SSPs). By incorporating these latest GCM projections, this research will provide a more current and robust assessment of the potential future changes in temperature and precipitation for the Hargeisa watershed, forming a critical foundation for the subsequent hydrological impact analysis.

2.8. Climate Change Impact on Water Resources

Climate change is significantly disrupting global water resources by altering the hydrological cycle. Rising temperatures and changing precipitation patterns are leading to increased evaporation, altered river flows, and a surge in extreme weather events like floods and droughts (Ciampittiello et al., 2024). These pressures, combined with growing water demand, are exacerbating water scarcity worldwide and putting extreme strain on available water supplies (Novruzova, 2022). These impacts are particularly acute across Africa, where climate change is leading to more variable weather and greater water scarcity. While some projections indicate an increase in precipitation in parts of East Africa, the overall trend is one of high variability, with changing rainfall patterns and rising temperatures impacting river flows across the continent (Emmanuel Augustine Etukudoh et al., 2024). These changes have profound socio-economic consequences for the many African communities that rely on rain-fed agriculture for their livelihoods (Thakur, 2024).

2.8.1. Empirical Review of Hydrological Impacts in East Africa

Impacts on Streamflow and Surface Runoff in the Wabi Shebelle Basin While specific studies on the Hargeisa watershed are limited, significant research has been conducted in the hydrologically similar Wabi Shebelle basin. Recent modeling efforts have produced contrasting results regarding future runoff, highlighting the uncertainty in regional climate projections. For instance, studies on the Melka Wakena catchment (Upper Wabi Shebelle) using the SWAT model driven by CORDEX-Africa projections predicted a statistically insignificant reduction in annual streamflow under both RCP4.5 and RCP8.5 scenarios for the mid-century. In contrast, research in the Weyib River sub-basin (also part of Wabi Shebelle) utilizing the WetSpass-M model found a dramatic increase in surface runoff, projecting rises of up to 36% by mid-century due to increased rainfall intensity. These diverging outcomes where some sub-basins dry and others flood underscore the high spatial variability of the Horn of Africa's climate and the necessity for localized, sub-basin specific modeling rather than generalized regional assessments.

Impacts on Groundwater Recharge in Semi-Arid Zones Groundwater recharge in semi-arid East Africa is highly sensitive to changes in rainfall intensity. Traditional "piston flow" models often predict decreased recharge due to rising evapotranspiration (ET). For example, studies in the Usangu catchment in Tanzania predicted a decrease in groundwater recharge of 7% to 26% under future climate scenarios, driven primarily by a 30% increase in ET that consumes the additional precipitation. However, other researchers have documented a counter-intuitive phenomenon in the Horn of Africa known as the "intensity effect." A study in the Sezibwa catchment (Uganda) observed a 40% increase in recharge despite warming temperatures. This occurs when increased rainfall intensity allows water to rapidly infiltrate via macropores (bypass flow) during flash floods, effectively escaping the evaporation zone before it can be consumed. This mechanism is particularly relevant for the Hargeisa watershed, where ephemeral flash floods are the primary source of aquifer replenishment.

Methodological Approaches in Data-Scarce Regions The challenge of modeling ungauged catchments in the Horn of Africa has driven the adoption of regionalization techniques. The use of "proxy-basin" or "donor catchment" calibration—where parameters are transferred from a physically similar gauged catchment—is a well-established methodology validated by the International Association of Hydrological Sciences (IAHS) during the "Predictions in Ungauged Basins" (PUB) decade.To establish a regional context for the impacts of climate change, this section provides a critical review of recent hydrological impact studies conducted in the nearby and hydrologically similar Wabi Shebelle River Basin in Ethiopia. A significant body of work investigated the impacts of climate change on hydrological processes in the Weyib River basin, a major sub-basin of the Wabi Shebelle. The main methodology involved using the ArcSWAT hydrologic model driven by downscaled climate data from three CMIP5 GCMs under RCP2.6, RCP4.5, and RCP8.5 scenarios. The conclusion was that the Weyib River Basin faces a dual risk of increased flooding in the wet seasons and more severe water shortages in the dry season, necessitating careful, season-specific water management strategies (Serur & Sarma, 2018).

On the hand, the other investigated blue and green water resources availability in the Weyib River basin, again using the ArcSWAT model with CMIP5 GCMs. The study's key findings showed a projected increase in mean annual blue water flow (streamflow and deep aquifer recharge) of up to 28% and green water flow (evapotranspiration) of up to 30% under a high-emissions scenario. A crucial conclusion from this work was that spatial variations between sub-basins are very high, emphasizing the need for sub-basin level adaptation strategies rather than a single basin-wide plan (Serur, 2020). These studies of the Wabi Shebelle basin collectively establish a clear regional trend of increasing seasonal variability and growing water stress due to population pressure. However, these studies were conducted using the older generation of CMIP5 climate models and their associated RCP scenarios, therefore is a clear need to re-evaluate these hydrological impacts using the latest, more advanced CMIP6 climate projections and their SSP scenarios, which this thesis will address. Furthermore, while these studies provide an excellent regional analogue, no known research has applied this level of detailed, process-based hydrological modeling specifically to the ungauged Hargeisa watershed.

2.8.2. Climate change impact on water resources on Somaliland

Somaliland is currently undergoing a dire water shortage, which has been worsened by climate change provides more details (Sharmake et al., 2022). Research on Somaliland consistently confirms that its water resources are under significant threat from climate change, with studies indicating a worsening water shortage driven by rising temperatures and erratic rainfall that strains limited water sources, leading to crop and livestock losses

(Omer, 2024). Future climate projections suggest a significant shift in seasonal patterns, with wet seasons expected to become shorter and more intense while dry seasons become longer, increasing the dual risk of both floods and droughts (Warsame et al., 2021b). However, while these studies effectively document the general nature of the threat, a critical knowledge gap remains. There is a notable lack of quantitative, process-based analysis showing precisely how future climate change will change the specific hydrological components such as surface runoff, groundwater recharge, and evapotranspiration within this watershed most critical water systems. The current understanding is largely descriptive and lacks the detailed, watershed-specific projections needed for effective, long-term water resource management. Therefore, this research addresses this specific gap. By employing the Soil and Water Assessment Tool plus (SWAT+) driven by the latest generation of CMIP6 climate projections, this research will provide a detailed, quantitative assessment of climate change impacts on the water availability of the Hargeisa watershed. Crucially, to overcome the challenge posed by the absence of a permanent streamflow gauging station in the watershed, this study will implement a regionalization method to effectively calibrate and validate the hydrological model that has never been made before. The findings will move beyond the general problem description to deliver the evidence-based projections required to develop robust and sustainable water management strategies for this vital region.

3. MATERIALS AND METHODS

3.1. Description of the Study Area

3.1.1. Location

The Hargeisa watershed is an important water basin located in the Marodi-jeh region of Somaliland, which includes the capital city of Hargeisa. It is a semi-arid region and geographically (ogo). The study area, as indicated in Figure 3.1, is located between 9°30' and 9°45' N latitude and 43°50' and 44°15' E longitude. This watershed is fed by a network of seasonal rivers and streams, covering roughly 1,270 square kilometers. It serves as the main water source for the region's population, estimated to be over 1.7 million in 2020. The basin's topography significantly affects its water flow, with a notable elevation change. The land slopes from the highlands in the south and west down to the lower plains in the northeast. This gradient influences how water runs off the surface and affects erosion.

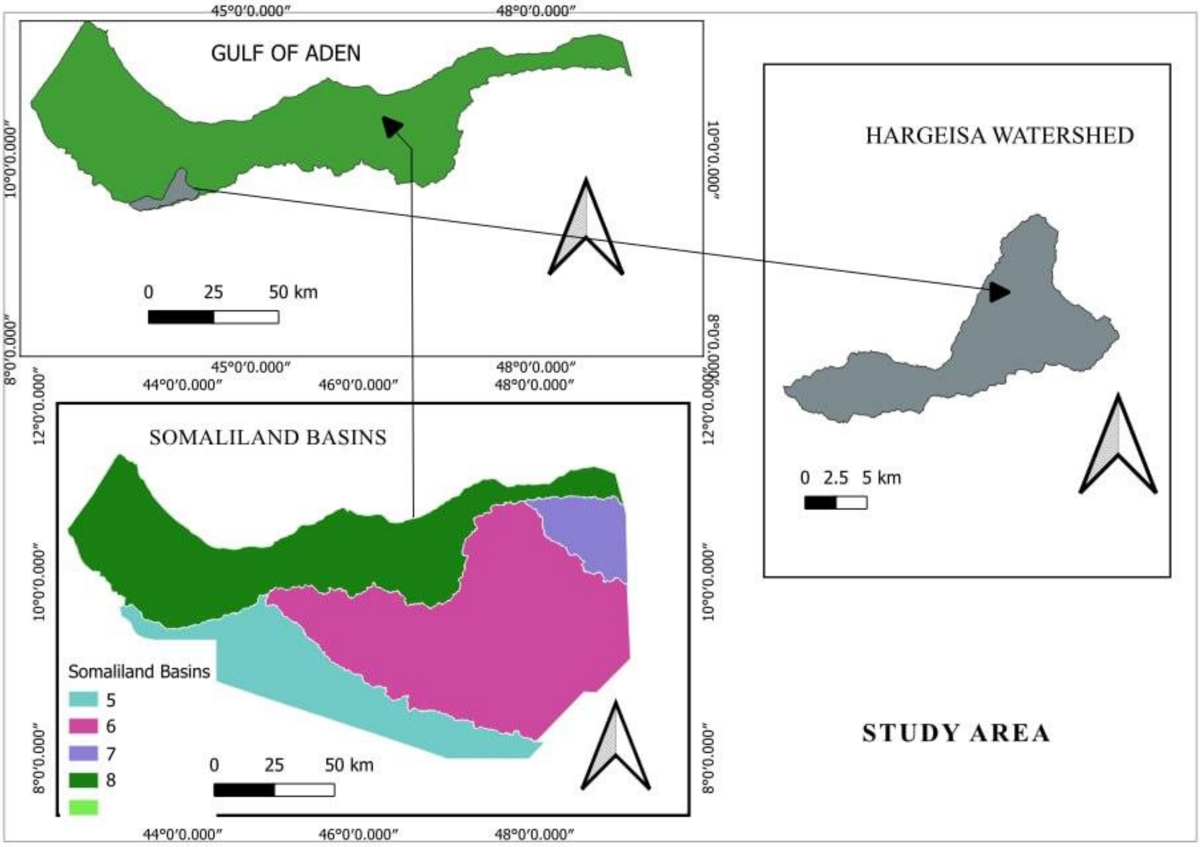

Figure 3. 1: Location map of Hargeisa watershed

3.1.2. Topography

The Hargeisa watershed is characterized by a varied topography with a significant elevation gradient, which is a key factor in its hydrological and erosional processes. The elevation within the watershed ranges from 877 m to 1693 m above sea level. As illustrated in Figure 3.2, the higher elevations are predominantly found in the southern and western parts of the catchment, gradually sloping down towards the lower plains in the northeast, where the dam is situated. The distribution of land across these elevation classes shows a clear pattern: the majority of the watershed lies at lower altitudes, with over 34% of the land below 1004 m and another 31% situated between 1004 m and 1145 m. Conversely, the higher, steeper regions are less extensive, with less than 3% of the catchment area located above 1464 m. This landscape, transitioning from steep upper regions to flatter lowlands, influences surface runoff patterns and helps identify potential areas of high erosive energy.

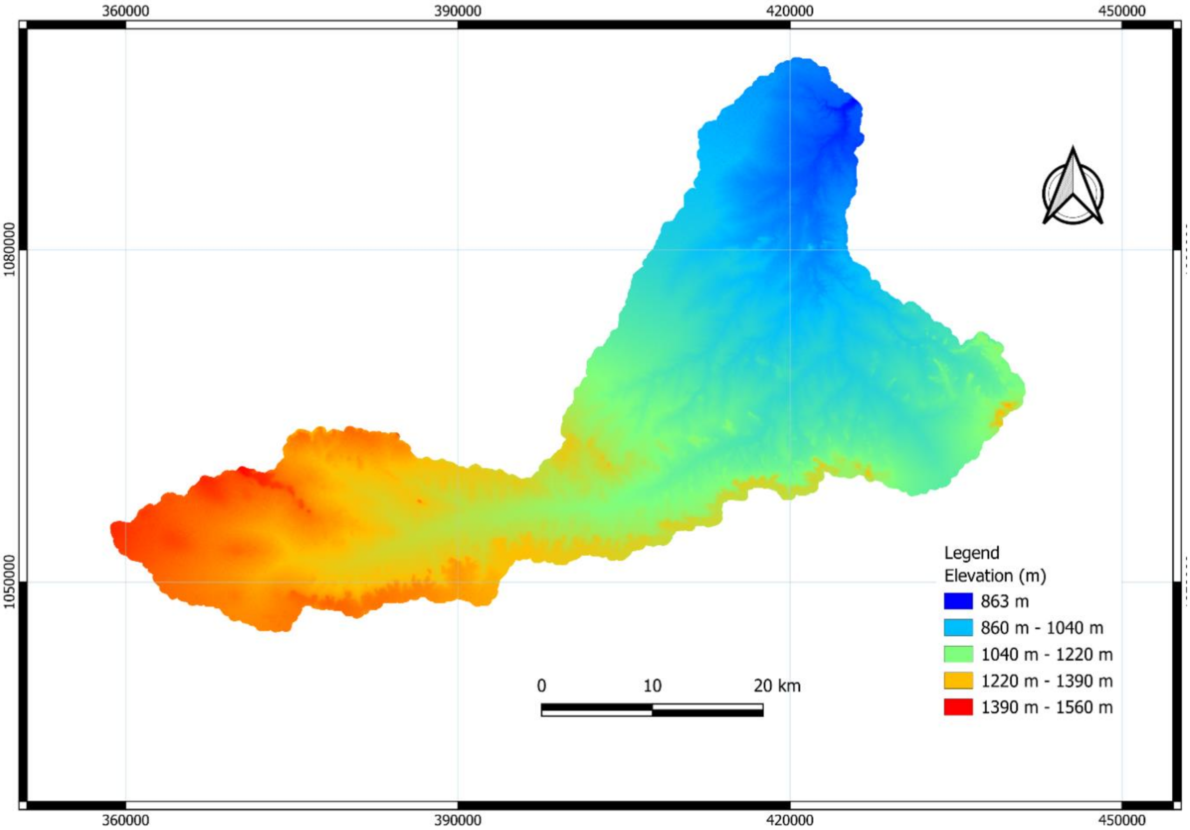

Figure 3. 2: Topographic Map of the Hargeisa watershed

3.1.3. Climate Condition

The climate of the Hargeisa watershed is characteristic of a semi-arid region, dominated by high temperatures year-round and a distinctly bimodal rainfall pattern. This precipitation cycle consists of two primary rainy seasons: the "Gu" rains from March to May, which peak in April with an average of approximately 58 mm, and the "Deyr" rains from August to October, peaking at around 48 mm. These wet periods are separated by a long, pronounced dry season ("Jilaal") from December to February, where rainfall is minimal, and a shorter, cooler dry spell ("Hagaa") in June and July. The hot temperatures are observed in a rainfall pattern that is bimodal. Having average monthly maximum temperatures ranging from 27.5 °C to 33.5 °C and average monthly minimums ranging between 13 °C to 19.5 °C, having average temperatures as stated also serves as a determinant of temperature regime. Having a large change in temperature from day time to nighttime is an important characteristic of this kind of climate. Along with the bimodal rainfall events, the watershed temperatures serve to characterize the watershed and set the fundamental considering the hydrological analysis of the study further.

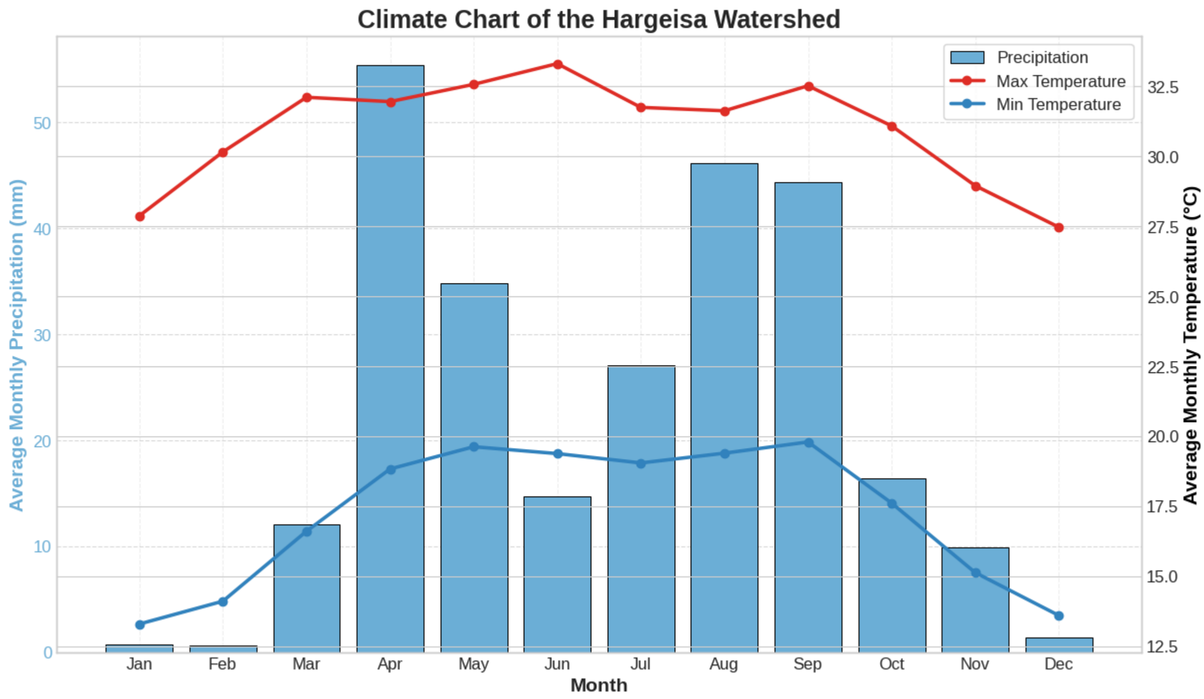

Figure 3. 3: Climate chart of Hargeisa watershed

3.1.4. Land Use/Cover

The land use and land cover (LULC) of the Hargeisa watershed are primary drivers of its hydrological and erosional response. The LULC distribution for this study was classified from satellite imagery, and the results indicate that the watershed is predominantly characterized by natural and semi-natural landscapes. The Shrub land is the single largest LULC class, covering 51.9% of the total area. This is followed by Barren or Sparsely Vegetated land, which occupies 24.6%. Land used for grazing (Pasture) and cultivation (Agricultural Land) together account for just over 21% of the catchment. Urban areas and forests constitute the smallest portions of the landscape. The spatial distribution of these classes, which was used as a key input for the SWAT model, is shown in Figure 3.4.

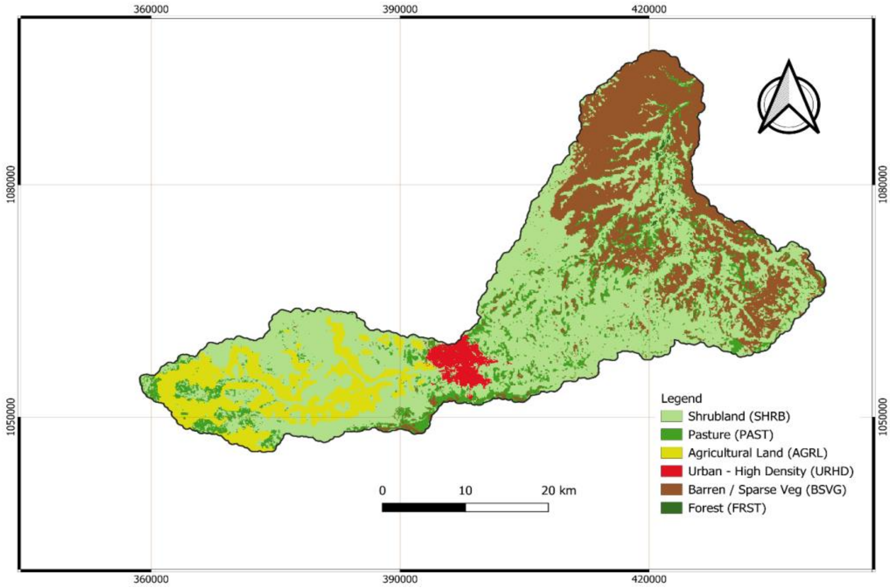

Figure 3. 4: Land Use/Cover Map of the Hargeisa watershed

3.1.5. Soil

The soil characteristics of the Hargeisa watershed were defined using the Digital Soil Map of the World (DSMW), with the spatial distribution of soil orders shown in Figure 3-4. The analysis reveals that the watershed is overwhelmingly dominated by Inceptisols, which cover 63.5% of the entire catchment area. These are young soils with minimal horizon development, common in a range of climates. Other significant soil orders present include Alfisols (16.4%) and Entisols (12.5%). The presence of these soil orders, which were a critical input for parameterizing the SWAT model, reflects the erosional and depositional environment of the region.

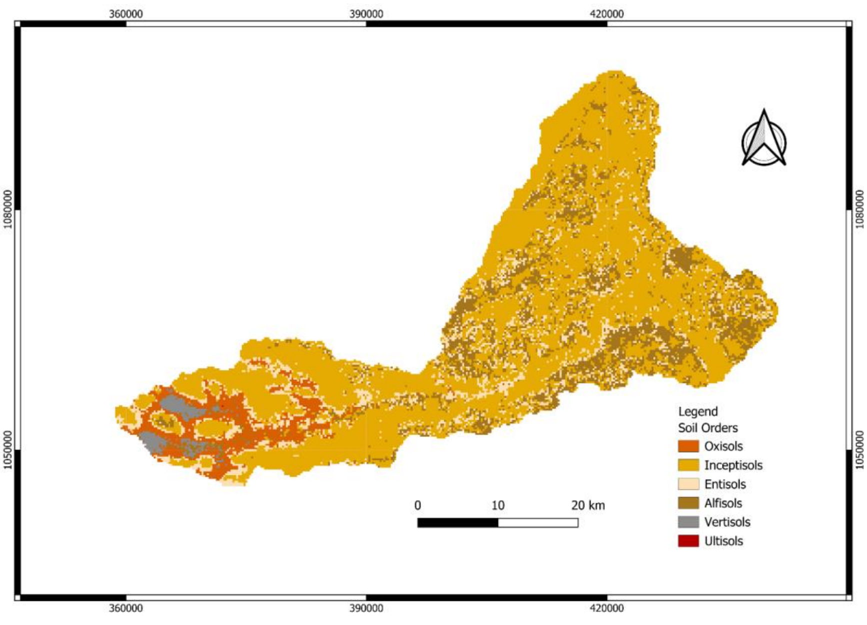

Figure 3. 5: Soil Map of the Hargeisa watershed

3.2. Datasets and Software

This research required spatial, hydro-meteorological, and climate datasets from diverse sources, which were focused on the hydrological evaluation of the Hargeisa watershed. Preprocessing of data began with obtaining GCM outputs using Google Earth Engine (GEE), running homogeneity tests on historical records using the Rainbow application, and performing all geospatial processing of DEM, soil, and land use data using the QGIS platform. The core hydrological simulation was executed using a strategic two-model regionalization approach, a method necessitated by software and cost constraints. First, an ArcSWAT model was developed for the gauged Dagahbur donor catchment, which was then calibrated and validated against observed streamflow using the SWAT-CUP tool. The resulting optimized parameters were then carefully transferred into the SWAT+ Editor to parameterize the target model. This crucial step prepared the model before beginning the final simulation of the Hargeisa watershed using the more advanced SWAT+ software. This two-step process was specifically adopted to overcome the prohibitive cost of the dedicated SWAT+ CUP calibration tool and the compatibility issues between SWAT+ and the available SWAT-CUP software. Throughout this workflow, the Python programming language was employed for various supplementary data analysis, statistical processing, and automation tasks.

3.3. Input Data Used and their Sources

Successful hydrological modeling of the Hargeisa watershed using the SWAT+ model relied on a comprehensive collection of spatial, hydro-meteorological, and physical datasets. Due to the data-scarce nature of the study region, a multi-source approach was essential, combining information from local governmental bodies, globally accessible satellite products, and climate model outputs. The primary inputs included spatial data (DEM LULC, Soil) to define the watershed's topography and land use; historical climate and streamflow records to establish a baseline and perform model calibration and validation; soil data to characterize subsurface properties; and projected climate data from Global Circulation Models (GCMs) to drive the future scenario analysis. Table 3.1 provides a detailed summary of each dataset required for this research, along with its specific description and source.

Table 3. 1: Data required and its sources

Data Type	Description	Source(s)
Spatial Data	Digital Elevation Model (DEM) for watershed delineation and topographic analysis. Land Use/Land Cover (LULC) map to define land surface characteristics.	Shuttle Radar Topography Mission (SRTM) via USGS, Copernicus Land Cover
Meteorological Data	Daily records of rainfall, maximum/minimum temperature, relative humidity, wind speed, and solar radiation.	Ministry of Agriculture (Somaliland), Ethiopian National Meteorological Agency, CHIRPS (Satellite Rainfall Data)
Streamflow data	Observed Monthly streamflow data used for model calibration and validation at the donor catchment.	Ministry of Water and Energy (Ethiopia)
Soil Data	Physical properties including soil classification, texture (sand, silt, clay proportions), bulk density, and available water capacity.	The Digital Soil Map of the World (DSMW
Projected Climate Data	Downscaled daily precipitation and temperature data from Global Climate Models (GCMs) for future climate scenarios (SSP2-4.5 & SSP5-8.5).	NASA Earth Exchange Global Daily Downscaled Projections (NEX-GDDP-CMIP6) via Google Earth Engine (GEE)

3.3.1. Meteorological Data

This study utilized two distinct sets of meteorological data for different purposes: one for the historical analysis of the Hargeisa watershed and another for the calibration of the model for the Dagahbur donor catchment. For the primary analysis of the Hargeisa watershed, a continuous daily time series was prepared for a 30-year period (1995-2024). Observed records for six stations were obtained from the Ministry of Agriculture (Somaliland). As these instrumental records contained gaps, they were supplemented with satellite and reanalysis products to create a complete dataset. Missing rainfall data were filled using the Climate Hazards Group InfraRed Precipitation with Station data (CHIRPS), while all other missing variables were sourced from the NASA Prediction of Worldwide Energy Resources (POWER) project. The details of these stations are summarized in Table 3.2.

Table 3. 2: Meteorological Stations of Hargeisa Watershed

No	Station Name	Latitude	Longitude	Elevation	Record Length in Years
1	Hargeisa	9.557778	44.05167	1271	1995-2024
2	Aburin	9.81743	43.80575	1445	1995-2024
3	Dararweye	9.432	44.23264	1057	1995-2024
4	Botor	9.637806	44.07053	1259	1995-2024
5	Geed deeble	9.76598	43.98228	1093	1995-2024
6	Dhubato	9.4013	44.4659	1125	1995-2024

For the regionalization process, meteorological data were required to drive the SWAT model for the gauged Dagahbur catchment. This data was provided by the Ethiopian National Meteorological Agency for three stations located within the donor catchment. The details of these stations are summarized in Table 3.3.

Table 3. 3: Meteorological Stations Used for the Dagahbur Donor Catchment

No	station name	latitude	longitude	ELEVATION	Record Length in Years
1	Dagahbur	8.230	43.560	1070.	1990-2019
2	Jijiga	9.370	42.7207	1557.	1990-2019
3	Lefessa	9.500	42.900	1700	1990-2019

3.3.2. Streamflow Data

Observed streamflow data were essential for the calibration and validation of the hydrological model via the regionalization approach. For this purpose, an 11-year record of observed monthly streamflow data was obtained for the Dagahbur catchment, which served as the gauged "donor" basin for this study. The Dagahbur catchment is located entirely within the Somali administrative state of Ethiopia. The data provided by the Ministry of Water and Energy (Ethiopia) was critical for developing a robust and reliable parameter set to be transferred to the ungauged Hargeisa watershed model.

Table 3. 4: Streamflow Gauging Station for the Dagahbur Donor Catchment

No	station name	Latitude	longitude	ELEVATION	Record Length in Years
1	Dagahbur	8.22	43.3	1070	1990-2000

3.3.3. Spatial Data

Spatial datasets are fundamental inputs for the SWAT model, as they are used to represent the physical characteristics of the watershed. This study utilized three key types of spatial data: a Digital Elevation Model (DEM) to define the topography, a Land Use and Land Cover (LULC) map to represent surface characteristics, and a soil map to define subsurface properties.

3.3.3.1. Digital Elevation Model (DEM)

Topography is characterized by a digital elevation model (DEM), which indicates the elevation of any point within a specified area at a certain spatial resolution. For this study, DEMs were obtained from the United States Geological Survey (USGS). A high-resolution 30-meter Shuttle Radar Topography Mission (SRTM). This data served as the primary input for watershed delineation and stream network generation, as well as the calculation of key topographic parameters such as sub-basin slope.

3.3.3.2 Land Use and Land Cover (LULC)

The Land Use/Land Cover (LULC) data were generated using the Copernicus Global Land Cover 100m map for the year 2020. This global dataset offers a detailed snapshot of the landscape's surface features. The raw data were downloaded and clipped to the respective watershed boundaries, and the original classes were then reclassified into specific categories required by the SWAT model, such as Shrub land (SHRB), Agriculture (AGRL), and Barren (BARR). This processed LULC map is essential for the model setup, as it defines the surface components of the Hydrologic Response Units (HRUs). Each LULC class is assigned unique parameters within the SWAT model, such as runoff curve numbers and surface roughness coefficients. These parameters directly influence the model's simulation of surface runoff, evapotranspiration, and infiltration, making the LULC layer a critical driver of the water balance.

3.3.3.3 Soil Data

Soil properties are a fundamental input for defining the Hydrologic Response Units (HRUs) and simulating key hydrological processes like infiltration, percolation, and soil water storage (Sulieman et al., 2020). For this study, soil characteristics were obtained from the Digital Soil Map of the World (DSMW), which provides globally consistent soil information. To prepare the data for the model, these soil classifications were linked to a specialized user database. Key physical properties essential for SWAT, including soil texture (sand, silt, and clay fractions), available water capacity (AWC), bulk density, saturated hydraulic conductivity, and organic carbon content were assigned to each soil type. This process provided the necessary soil-specific parameters to accurately simulate water movement through the soil profile, critically influencing infiltration rates, subsurface water storage, and percolation to deeper groundwater layers.

3.4 Data Preparation and Analysis

This section provides an overview of the essential steps required to process the historical climate and hydrology data before its integration into the SWAT model. In order to maintain the quality and integrity of the time-series data, several preparatory activities were conducted. These activities include filling minor gaps in climate records, testing the homogeneity of the data to ensure consistency, and conducting statistical trend analyses to detect any significant historical trends in the watershed's climate. Such analyses are essential to create dependable baselines and ensure solid material inputs for the hydrological modeling and climate impact analyses that follow.

3.4.1. Missing data filling

The historical hydro-meteorological records used in this study, particularly the daily rainfall and temperature time series, contained intermittent gaps due to instrument error or periods of no observation. Because a complete and continuous dataset is required for hydrological modeling with SWAT, a robust method was needed to fill these missing values. To address this challenge, the quintile mapping technique was used. This statistical method is used to fill the gaps by adjusting the distribution of a complete secondary dataset (such as data from a nearby station or a gridded product) to match the observed statistical distribution of the primary station's data. This process ensured that the missing data was filled in a way that well-maintained the unique statistical characteristics of the local climate records, resulting in a complete and consistent input dataset for the subsequent analyses.

3.4.2. Homogeneity Test

Homogeneity testing of hydro-meteorological data is crucial to determine whether time series, such as rainfall, temperature, or streamflow, maintain consistent statistical characteristics over time, free from artificial shifts caused by changes in measurement techniques, station relocations, or other non-climatic influences (Patakamuri et al., 2020). The homogeneity of the daily precipitation records from the meteorological stations can evaluated using the Rainbow software package (Patakamuri et al., 2020). The primary method of the double-mass curve analysis is used to check the consistency of a station's data over time relative to its neighbors. In addition to the visual inspection of the curve, the Rainbow software plots the cumulative deviation from the mean against statistical confidence limits (Khalil, 2021; Singh, 1968), . For this study, the double-mass curve analyses for all six stations produced straight trend lines, and the cumulative deviation remained well within the 95% confidence limit. This provided both visual and statistical confirmation that the precipitation datasets were homogeneous and suitable for use in the SWAT model. The graphical outputs from the Rainbow software is presented in Appendix figure 3-6

3.4.3. Variability analysis

An analysis of the historical hydro-meteorological data was performed to quantify its inter-annual and seasonal variability. This step was essential for understanding the magnitude of natural fluctuations in the climate system before assessing long-term trends. Standard statistical metrics, including the standard deviation and the coefficient of variation (CV), were calculated for key variables such as precipitation and temperature. The analysis was conducted on both an annual and a seasonal basis to characterize the historical patterns of wet and dry periods. This provided a quantitative baseline of the climate's variability, which is critical for contextualizing the results of the trend analysis and for evaluating the significance of future projected changes. The coefficient of variation (CV) was calculated using the following standard equation

$$\mathbf{CV} = \left(\frac{\boldsymbol{\mu}}{\boldsymbol{\sigma}}\right) \times \mathbf{100}\% \qquad \text{Equation 0-1}$$

Where CV is the coefficient of variation

σ is the standard deviation of the data

μ is the mean of the data

3.4.4. Trend analysis

To identify any significant, long-term changes in the historical climate records, a trend analysis was performed using the Mann-Kendall (MK) test and the Sen's Slope estimator. This approach was chosen to statistically detect if a consistent (monotonic) upward or downward trend exists in the data and to quantify the magnitude of that trend over the entire period of record.

3.4.4. 1. Mann-Kendall (MK) Trend Test

The Mann-Kendall (MK) test is a widely used statistical method for assessing if there is a monotonic (consistently increasing or decreasing) trend in a time series of data (Sudarsan & Lasitha, 2023). As a non-parametric test, it does not require the data to be normally distributed, making it a robust tool for analyzing hydro-meteorological variables, which often have skewed distributions (Yue & Wang, 2002). The test evaluates the null hypothesis (H 0), which assumes that no significant trend exists, against the alternative hypothesis (H a) that a monotonic trend is present. It functions by systematically comparing each data value with all subsequent data values to calculate the test statistic, S. This statistic is the sum of the positive and negative signs of the differences between data points. A large positive or negative S value indicates a likely trend, which is then formally assessed by calculating a p-value. If the p-value is less than a chosen significance level (e.g., α = 0.05), the null hypothesis is rejected, and the trend is considered statistically significant (Balakrishnan & Tan, 2016). This comprehensive statistical approach was employed in this study to analyze the historical time series of key climate variables like precipitation and temperature. The test statistic S is calculated as Equation 3.2:

$$\mathbf{S} = \sum_{i=1}^{n-1} \sum_{j=i+1}^{n-1} sign(xj - xi) \qquad \text{Equation 0-2}$$

Where:

n is the number of data points

xi and xj are the data values at times i and j (where j>i)

sgn (xj−xi) is the sign function, which is +1 if the difference is positive, -1 if it is negative, and 0 if there is no difference.

2. **The Variance of S (Var (S))**

The variance of S is calculated to standardize the test statistic, accounting for any tied values in the data.

$$\mathbf{Var(S)} = \frac{\mathbf{n(n-1)(2n+5)-\sum_{k=1}^{m} tk(tk-1)(2tk+5)}}{\mathbf{18}} \qquad \text{Equation 0-3}$$

Where:

n = number of data points

m = number of tied groups

tk = number of data points in the k-th tied group

3. **The Standardized Test Statistic (Z)**

This value allows the trend's significance to be tested against the standard normal distribution.

$$\mathbf{Z} = \begin{cases} \frac{s-1}{\sqrt{v(s)}} \\ 0 \\ \frac{s+1}{\sqrt{v(s)}} \end{cases} \qquad \text{Equation 0-4}$$

Where:

S = The Mann-Kendall trend statistic; a positive value means an increasing trend, a negative value means a decreasing trend.

Var(S) = the variance of the S statistic, used to standardize the result

3.5. Assessment of climate change impacts on rainfall and temperatures characteristics

The impacts of climate change on rainfall and temperature are critical for understanding water availability in the Hargeisa watershed. This section outlines the methodologies and approaches used to assess these impacts, focusing on the types of General Circulation Models (GCMs) and Shared Socio-economic Pathways (SSPs), downscaling techniques, and future projections of rainfall and temperature.

3.5.1 Types of GCMs and SSPs Used in this Research

To project the future climate of the Hargeisa watershed, this study used a set of climate projections from the Coupled Model Intercomparison Project Phase 6 (CMIP6). Three distinct Global Circulation Models (GCMs) were selected: CanESM5 (with a spatial resolution of approximately 2.81° × 2.81°), NorESM2-MM (0.9° × 1.25°), and GFDL-ESM4 (1.25° × 1.00°). The reason for selecting these three models is based on their differing climate sensitivities and regional performance in East Africa, which allows this study to capture a wide range of potential future climate outcomes, thus providing a robust assessment of uncertainty (Balcha et al., 2022).

To capture a representative range of future climate possibilities for the Hargeisa watershed, this study utilizes projections from three distinct Global Circulation Models (GCMs) selected from the Coupled Model Intercomparison Project Phase 6 (CMIP6) ensemble: CanESM5, GFDL-ESM4, and NorESM2-MM. These specific models were chosen based on their differing equilibrium climate sensitivities and their established performance in reproducing historical climate patterns across East Africa. By selecting models with distinct physical parameterizations, the research aims to minimize the bias inherent in relying on a single climate model and provide a robust assessment of potential future conditions. The experimental design of this research involves a factorial combination of these three GCMs across multiple time horizons and emission pathways, resulting in a total of 15 distinct climate simulations. This ensemble includes three historical baseline simulations (1995–2024) to establish reference conditions. For future projections, each of the three GCMs was simulated under two contrasting Shared Socioeconomic Pathways: the "middle-of-the-road" scenario (SSP2-4.5) and the high-emissions "fossil-fueled development" scenario (SSP5-8.5). Furthermore, these scenarios were analyzed across two future time periods: the Mid-Century (2031–2060) and the End-of-Century (2071–2100).

Table 3. 5: List of Climate Simulation Scenarios Used in this Research

ID	Model	Scenario	Period	Symbol
1	CanESM5	Historical	1995-2024	CanESM5_hist_95-24
2	GFDL-ESM4	Historical	1995-2024	GFDL_hist_95-24
3	NorESM2-MM	Historical	1995-2024	NorESM2_hist_95-24
4	CanESM5	SSP2-4.5	2031-2060	CanESM5_245_31-60
5	CanESM5	SSP2-4.5	2071-2100	CanESM5_245_81-00
6	GFDL-ESM4	SSP2-4.5	2031-2060	GFDL_245_31-60
7	GFDL-ESM4	SSP2-4.5	2071-2100	GFDL_245_71-00
8	NorESM2-MM	SSP2-4.5	2031-2060	NorESM2_245_31-60
9	NorESM2-MM	SSP2-4.5	2071-2100	NorESM2_245_71-00
10	CanESM5	SSP5-8.5	2031-2060	CanESM5_585_31-60
11	CanESM5	SSP5-8.5	2071-2100	CanESM5_585_71-00
12	GFDL-ESM4	SSP5-8.5	2031-2060	GFDL_585_31-60
13	GFDL-ESM4	SSP5-8.5	2081-2100	GFDL_585_71-00
14	NorESM2-MM	SSP5-8.5	2031-2060	NorESM2_585_31-60

15	NorESM2-MM	SSP5-8.5	2081-2100	NorESM2_585_71-00

3.5. 2. Downscaling Approach and Bias Correction

A critical challenge in climate change impact studies is the scale mismatch between the outputs of General Circulation Models (GCMs) and the requirements of watershed-scale hydrological models (Chang et al., 2023). GCMs operate at a coarse spatial resolution, often hundreds of kilometers per grid cell, which is unsuitable for representing the local climate and topography of a specific basin like the Hargeisa watershed. Therefore, downscaling is the process of translating these coarse GCM outputs to a finer, local scale.

Given its suitability for hydrological impact studies, a statistical downscaling approach was selected for this research, specifically the Bias Correction and Spatial Disaggregation (BCSD) method. The BCSD method is a scientifically robust and widely accepted technique designed to correct two fundamental limitations of raw GCM data, their systematic statistical biases and their coarse spatial resolution (Chandel et al., 2024). The process first corrects the GCM's statistical distribution to match the observed local climate record, then translates this corrected data onto a finer grid. This two-step approach is essential for creating the analysis-ready, high-resolution daily climate data required to accurately drive a detailed hydrological model like SWAT+.

3.5. 3. Future projection of rainfall and temperatures and scenarios statistics

This subsection outlines the statistical analysis performed on the downscaled GCM projections to quantify future changes in the characteristics of precipitation and temperature for the Hargeisa watershed. The analysis was conducted by comparing projected climate data for two future 30-year periods, the Mid-Century (2031–2060) and the End-of-Century (2071–2100), against the historical Baseline (1995–2024). To quantify these changes, a percentage change approach was used for precipitation, while a delta change (absolute change) approach was used for maximum and minimum temperatures.

Change in Precipitation (%)

The projected percentage change in mean precipitation (annual or seasonal) was calculated to determine the relative increase or decrease in rainfall. The standard equation used is:

$$\textbf{Percentage Change}(\%) = \left(\frac{\textbf{Pfuture} - \textbf{Pbaseline}}{\textbf{Pbaseline}}\right) \times \mathbf{100}$$

Equation 0-5

Where:

Pfuture is the mean precipitation for the future period

Pbaseline is the mean precipitation for the historical baseline period

Delta Change in Temperature (°C)

The projected change in mean maximum (T max) and minimum (T min) temperature was calculated as the absolute difference, or delta change, between the future and baseline periods. The standard equation used is:

$$\boldsymbol{\Delta T = Tfuture - T\ baseline}$$
Equation 0-6

Where:

ΔT is the delta change in temperature (°C)

T future is the mean temperature (T max or T min) for the future period

T baseline is the mean temperature (T max or T min) for the historical baseline period

3.6. Soil and Water Assessment Tool plus (SWAT+)

SWAT is a semi-distributed hydrological model that was established in the early 1990s. It is one of the most popular tools for simulating water quality and quantity (Tapas, Etheridge, Tran, Le, et al., 2024). Since the original model was built, technology has improved, allowing for more comprehensive hydrological modeling and making the model more complex (Tumsa et al., 2022). SWAT+ is an advanced version of SWAT with respect to data management, data analysis, data visualization, and process interaction at a watershed and sub-watershed level (Tapas, Etheridge, Tran, Finlay, et al., 2024). SWAT+ divides the watershed into sub-watersheds, sub-watersheds into landscape units, and landscape units into HRUs. An HRU is the smallest spatial unit in the SWAT+ i.e., there is at least one HRU per sub-basin. SWAT+ considers land cover, soil, and slope data for creating the HRUs. Although the basic equations for calculating flow in SWAT+ , such as the water balance equation, Manning's equation for channel flow, and the SCS curve number method for runoff estimation, have not been changed, significant changes have been made in the code and the formatting of the input files (Tapas, Etheridge, Tran, Finlay, et al., 2024). Such as checking groundwater recharge in Bangladesh, figuring out how likely soil erosion is in the Philippines, simulating urban flooding in India, predicting water shortages in different climate scenarios, and making hourly streamflow and soil moisture estimates better. While SWAT+ offers valuable insights for water resource management and environmental planning, continuous model refinement and validation are crucial to address challenges in accurately capturing complex interactions within watershed systems(University of the Philippines Los Banos et al., 2024).

3.6.1. Hydrological component of SWAT+

The hydrological component of SWAT+ simulates the movement and transformation of water within a watershed by tracking water balance within each Hydrological Response Unit (HRU). Key processes contain surface runoff generation, infiltration, percolation, groundwater flow, evapotranspiration, and channel routing. Surface runoff is simulated using approaches like the Curve Number method, while infiltration and percolation processes govern water movement through soil layers. Groundwater flow is modeled considering factors like aquifer properties and recharge rates. Evapotranspiration is estimated based on plant characteristics, soil moisture, and meteorological conditions. Finally, channel routing simulates water movement through the channel network, considering factors like channel geometry and flow velocity. This united approach provides a complete framework for simulating the hydrological response of a watershed to various inputs, enabling researchers to analyze water resources availability, assess flood risks, and evaluate the impacts of different management scenarios.

3.6.2. Watershed delineation

After preparing the Digital Elevation Model (DEM) data, the watershed delineation, a foundational step in setting up the SWAT+ model for the Hargeisa watershed, was carried out. In this step, the stream network, watershed outlet, and sub-basin boundaries were determined. The stream network was generated based on a specified flow accumulation threshold. The threshold used in this study was 300 ha or 3 km^2, which defines the minimum drainage area required to initiate a stream. Next, the main outlet for the entire watershed was defined within the QGIS interface. After establishing the streams and the outlet, the model performed an initial delineation. If any sub-basins were smaller than a required minimum size, they were merged with adjacent sub-basins to ensure model stability. This process resulted in a final delineation of 17 sub-basins for the Hargeisa watershed, as shown in figure 3.6.

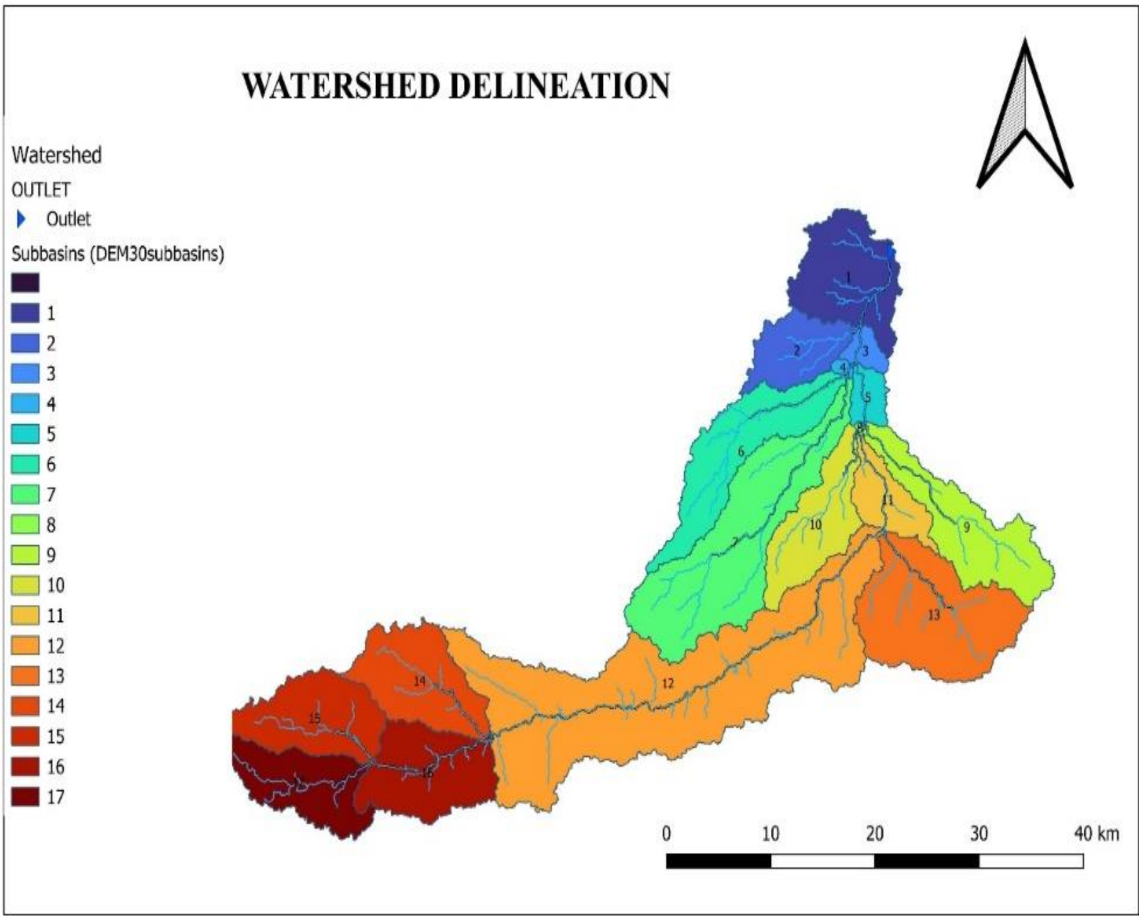

Figure 3. 6: Watershed delineation

3.6.3. Hydrologic response unit's determination

Identifying HRUs is essential for successful hydrological modeling, allowing the representation of spatial variability within a watershed. Techniques like PCA/HCPC, which employ gridded meteorological data and hydrological parameters, have been used to define HRUs, leading to enhanced model accuracy (Poblete et al., 2020). The Curve Number method, using GIS-based analysis, improves parameterization and simplifies calibration complexity (Savvidou et al., 2018). Remote sensing data aids HRU delineation by considering terrain, land use, and vegetation coverage, offering valuable insights into hydrological characteristics (Wei et al., 2017). In urban environments, adjusting HRU parameters is critical due to modified hydrological systems. While these methodologies offer robust frameworks, challenges remain in integrating various data sources and ensuring model applicability across various hydrological contexts. Additional research is required to improve these methods and boost predictive performance in intricate environments.

Following the sub-basin delineation, a Hydrologic Response Unit (HRU) analysis was conducted to discretize the watershed into smaller, computationally distinct areas representing unique combinations of land use, soil type, and slope. The creation of HRUs was performed by overlaying the project's land use map and soil map with a slope map derived from the DEM. The watershed was discretized using four slope classes based on specified slope bands: 0–4%, 4–12%, 12–30%, and >30%. This initial, unfiltered overlay of the land use, soil, and slope layers generated a total of 7,625potential HRUs across the watershed's 17 sub-basins. To find a balance between computational efficiency and model resolution, a thresholding method was then applied to combine and exclude small combinations. The combination procedure resulted in a final, acceptable number of HRUs for application in the subsequent hydrological simulations.

3.6.4. Sensitivity analysis

Sensitivity analysis was conducted to find which streamflow parameters affect to the greatest degree. This assists focused calibrations by guiding initial attempts toward those parameters that will achieve the greatest calibration efficiency. This analysis was done within the SWAT-CUP framework under the Sequential Uncertainty Fitting (SUFI-2) approach.

3.6.5. Model Calibration and Validation

To ensure that the model parameters accurately represent the regional hydrological processes, a rigorous calibration and validation procedure was performed on the Dagahbur catchment. This step is essential, as modern hydrological modeling practices emphasize the need for robust calibration to enhance model accuracy and reliability, particularly in data-scarce regions (Akoko et al., 2021). The entire process utilized the SWAT-CUP software package (Abbaspour, 2015), which integrates the Sequential Uncertainty Fitting (SUFI-2) algorithm with the SWAT model. The calibration and validation procedure was performed using the 11-year streamflow record for the Dagahbur station (1990–2000). This dataset was partitioned into three distinct phases: a warm-up period (1990–1991) to initialize the model, a calibration period (1992–1997) where model parameters were adjusted against observed data, and a separate validation period (1998–2000) to test the model's predictive accuracy on data it had not been trained on. Due to the complete absence of historical streamflow records for the Hargeisa watershed, a direct calibration was not possible. To overcome this critical data gap, a regionalization approach was employed.

3.6.6. Regionalization Approach and Justification of Donor Catchment

Due to the absence of a permanent streamflow gauging station within the Hargeisa watershed, direct calibration of the SWAT+ model was not possible. To overcome this limitation, a regionalization approach was employed, specifically the parameter transfer method. This method involves calibrating the model parameters in a gauged "donor" catchment and transferring the optimized parameter set to the ungauged "target" watershed (Hargeisa). Regionalization is a fundamental technique in hydrology for making predictions in ungauged basins where direct streamflow measurements are unavailable (Narbondo et al., 2020). This is a standard hydrological technique that involves calibrating a model for a nearby, gauged "donor" catchment and then transferring the optimized model parameters to the target ungauged basin. For this study, the combination of spatial proximity and physical similarity, to select the Dagahbur catchment in the Wabi Shabele basin in Ethiopia, approach was considered. The spatial proximity principle suggests that nearby catchments are more likely to have similar climate patterns and produce similar hydrological responses (Narbondo et al., 2020a). The Dagahbur catchment was a top candidate because it is one of the closest gauged basins to the study area. However, proximity alone is not enough, as well as physical similarity, which showed that the Dagahbur catchment shares important features with the Hargeisa watershed, such as its semi-arid climate, a bimodal rainfall pattern, and similar topography was considered. Using this dual-criterion approach increased confidence that the donor catchment was a suitable hydrological analogue, providing a solid basis for the parameter transfer that would follow.

3.6.6.1 Selection of the Donor Catchment (Hydrological Similarity)

The Dagahbur catchment, located in the Wabi Shebelle basin of the Ethiopian Somali region, was selected as the donor catchment based on the dual criteria of spatial proximity and physical similarity. Hydrological theory suggests that catchments with similar climatic, topographic, and land cover characteristics will exhibit similar hydrological responses (Runoff, Infiltration, ET). As detailed in Table 3.4 (see below), the Dagahbur catchment functions as a suitable hydrological analogue to the Hargeisa watershed. Both catchments are situated within the same semi-arid climatic zone of the Horn of Africa and share the distinct bimodal rainfall pattern ("Gu" and "Deyr" seasons) that drives the region's hydrology. Furthermore, both watersheds are dominated by shrubland vegetation and Inceptisol soil groups, ensuring that the parameters governing surface roughness and soil moisture retention are comparable. Parameter transfer was the particular regionalization technique employed in this Research (Poblete et al., 2020). In order to choose the best donor catchment, this procedure was guided by a dual-criterion approach that evaluated both physical similarity and spatial proximity. Because it is one of the closest gauged basins and shares important traits with Hargeisa, such as a semi-arid climate and bimodal rainfall, the Dagahbur catchment was selected. In order to create an optimal parameter set, the SWAT model for the gauged Dagahbur catchment was first calibrated and validated against its observed streamflow record. The hydrological response of the ungauged Hargeisa watershed was then simulated by directly transferring this optimized set of parameters to the SWAT+ model via SWAT+ Editor.

Table 3. 6: Comparison of Physical and Climatic Characteristics between Donor and Target Catchments

Characteristic	Target: Hargeisa Watershed	Donor: Dagahbur Catchment	Similarity Justification
Climate Zone	Semi-Arid	Semi-Arid	Both regions experience high evaporation and water scarcity.
Rainfall Pattern	Bimodal (Gu & Deyr seasons)	Bimodal	Similar seasonal rainfall distribution drives runoff timing.
Dominant Land Cover	Shrubland (51.9%)	Shrubland/Grassland	Similar vegetative resistance to flow and transpiration rates.
Dominant Soil	Inceptisols (63.5%)	Inceptisols/Xerosols	Similar infiltration capacities and soil water storage properties.
Topography	Highland slopes to plains	Highland slopes to plains	Similar elevation gradients influencing runoff velocity.

3.7. Model performance evaluation

The performance of the SWAT model for the donor catchment was quantitatively evaluated by comparing the simulated monthly streamflow against the observed data from the

Dagahbur station. To provide a comprehensive assessment, four widely accepted statistical performance indicators were used. These metrics were calculated for both the calibration and validation periods to ensure a robust assessment of the model's predictive capability. The primary metric was the Nash-Sutcliffe Efficiency (NSE), The Nash-Sutcliffe efficiency is a normalized statistic that determines the relative magnitude of the residual variance ("noise") compared to the measured data variance ("information") (Nash and Sutcliffe, 1970). NSE describes how well the simulated line matches the observed line by plotting on the same scales. NSE ranges from -∞ to 1, and 1 is the optimal value of NSE. That NSE is close to 1 indicates good model quality and high model reliability. That NSE is close to 0 indicates that the simulation results are close to the average level of the observed values. If NSE is much less than 0, the model is not credible.

The general presentation ratings can be classified into four levels for a one-month time step model. When NSE is between 0.75 and 1, the show rating of the hydrological model is very good. Performance rating is good when NSE is between 0.65 and 0.75. Furthermore, performance rating is satisfactory when NSE is between 0.65 and 0.75. Furthermore, performance rating is satisfactory when NSE is between 0.50 and 0.65. While when NSE is between 0.5, performance rating is unsatisfactory (Yimer et al., 2023). In addition, the Coefficient of Determination (R^2) was used to measure the degree of linear correlation between simulated and observed data, with values greater than 0.5 generally considered acceptable (Ines Gharnouki et al., 2024). To provide a more robust diagnostic assessment, the Kling-Gupta Efficiency (KGE) was also employed; with an optimal value of 1, this metric evaluates the model by balancing the trade-offs between correlation, bias, and variability.

Finally, Percent Bias (PBIAS) is used. PBIAS is a key performance indicator that measures the average tendency of the simulated data to be larger (overestimation) or smaller (underestimation) than the observed data. It is a crucial metric for evaluating the model's overall water balance error. The optimal PBIAS is 0%, with fewer values indicating fewer average errors that the simulated series have. When PBIAS is in the range of ±10%, the performance rating of the hydrological model is very good. Performance rating is good when the absolute PBIAS is between 10% and 15%. Furthermore, performance rating is satisfactory when absolute PBIAS is between 15% and 25%. When PBIAS is lower than -25% or higher than 25%, the performance rating is unsatisfactory (Jose & Dwarakish, 2022).

The formulas for these indicators are presented here:

$$R^2 = \frac{\sum_{i=1}^{N}(O_i - O_i)^2(n(O_i - O_i)^2)}{\sum_{i=1}^{N}(O_i - O_i)^2((P_i - P_i)^2)}$$ Equation 0-7

$$NSE = 1 - \frac{\sum_{i=1}^{N}(O_i - P_i)^2}{\sum_{i=1}^{N}(O_i - \bar{O})^2}$$ Equation 0-8

$$PBIAS = 1 - \frac{\sum_{i=1}^{N}(O_i - P_i)^2}{\sum_{i=1}^{N} O_i} \times 100$$ Equation 0-9

Where:

- $\boldsymbol{O_i}$ Is the observed value
- $\boldsymbol{P_i}$ is the simulated value
- $\boldsymbol{\bar{O}}$ is the mean of observed data
- N Is the total number of observations.

$$KG = -1\sqrt{((r - 1)^2 + (\alpha - 1)^2 + (\beta - 1)^2}$$ Equation 0-10

Where:

r (Correlation): Measures the timing and shape of the data

α (Variability Ratio): Measures the data's fluctuation

β (Bias Ratio): Measures the model's overall bias

3.7. Climate Change Impact Analysis on Water Availability

The final step of the methodology was to quantify the potential impacts of climate change on the water availability of the Hargeisa watershed. This analysis was conducted by driving the calibrated and validated SWAT+ model with the downscaled climate projection data for the selected future periods and scenarios (SSP2-4.5 and SSP5-8.5).

The simulated hydrological outputs from these future scenarios were then systematically compared against the outputs from the established historical baseline period. This comparison focused on identifying the magnitude and direction of change (%) in the key water balance components, including surface runoff, groundwater recharge, actual evapotranspiration, and net water yield. This scenario-based analysis provided a quantitative assessment of the potential future climate changes to the watershed's hydrology, the results of which are presented and discussed in the subsequent chapters.

3.8. Overall Methodology Flowchart of Hargeisa Watershed Study

The overall methodology employed in this study is organized into three interconnected stages. The first is the Hydrological Modeling Workflow, which involved setting up and calibrating the donor catchment model using ArcSWAT, followed by transferring the parameters to and simulating the historical baseline for the Hargeisa watershed using the SWAT+ model. The second stage is the GCM Climate Data Workflow, which focused on preparing and downscaling future climate projections. Finally, in the Impact Analysis stage, the outputs from the historical and future simulations were compared to quantify the projected impacts of climate change on water availability.

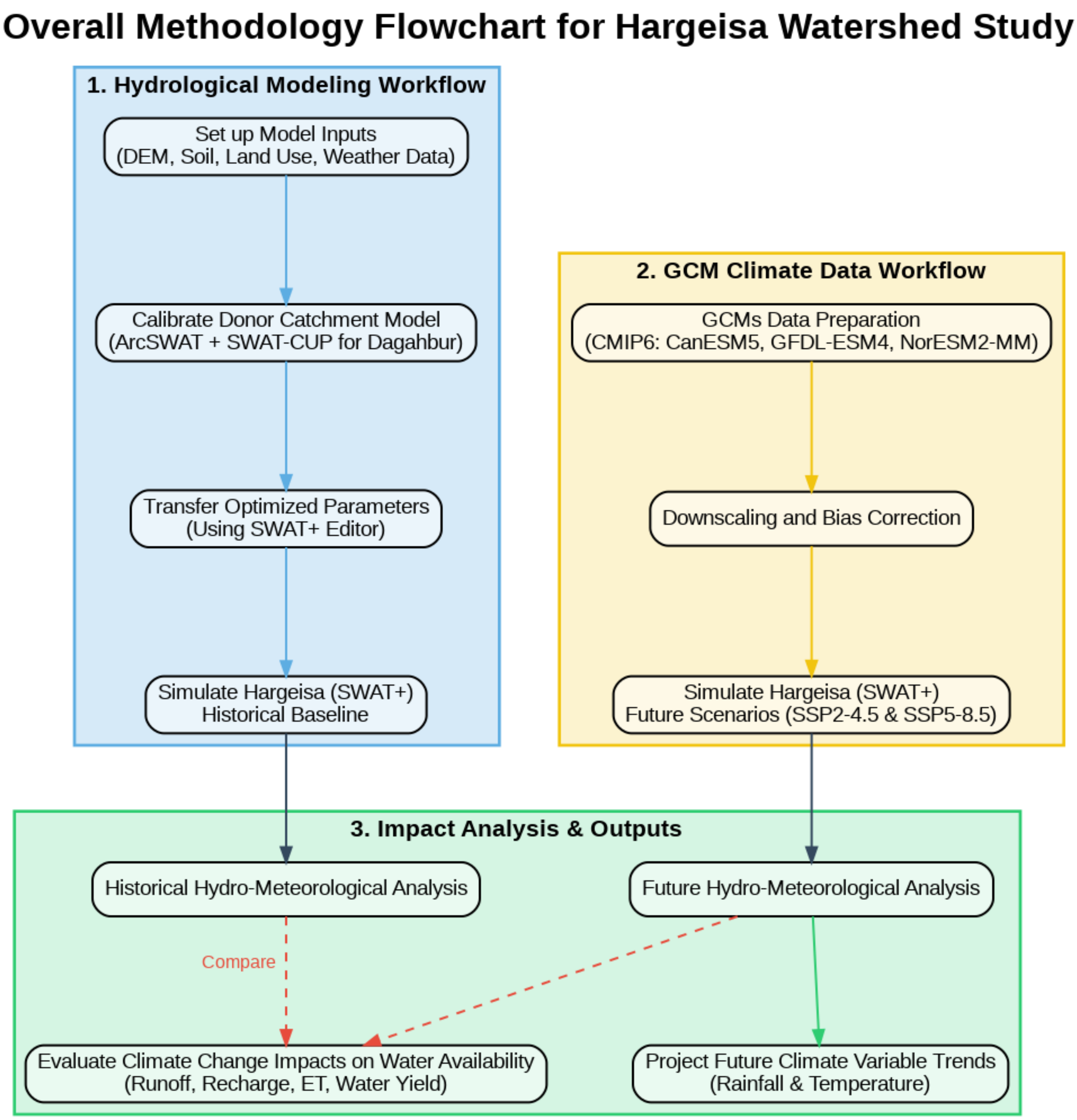

Figure 3. 7: Flowchart of Overall Methodology

4. RESULTS AND DISCUSSION

This chapter presents the findings of the study, beginning with the spatiotemporal variability and trend of rainfall and temperatures over the Hargeisa Watershed in Somaliland, followed by the future climate projections, the performance of the calibrated SWAT+ model, and finally, the projected impacts of climate change on the water availability of the Hargeisa Watershed.

4.1 Spatiotemporal Variability and Trend of Historical Data (1995-2024)

To fulfill the first objective, a trend analysis was conducted on the historical (1995-2024) daily time series of precipitation and temperature (T max and T min) for the six meteorological stations within and around the Hargeisa watershed. The non-parametric Mann-Kendall test was used to identify statistically significant trends, while the Sen's Slope estimator was employed to quantify their magnitude. The analysis revealed significant trends in precipitation and minimum temperature, while maximum temperature showed no significant. A detailed summary of the results is presented in Table 4.1.

Table 4. 1: Summary of Trend Analysis for Key Climate Variables (Precipitation, Tmax, and Tmin) in the Hargeisa watershed (1995-2024)

Station	Variable	Kendall's tau	MK Statistic (S)	P-Value	Sen's Slope Estimate	Trend	Statistically Significant (Yes/No)
Aburin	Precipitation	0.577	251	0	+13.19 mm/year	Increasing	Yes
	Tmax	0.1402	61	0.2844	+0.016 °C/year	Increasing	No
	Tmin	0.2828	123	0.0295	+0.018 °C/year	Increasing	Yes
Botor	Precipitation	0.4253	185	0.001	+7.83 mm/year	Increasing	Yes
	Tmax	0.1908	83	0.1435	+0.016 °C/year	Increasing	No
	Tmin	0.2414	105	0.0635	+0.020 °C/year	Increasing	No
Dararweyne	Precipitation	0.554	241	0	+7.02 mm/year	Increasing	Yes
	Tmax	0.1908	83	0.1435	+0.016 °C/year	Increasing	No
	Tmin	0.2414	105	0.0635	+0.020 °C/year	Increasing	No
Dhubato	Precipitatio	0.3931	171	0.002	+12.95	Increasi	Yes

	n			4	mm/year	ng	
	Tmax	0.1908	83	0.1435	+0.016 °C/year	Increasing	No
	Tmin	0.2414	105	0.0635	+0.020 °C/year	Increasing	No
Geed_deeble	Precipitation	0.4161	181	0.0013	+6.85 mm/year	Increasing	Yes
	Tmax	0.1908	83	0.1435	+0.019 °C/year	Increasing	No
	Tmin	0.3241	141	0.0125	+0.025 °C/year	Increasing	Yes
Hargeisa	Precipitation	0.3977	173	0.0022	+12.67 mm/year	Increasing	Yes
	Tmax	0.1908	83	0.1435	+0.016 °C/year	Increasing	No
	Tmin	0.2414	105	0.0635	+0.020 °C/year	Increasing	No

To visually illustrate the year-to-year variability and the nature of the trends summarized in Table 4.1, the complete time-series plots for annual precipitation, maximum temperature, and minimum temperature are presented in Figures 4.1, 4.2, and 4.3, respectively. The analysis reveals a distinct and consistent increasing trend in annual precipitation across all six stations, though this is accompanied by high inter-annual variability. The magnitude of this positive trend ranges from +6.85 mm/year at Geed_deeble station to a high of +13.19 mm/year at Aburin station. Concurrently, the watershed has experienced a clear warming trend. The average maximum temperature (Tmax) shows a consistent increase at all locations. Similarly, the average minimum temperature (Tmin) also exhibits a strong positive trend across the board, with warming rates between +0.018°C/year and +0.025°C/year. Collectively, these trends paint a clear picture of a changing climate in the Hargeisa watershed over the past three decades, characterized by a definitive shift towards warmer and wetter conditions.

Figure 4. 1: Historical trends of annual precipitation

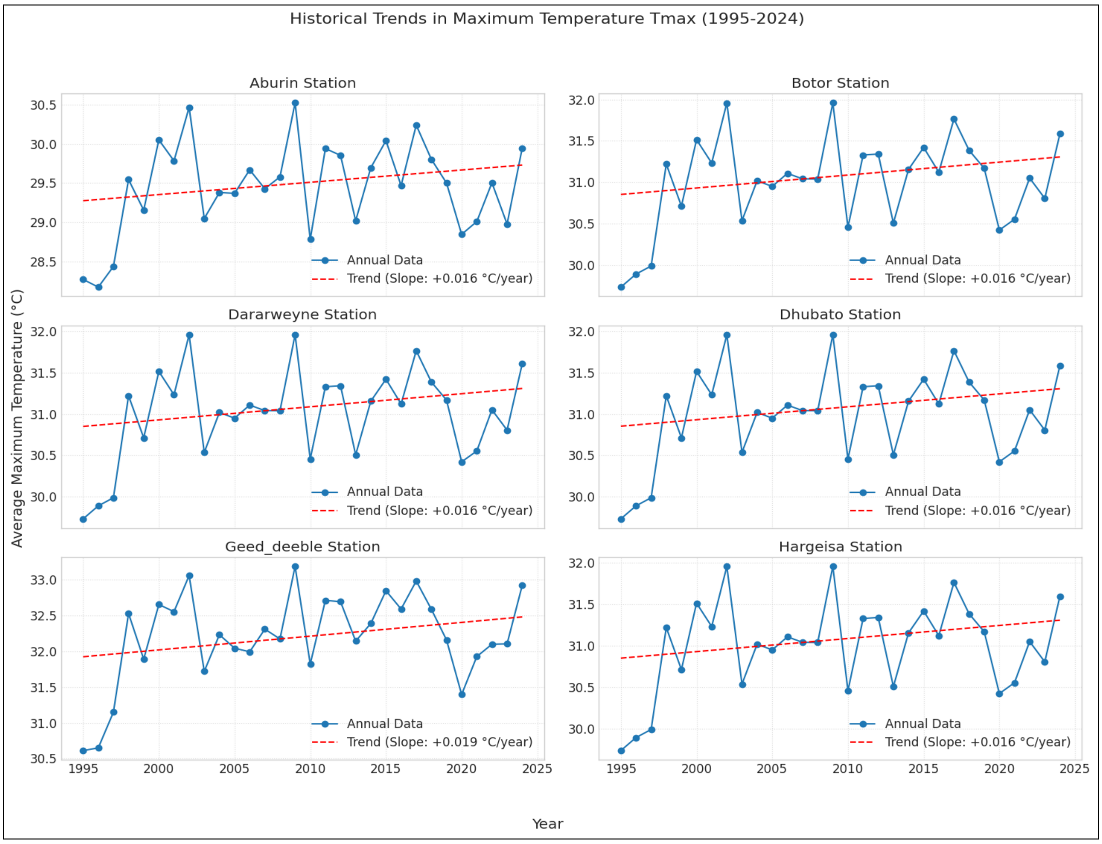

Figure 4. 2: Historical trends in maximum temperature

Figure 4. 3: Historical trend of minimum temperature

The analysis of historical climate data from 1995-2024 reveals a clear pattern of change within the Hargeisa watershed, with significant implications for regional water resources. The most critical finding is the statistically significant increasing trend in annual precipitation observed across all six meteorological stations. This result provides localized, data-driven evidence that helps resolve the long-debated 'East African Climate Paradox,' which contrasts observed drying trends with climate model projections of a wetter future. The findings of this study align with authoritative analyses by researchers (Onyutha, 2024), who forecast an increase in heavy precipitation for the region. While an increase in total rainfall may seem beneficial for a semi-arid region, the high year-to-year variability shown in the figures suggests a trend towards more intense rainfall events rather than more frequent gentle rains. This pattern could lead to increased surface runoff and soil erosion, potentially reducing the overall effectiveness of rainfall for groundwater recharge (Wainwright et al., 2021).

In terms of temperature, the analysis reveals a nuanced pattern of asymmetric warming. While both Tmax and Tmin are showing an increase, but Tmin a significant increase in nighttime temperatures (Tmin) at a majority of the stations indicates a clear warning signal, a phenomenon referred to as asymmetric warming (Cook et al., 2020). This pattern has significant implications for the watershed's water balance and local livelihoods. Warmer nights increase the nighttime respiration rate of plants, which leads to higher overall evapotranspiration (ET) and can offset the benefits of rising precipitation, potentially resulting in drier soil conditions (Faculty of Engineering Kampala International University Uganda & Ukwuaba, 2024). Furthermore, many local crops and native plants in the Hargeisa watershed are adapted to cool, dewy nights. The reduction in dew formation caused by warmer nighttime temperatures removes a crucial moisture source for seedlings and grasses. Therefore, this warming trend represents a direct, negative pressure on the Hargeisa watershed's overall water availability and ecosystem health.

4.1.2 Spatial Pattern of Historical Trends

To visualize the spatial distribution of the historical climate trends summarized in Table 4.1, interpolated maps were created from the station-level data. This analysis reveals that the changes in precipitation and temperature are not uniform across the Hargeisa watershed.

The spatial trend for total annual precipitation shown in Figure 4.2 confirms a widespread and statistically significant increase in rainfall across the watershed. However, the magnitude of this increase shows a clear spatial pattern. The trend toward wetter conditions is most pronounced in the western and southwestern portions, where the rate of increase exceeds 13 mm/year, as seen at the Aburin station (+13.19 mm/year). In contrast, the trend is less intense in the northeastern areas, with the rate of increase dropping to approximately 7 mm/year. This spatial heterogeneity suggests that the climatic shifts are not uniform across the region, likely influenced by local topography. The more pronounced increase in precipitation in the western, lower-elevation areas could have significant hydrological implications, potentially leading to a greater increase in both surface runoff and groundwater recharge in those specific sub-basins.

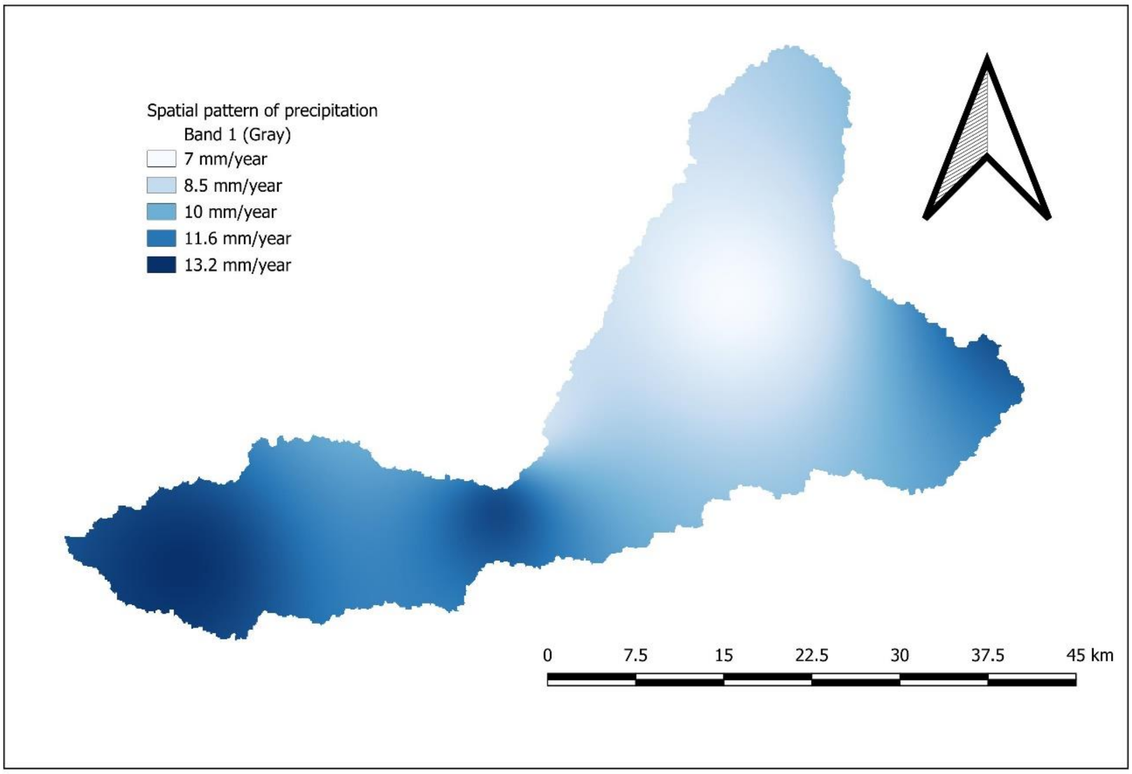

Figure 4. 4: Spatial pattern of the historical trend in total annual precipitation

The spatial analysis of mean annual temperature, shown in Figure 4.3 reveals a warming pattern across the entire watershed, although the trend was only statistically significant at the Geed_deeble station (+0.025 °C/year). The map illustrates a distinct spatial gradient, with the warming trend being most pronounced in the central and eastern, higher-elevation portions of the watershed, where rates generally exceed +0.020 °C/year. This pattern is consistent with the phenomenon of elevation-dependent warming, a concept in climate science where higher-altitude regions experience more rapid temperature increases (Cheng, 2022). The implications of this spatial pattern are critical for the watershed's hydrology. Accelerated warming in the eastern, higher-elevation headwaters will likely lead to significantly higher evapotranspiration rates in these crucial water source areas. This may reduce the overall water yield that flows to the downstream parts of the watershed, posing a long-term risk to water security for the entire region and potentially offsetting some of the benefits gained from increased precipitation.

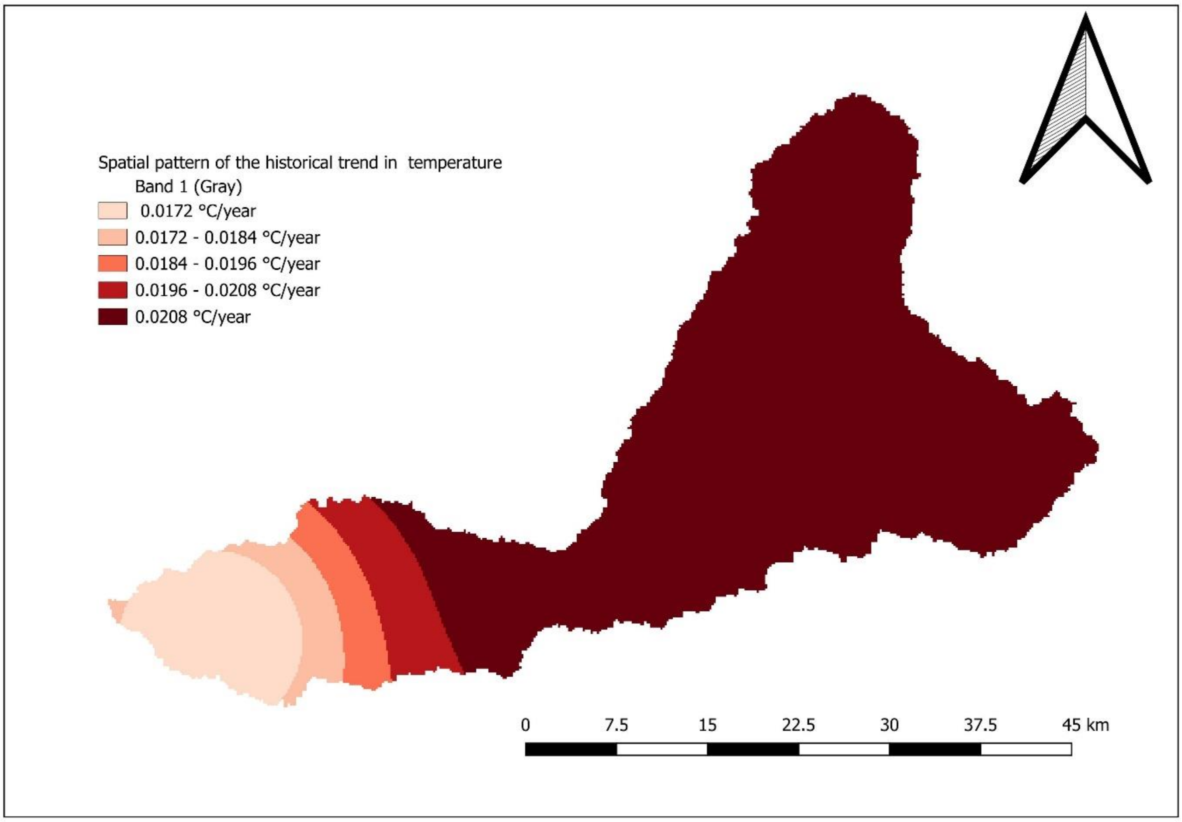

Figure 4. 5: Spatial pattern of the historical trend in mean annual temperature

4.2 Future Climate Projections

To fulfill the second objective, the future climate of the Hargeisa watershed was projected using downscaled data from three Global Circulation Models (GCMs): CanESM5, GFDL-ESM4, and NorESM2-MM. The analysis was conducted for two future periods, the Mid-Century (2031–2060) and the End-of-Century (2071–2100), under both a moderate emissions scenario (SSP2-4.5) and a high emissions scenario (SSP5-8.5). All projected changes were calculated as deviations from the simulated historical baseline period of 1995–2024. The most robust finding from the GCM ensemble is the strong consensus for significant and accelerating warming throughout the 21st century. The ensemble average of the three models resulted in a mean annual temperature of approximately 23.31 °C and a mean annual precipitation of 356.35 mm/year. All three models, under both emissions scenarios, project a continued increase in mean annual temperature. This finding is consistent with, yet exceeds, earlier projections for the region. For example, a previous study like Climate Change Impacts on Water Resources of Somaliland and Puntland (Petersen & Gadain, 2012) projected a rise of up to 3.0°C for Somaliland. Our findings, based on the latest generation of CMIP6 models, suggest that the rate of warming could be substantially higher, potentially reaching as high as +6.8°C by the end of the century under the high-emissions SSP5-8.5 scenario (Figure 4.5). This intensification of the warming trend underscores the vulnerability of the Hargeisa watershed and has critical implications for water availability, as higher temperatures will drive up evapotranspiration rates, increasing stress on all water resources. The visual results of these projections are shown in Figure 4.6.

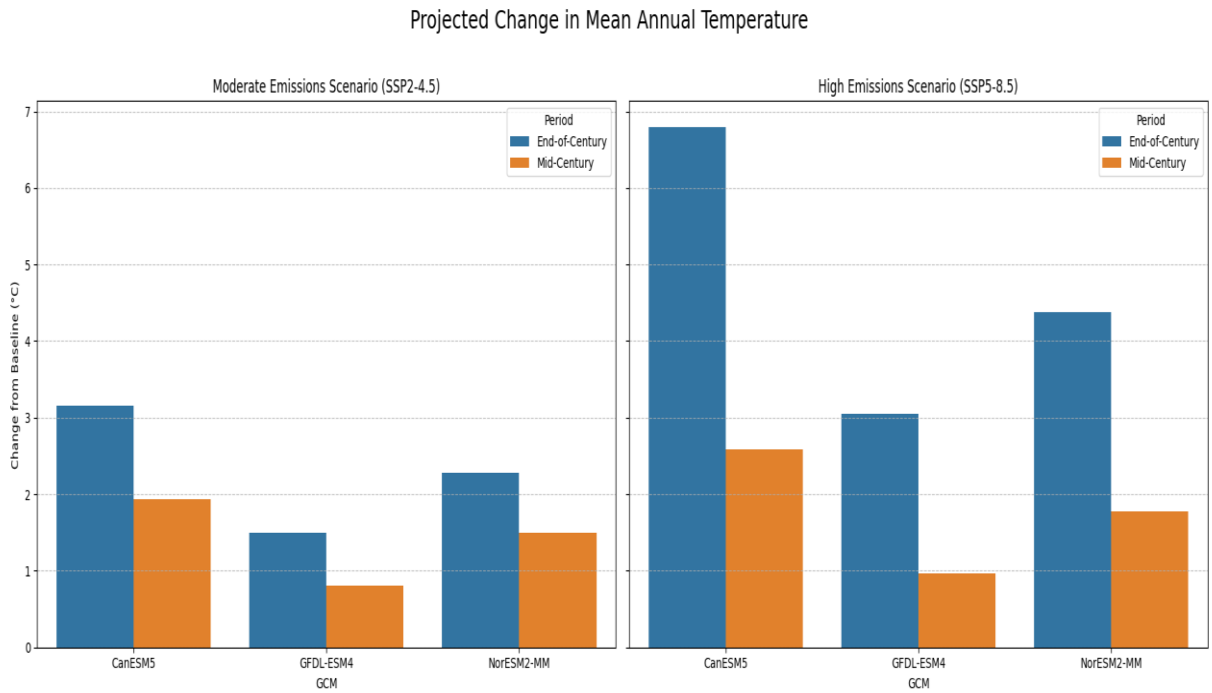

Figure 4. 6: Projected change in mean annual temperature

In contrast to the strong consensus on warming, the projections for future precipitation are characterized by deep uncertainty among the GCMs Figure 4.6. This uncertainty is a well-documented challenge in climate modeling for East Africa and is rooted in the region's complex climate drivers. The area's bimodal rainfall is heavily influenced by competing signals from large-scale systems like the Indian Ocean Dipole (IOD) and the El Niño-Southern Oscillation (ENSO) (Farah & Muhumed, 2024). Each GCM uses slightly different physical equations and has varying sensitivity to these drivers, which causes them to diverge in their projections. This divergence is evident in the results, where the CanESM5 model projects an extremely wet future (up to a +170.5% increase), while the NorESM2-MM model introduces the possibility of a drier future, with a projected decrease in rainfall of -5.1% by mid-century under the SSP2-4.5 scenario. The critical implication of this deep uncertainty is that water resource managers cannot plan for a single future;

instead, adaptation strategies for the Hargeisa watershed must be robust enough to handle dual risks of both more severe droughts and more extreme flooding.

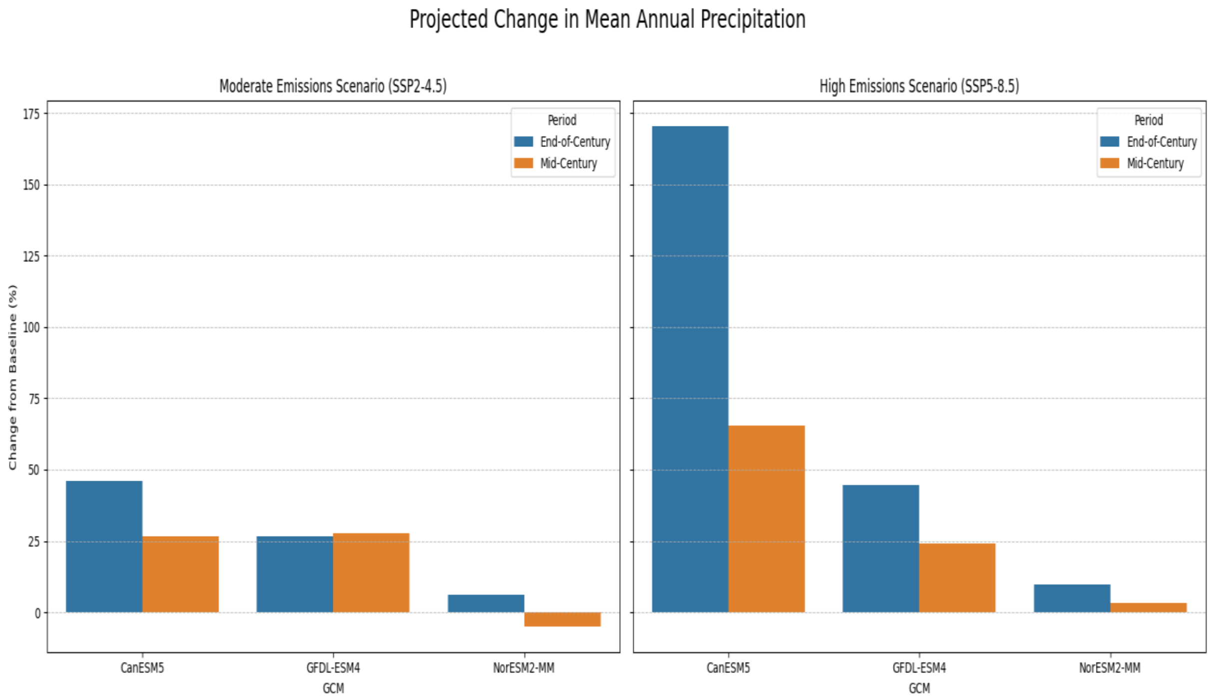

Figure 4. 7 : Projected mean annual precipitation for the Hargeisa watershed

The analysis for the other climate variables, solar radiation, wind speed, and relative humidity showed a general consensus among the GCMs on future stability, with no strong directional trends projected under either scenario. The detailed bar charts for these variables are provided for reference in Figure 4.7 Projected Mean Annual Humidity, Solar, and wind speed

4.3 SWAT Model Performance

This section presents the performance of the SWAT model for the Dagahbur donor catchment, which provides the foundation for the Hargeisa watershed model. A direct calibration for the Hargeisa watershed was not possible due to the absence of observed streamflow data; therefore, a regionalization approach was employed by calibrating a model for the nearby, gauged Dagahbur catchment and transferring the optimized parameters. A thorough calibration process was carried out to make sure the model was as precise as possible. The initial step of calibration is to conduct a sensitivity analysis to focus calibration efforts on a manageable set of the most influential variable so here will present the results of sensitivity analysis.

4.3.1 Sensitivity analysis

Here, a global sensitivity analysis measured the sensitivity for all the parameters using the t-Stat and the corresponding p value of the parameters. This analysis provided a certain order on the parameters which were tested for a model of the system, the order ensuring that the most sensitive parameters gained the most scrutiny for the final calibration. Figure 4.6 provides the results of the analysis in a more visual format. The graph illustrates emphatically that a small number of parameters dominate the results of the model. The SWAT-CUP analysis results revealed CN2 (SCS Curve Number) as the most dominant parameter (t-Stat = 16.59), followed by factors associated with groundwater and soil dynamics, such as ALPHA_BF.gw (Baseflow alpha factor), ESCO.hru (Soil evaporation compensation factor), and GW_DELAY.gw (Groundwater delay), each identified as highly significant ($p < 0.01$). This recognized parameter influence order guided the prioritization of adjustments during the next model calibration.

Comprehensive statistical findings of the analysis are presented in Table 4.2, which orders the parameters according to their sensitivity.

Table 4. 2: Sensitivity Ranking of SWAT Parameters for Streamflow Simulation in the Dagahbur Catchment

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

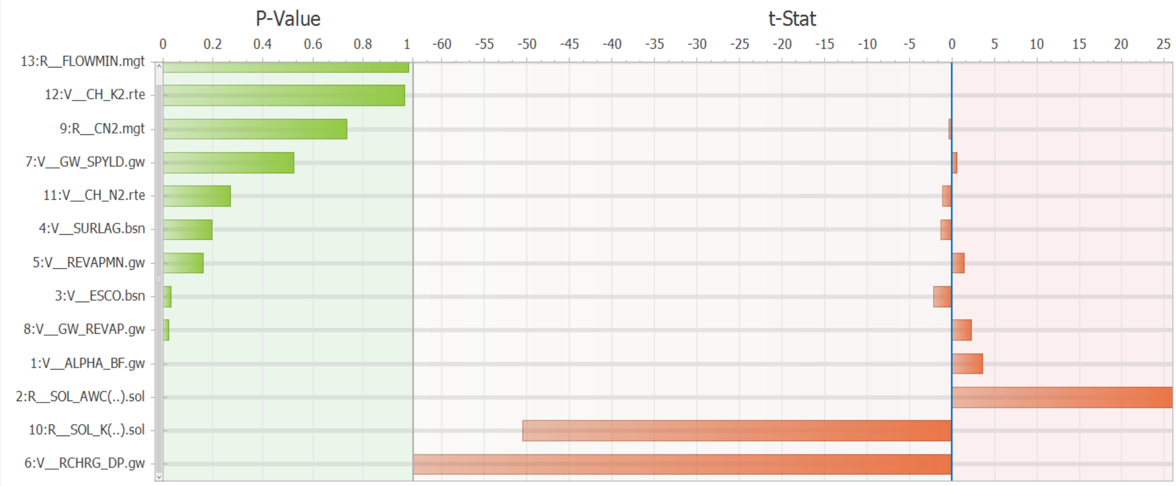

Figure 4. 8: Sensitivity Ranking of SWAT Parameters for Streamflow Simulation in the Dagahbur Catchment

4.3.2. Calibration

Calibration is the process of adjusting model parameters to achieve the best possible match between simulated streamflow and observed data. Given the large number of parameters in SWAT, this process is crucial for ensuring the model accurately represents the hydrological processes of the study area. For this study, an extensive calibration was performed for the gauged Dagahbur donor catchment using the SWAT-CUP program. This involved running 38 separate iterations, totaling over 20,000 individual simulations, to identify the optimal parameter set. The model was calibrated against observed streamflow for the period 1992–1997. The final statistical performance of the model, achieved after this extensive calibration, is summarized in Table 4.3.

Table 4. 3: Statistical Performance for the calibration of the gauged watershed

Performance Metric	Value	Performance Rating
PBIAS (Percent Bias)	4.50%	Very Good

KGE (Kling-Gupta Efficiency)	0.65	Good
R^2 (Coefficient of Determination)	0.55	Satisfactory
NSE (Nash-Sutcliffe Efficiency)	0.52	Satisfactory

The model achieved a "Satisfactory" rating for both NSE and R^2, a "Good" rating for the comprehensive KGE metric, and a "Very Good" rating for PBIAS. The strong performance in KGE and particularly PBIAS indicates that the model simulates the overall water balance with high accuracy, which is the most critical factor for this study. The hydrograph comparing the simulated and observed monthly streamflow is shown in Figure 4.9.

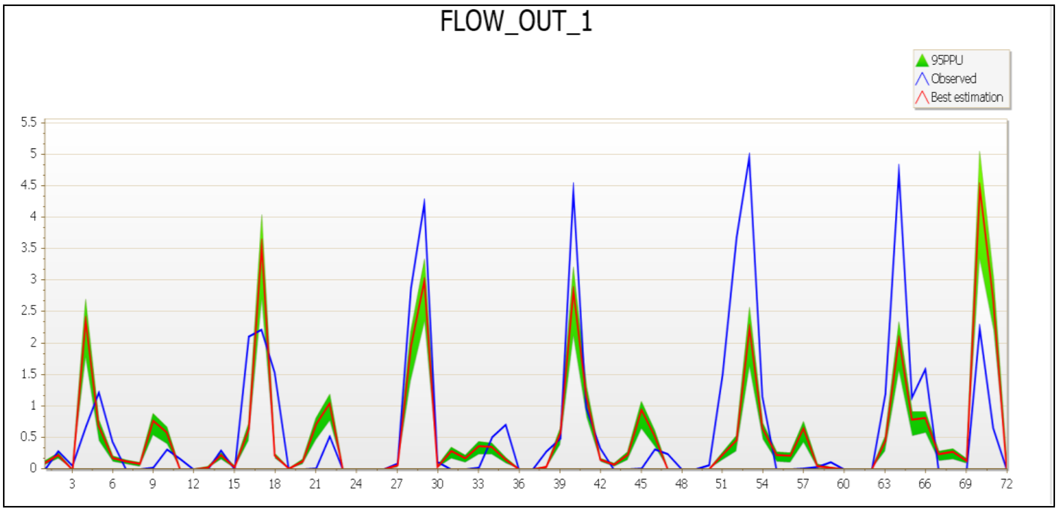

Figure 4. 9: Comparison of simulated and observed monthly streamflow (m^3/s) for the Dagahbur catchment

Based on this performance, particularly the strong KGE and PBIAS results, the calibrated parameter set was deemed suitable for transfer to the Hargeisa watershed model.

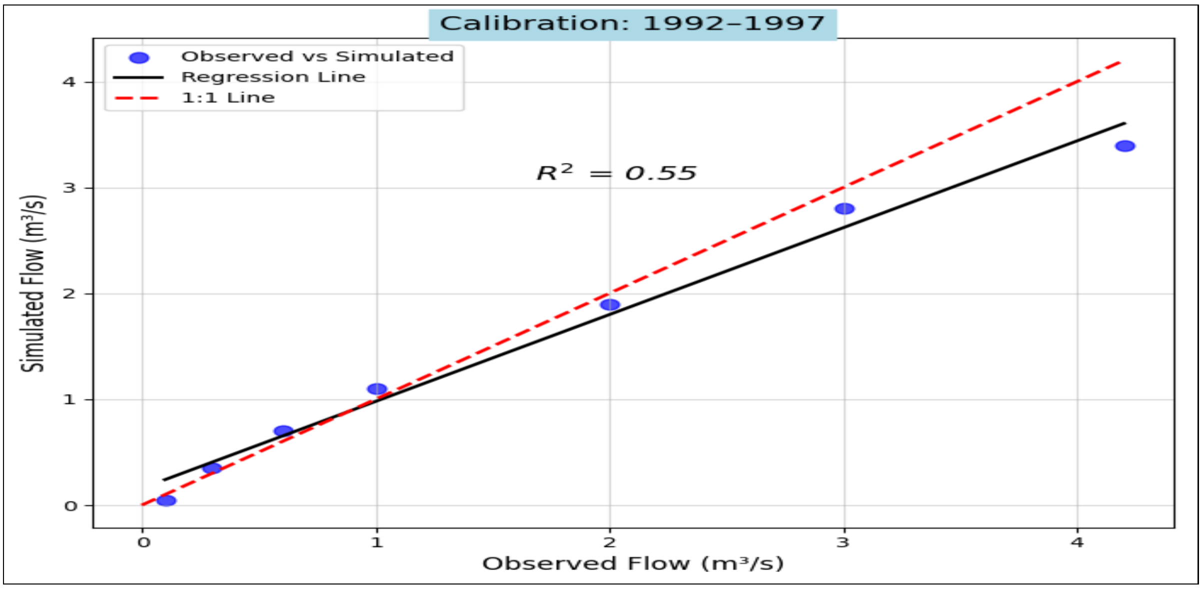

Figure 4. 10: Scatter plot of observed versus simulated monthly streamflow for the model calibration

4.3.3. Validation

Validation is the process of testing how accurately a calibrated model can predict new, real-world data that it wasn't trained on. It's the crucial step that confirms the model's reliability and predictive power. Following calibration, the model's robustness was tested by validating it against an independent dataset from 1998 to 2000. No further adjustments were made to the calibrated parameters, ensuring an objective assessment of the model's predictive capability. The validation results confirm the model's reliability. The performance metrics remained in the satisfactory range, with an NSE 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 to 16.2%, moving from "Very Good" to "Good" and indicating a slight tendency to underestimate the total streamflow volume during the validation period. The statistical performance for the validation period is shown in Table 4.4

Table 4. 4: Model performance statistics for the Validation period (1992-1997) for the Dagahbur catchment

Variable	R^2	NS	PBIAS (%)	KGE
Validation	0.53	0.50	16.2	0.57

The scatter plot for the validation period Figure 4.11 visually illustrates this performance. The R^2 value of 0.53 is reflected in the moderate scatter of points around the regression line. More importantly, the plot reveals that the slope of the regression line is considerably flatter than the 1:1 line. This visually confirms the behavior identified by the PBIAS, showing that the model tends to underestimate higher flow events while performing better at lower flows. This successful, albeit imperfect, validation provides the necessary confidence that the calibrated parameter set is reliable and suitable for regionalization to the Hargeisa watershed.

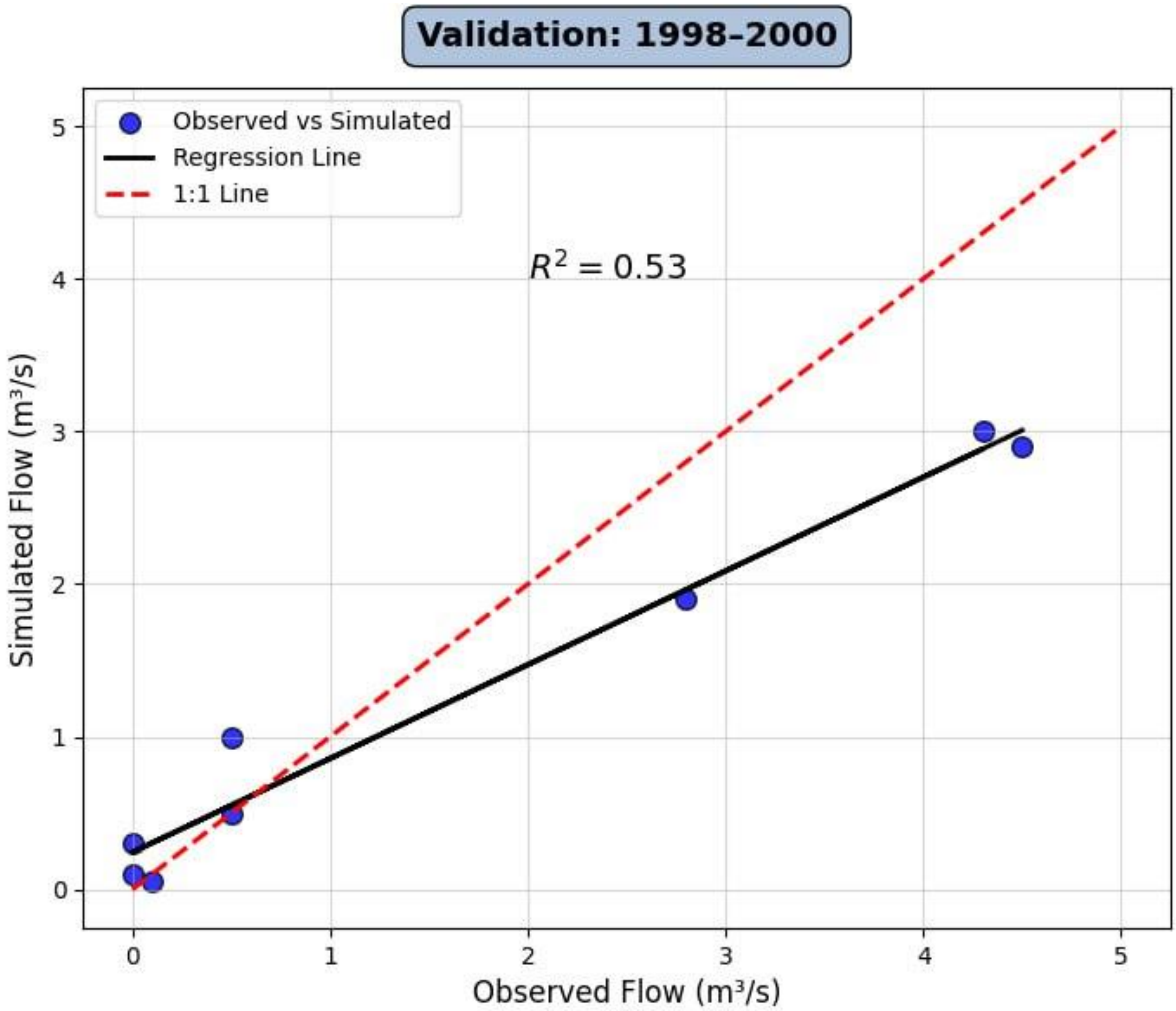

Figure 4. 11 : Scatter plot of observed versus simulated monthly streamflow for the model validation period

4.4 Baseline Hydrology of the Hargeisa Watershed (1995-2024)

This section presents the simulated water balance of the Hargeisa watershed under historical conditions. The results were generated by driving the calibrated SWAT+ model with the observed data from the six local meteorological stations for the period 1995-2024. These findings represent the baseline hydrological conditions against which the future impacts of climate change will be assessed.

The mean annual water balance for the entire watershed is summarized in Table 4.5. The results depict a water-scarce, high-evaporation environment, which is characteristic of the semi-arid climate of the region.

Table 4. 5: Mean annual water balance for the Hargeisa watershed (1995-2024)

Water Balance Component	Value (mm/year)	Percent of Precipitation (%)
Precipitation	200.43	100.00
Evapotranspiration (ET)	176.16	87.90
Surface Runoff	12.88	6.40
Groundwater Recharge	10.03	5.00
Total Water Yield	13.22	6.60

The analysis of the water balance reveals several key characteristics of the watershed's hydrology. The most dominant process is evapotranspiration, which accounts for nearly 88% of all incoming precipitation. This indicates that the vast majority of rainfall is returned to the atmosphere and does not contribute to the watershed's renewable water resources. Of the remaining water, only a very small fraction contributes to the water supply. Groundwater recharge accounts for just 5.0% of total precipitation. This is a critical finding, as it highlights the limited rate at which the region's vital groundwater aquifers are replenished. Similarly, surface runoff is also very low, at only 6.4% of rainfall. These results paint a clear picture of a water-stressed system that is highly efficient at returning water to the atmosphere and inefficient at generating runoff or recharging groundwater, which provides a quantitative foundation for evaluating the potential impacts of future climate change.

4.5 Climate Change Impacts on Water Availability

To fulfill the final research objective, the calibrated SWAT+ model for the Hargeisa watershed was driven by the downscaled climate data from the three GCMs for both the SSP2-4.5 and SSP5-8.5 scenarios. The projected percentage changes in the key water balance components for the Mid-Century (2031-2060) and End-of-Century (2071-2100) periods, relative to the historical baseline (1995-2024), are summarized in Table 4.6.

Table 4. 6 : Projected percentage change (%) in key water balance components for the Hargeisa watershed across all future scenarios

GCM	Scenarios	Period	Surface Runoff (%)	Groundwater Recharge (%)	ET (%)	Total Water Yield (%)
CanESM5	SSP2-4.5	Mid-Century	-32.70	+4.1	+72.1	-32.20
		End-of-Century	-22.70	+171.2	+85.0	-19.30
	SSP5-8.5	Mid-Century	-14.60	+206.5	+103.8	-10.50
		End-of-Century	+125.6	+781.0	+184.2	+137.8
GFDL-ESM4	SSP2-4.5	Mid-Century	+11.1	+210.4	+81.4	+14.5
		End-of-Century	+1.8	+249.8	+73.5	+6.3
	SSP5-8.5	Mid-Century	+18.0	+192.9	+75.1	+20.9
		End-of-Century	+21.3	+308.8	+87.7	+26.4
NorESM2-MM	SSP2-4.5	Mid-Century	+135.8	+142.5	+46.0	+134.9
		End-of-Century	-16.80	+177.9	+56.7	-13.40
	SSP5-8.5	Mid-Century	-8.80	+170.9	+58.5	-5.70

		End-of-Century	+12.8	+290.9	+59.3	+17.8

The comprehensive analysis of all 12 future scenarios reveals several key patterns regarding the future of water availability in the Hargeisa watershed. There is a strong agreement across all scenarios that evapotranspiration (ET) will rise dramatically as a direct consequence of projected warming, with increases ranging from +46.0% to as high as +184.2%. Critically, despite this higher atmospheric water demand, all 12 scenarios project an increase in groundwater recharge. This is a major positive finding for the region, with increases ranging from a marginal +4.1% to an extreme +781.0%, suggesting that projected increases in precipitation are generally sufficient to enhance the replenishment of aquifers. In contrast, the projections for surface runoff and total water yield are highly uncertain and show no clear agreement, with outcomes ranging from a significant increase (e.g., +135.8%) to a significant decrease (e.g., -32.7%). This highlights a major challenge for managing future surface water resources and the associated risks of floods and droughts.

4.5.1 Impact on Groundwater Recharge

The examination of future climate impacts on groundwater recharge shows a clear and significant expected rise across all three Global Circulation Models (GCMs) for both the mid-century and the end-of-century. It is very concerning that all 12 future scenarios, spanning three different GCMs and two emission pathways, suggest that more water will seep through and recharge the region’s aquifers. This has grave consequences for the Hargeisa region, which relies on groundwater resources, especially the Geed Deeble aquifer, for its domestic, agricultural, and economic needs (Khalif, 2023). This positive trend is an important finding for the water security of the Hargeisa watershed, which depends heavily on groundwater resources. The magnitude of these projected increases is detailed in Figure 4.12.

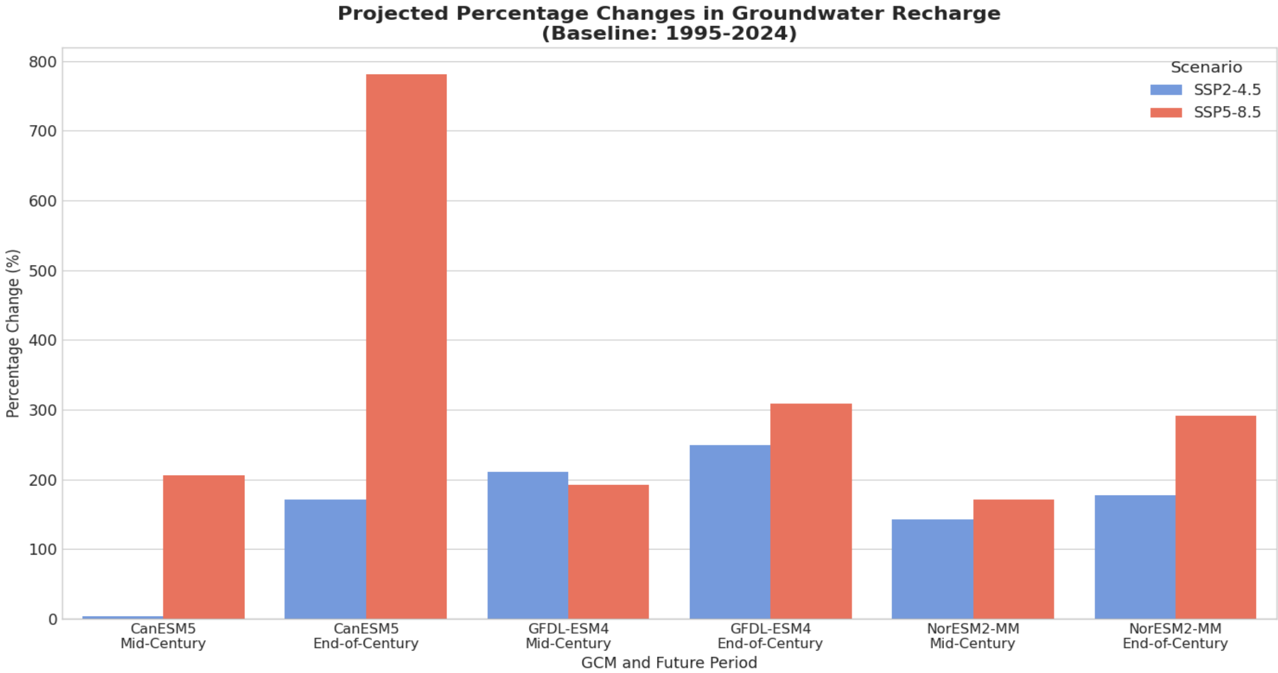

Figure 4. 12: Projected percentage change in groundwater recharge

For the mid-century, all models project a significant rise in groundwater recharge relative to the baseline period (1995-2024). Under the moderate SSP2-4.5 scenario, the projected increases are already pronounced, with the GFDL-ESM4 and NorESM2-MM models indicating increases exceeding 200%. The CanESM5 model projects a more modest, yet still positive, increase. Under the high-emissions SSP5-8.5 scenario, these projections are amplified further, with all models showing recharge increases greater than 200%. The trend of increasing groundwater recharge becomes even more definite by the end-of-century. Projections under the SSP2-4.5 scenario show substantial increases across all models. However, the most striking results are observed under the SSP5-8.5 scenario. The projections from GFDL-ESM4 and NorESM2-MM are exceptionally high, but they are surpassed by the CanESM5 model, which projects a remarkable increase of 781%. In summary, despite the projected increases in evapotranspiration, the findings strongly suggest that future changes in precipitation patterns likely an increase in the intensity and magnitude of rainfall events will overwhelmingly favor enhanced groundwater recharge. This robust consensus across different models and emission scenarios points to a potential future where groundwater resources in the Hargeisa watershed are more readily replenished, offering a significant opportunity for sustainable water resource management.

4.5.2 Impact on Surface Runoff

The projections for surface runoff in the Hargeisa watershed present a complex picture characterized by significant divergence and uncertainty among the selected Global Circulation Models (GCMs). Unlike the consistent trends observed for groundwater recharge and evapotranspiration, the models disagree on the direction of change for surface runoff, highlighting a key challenge for future water management. The contrasting projections are illustrated in Figure 4.13.

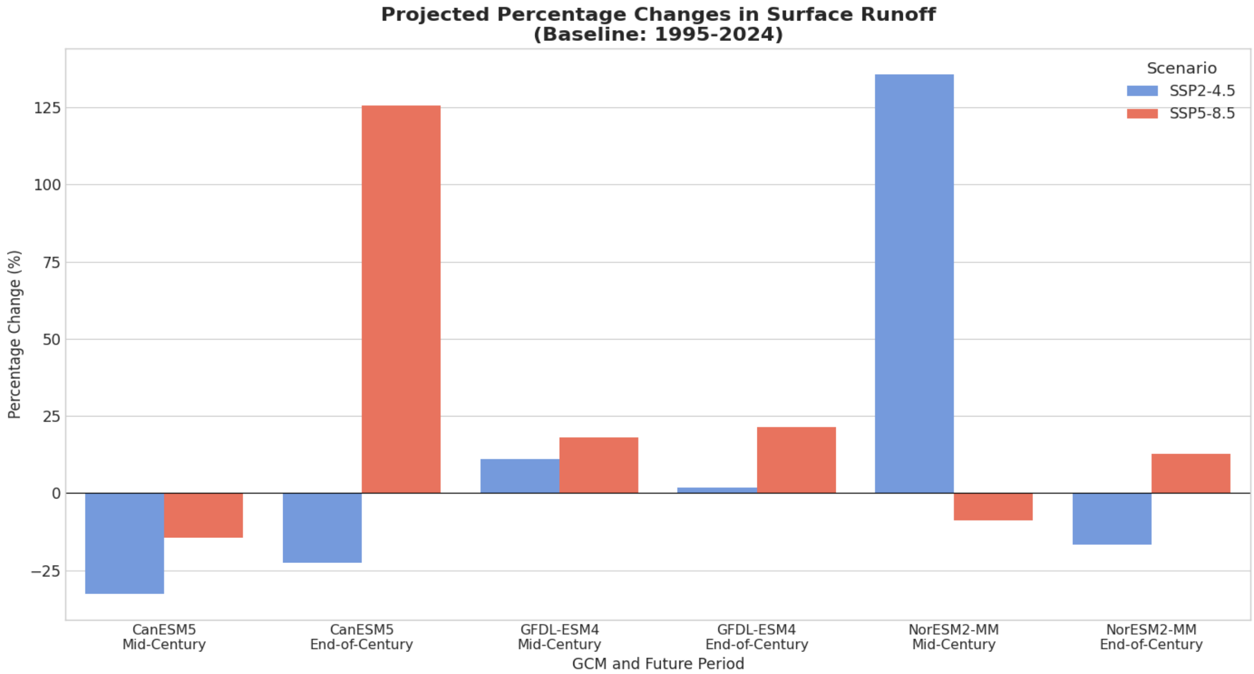

Figure 4. 13: Projected percentage change in surface runoff

The CanESM5 model stands apart from the others in its projections. For the mid-century, it projects a decrease in surface runoff under both the SSP2-4.5 (-32.7%) and SSP5-8.5 (-14.6%) scenarios. This trend of decreasing runoff continues into the end-of-century under the moderate SSP2-4.5 scenario (-22.7%). However, a critical reversal is projected for the end-of-century under the high-emissions SSP5-8.5 scenario, where CanESM5 projects a substantial increase in runoff of 125.6%. In stark contrast, the GFDL-ESM4 and NorESM2-MM models consistently project an increase in surface runoff across all scenarios and time periods. For both models, the magnitude of the increase is greater for the end-of-century and is significantly amplified under the SSP5-8.5 scenario. The most dangerous projection comes from the NorESM2-MM model, which indicates a potential increase in surface runoff of over 300% by the end of the century under SSP5-8.5. This divergence among the GCMs underscores the high degree of uncertainty in forecasting surface runoff. This uncertainty is likely rooted in the different ways each model simulates regional changes in precipitation characteristics, particularly rainfall intensity. While some futures may see conditions leading to reduced runoff, the results from all three models under the high-emissions, end-of-century scenario project a significant increase. This suggests that planning for increased flood risk and managing potentially higher surface water flows should be a critical component of long-term climate adaptation strategies for the Hargeisa watershed.

4.5.3 Impact on Evapotranspiration

The analysis of future evapotranspiration (ET) rates in the Hargeisa watershed reveals a strong and consistent trend across all three Global Circulation Models (GCMs). The findings indicate a projected significant increase in ET for both the mid-century and end-of-century periods under both climate scenarios. This consensus provides a high degree of confidence in this aspect of the future water balance, as detailed in Figure 4.14.

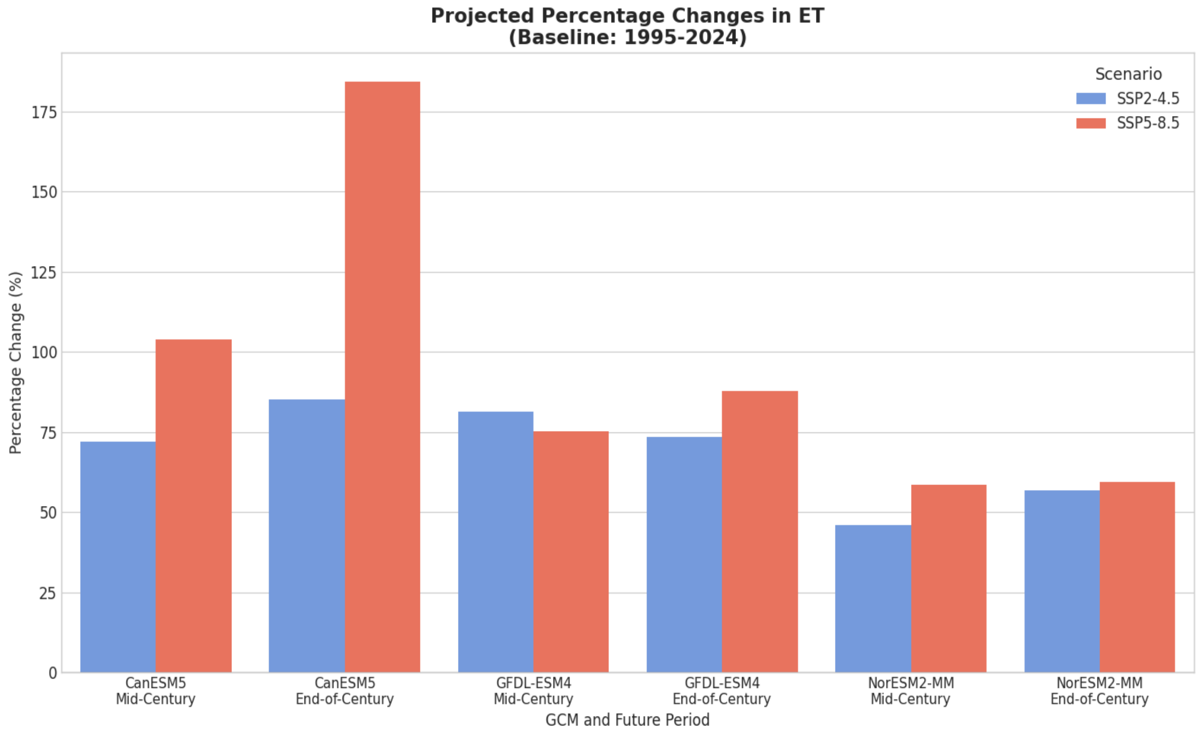

Figure 4. 14: Projected percentage change in evapotranspiration

A clear pattern emerges from the projections: the magnitude of the increase in ET is directly influenced by the time horizon and the severity of the emissions scenario. For any given model, the projected increase is greater for the end-of-century compared to the mid-century, and greater under the high-emissions SSP5-8.5 scenario than the moderate SSP2-4.5 scenario. By the end-of-century, these increases become particularly pronounced.

Under the SSP5-8.5 scenario, all models project ET to increase by over 135%. The most extreme projection is from the CanESM5 model, which indicates a potential increase of 184.2% relative to the baseline period. This projected rise in ET is an expected consequence of the increasing temperatures associated with climate change. Higher air temperatures boost the energy available for evaporation from soil and water bodies and increase the rate of transpiration from plants. The implications for the Hargeisa watershed are significant, as higher ET rates represent a substantial loss of water to the atmosphere. This will likely lead to increased water stress on natural vegetation and agricultural crops, potentially heightening the demand for irrigation. Furthermore, it signifies that a larger fraction of future precipitation will be lost before it can contribute to surface runoff or groundwater recharge, making the projected gains in those areas even more noteworthy.

4.5.4 Impact on Total Water Yield

Total water yield, which represents the net amount of water leaving the watershed as streamflow after accounting for evapotranspiration, shows a complex and divergent future outlook. Similar to surface runoff, the projections are characterized by significant uncertainty among the three Global Circulation Models (GCMs), presenting a challenging picture for future water resource availability. The contrasting outcomes are illustrated in Figure 4.15.

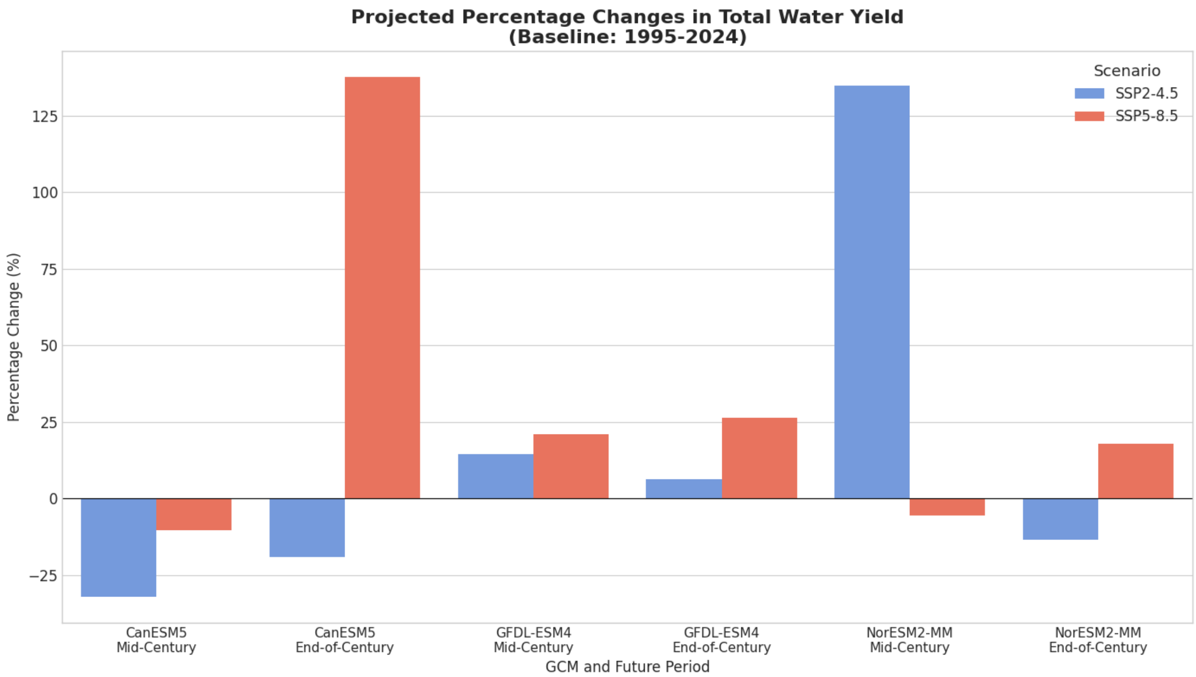

Figure 4. 15: Projected percentage change in Total water yield

The results highlight two distinct potential pathways for the watershed. The GFDL-ESM4 and NorESM2-MM models consistently project an increase in total water yield across all scenarios and time periods. For these models, the surplus is most pronounced at the end of the century under the high-emissions SSP5-8.5 scenario, with the NorESM2-MM model projecting an increase of 125.8%. Conversely, the CanESM5 model projects a decrease in total water yield for three out of the four scenarios, suggesting a future with less available water. However, in a critical reversal mirroring its surface runoff projection, the CanESM5 model projects a dramatic shift under the end-of-century, SSP5-8.5 scenario. In this high-emissions future, it not only projects an increase but predicts the largest increase of all models at 137.8%. This divergence underscores the fundamental uncertainty in the future water balance of the Hargeisa watershed. The outcome is highly sensitive to future precipitation patterns and temperature increases as simulated by each GCM. The conflicting projections ranging from a significant deficit to a large surplus create a difficult scenario for long-term water resource planning. Management strategies must therefore be robust and adaptive, capable of handling a future with either decreased water availability, requiring enhanced conservation or efficiency, or a significant surplus, requiring infrastructure to manage higher flows and potentially capture excess water for storage.

4.6 Discussion of Hydrological Impacts and Uncertainties

This study aimed to evaluate the impacts of climate change on water availability in the Hargeisa watershed. The results indicate a complex future characterized by a "Dual-Risk" scenario: significantly improved groundwater potential masked by high evaporation and uncertain surface risks. This section discusses these hydrological implications and the reliability of the modeling framework used to derive them.

4.6.1. Implications for Groundwater Security

The most critical finding of this research is the consistent and substantial increase in groundwater recharge across all projected scenarios, ranging from +4.1% to +781%. This finding challenges the prevailing narrative of absolute water scarcity in the Horn of Africa. The projected increase is driven by the "intensity effect" of climate change; while rising temperatures increase potential evaporation, the projected intensification of rainfall events allows water to infiltrate rapidly during flash floods, bypassing the evaporation zone and replenishing the deep aquifers. For the city of Hargeisa, which relies heavily on the Geed

Deeble aquifer, this suggests that climate change may actually improve long-term water security, provided that the increased recharge can be effectively captured and managed. However, this "blue water" gain is threatened by the projected +184% increase in evapotranspiration, which implies that "green water" (soil moisture for agriculture) will become scarcer, potentially increasing the demand for groundwater irrigation and offsetting the benefits of increased recharge.

4.6.2. The Dual Risk of Flood and Drought

Unlike the clear signal for groundwater, the projections for surface runoff are highly uncertain, ranging from a decrease of -32.7% to an increase of +135.8%. This divergence among the GCMs implies that the Hargeisa watershed faces a non-stationary future where historical patterns are no longer a reliable guide.

The uncertainty itself is a key finding. It suggests that water infrastructure in Somaliland cannot be designed for a single "average" future. Instead, adaptation strategies must be robust enough to handle two extremes:

Flood Risk: The potential for a +135.8% increase in runoff under high-emissions scenarios indicates a severe risk to urban infrastructure in Hargeisa city, necessitating enhanced drainage and flood retention dams.

Drought Risk: The potential for a -32.7% reduction in runoff warns of prolonged dry spells that could cripple surface water harvesting efforts.

4.6.3. Reliability of the Modeling Framework

While the regionalization approach introduces inherent uncertainty, the model performance metrics confirm that the SWAT+ model provides a reliable basis for these volumetric assessments. The model achieved a Nash-Sutcliffe Efficiency (NSE) of 0.52. While an NSE > 0.50 is considered "Satisfactory" for complex, semi-arid catchments, it reflects the difficulty of capturing the precise timing of flash floods in ephemeral rivers. Crucially, however, the model achieved a Percent Bias (PBIAS) of 4.5%, which is rated as "Very Good". In the context of water resources estimation, PBIAS is the most decisive metric because it measures the model's accuracy in simulating the total volume of water over time. Since the primary objective of this study is to quantify long-term changes in water balance components (e.g., total annual recharge and yield) rather than daily flood routing, the high volumetric accuracy (low PBIAS) ensures that the projected percentage changes in water availability are robust and scientifically defensible.

The SWAT model for the Dagahbur catchment performed well, providing a solid basis for the parameter transfer. The statistical outcomes for the calibration period (1992-1997) showed a Nash-Sutcliffe Efficiency (NSE) of 0.52 and a Coefficient of Determination (R^2) of 0.55. Both scores are considered "Satisfactory" according to hydrological guidelines. While these numbers indicate that the model does not fully match the shape and timing of every monthly flow event in the observed hydrograph, the performance of other metrics confirms that the model meets the study's objectives.

Importantly, the model achieved a "Good" performance for the Kling-Gupta Efficiency (KGE) with a score of 0.65 and a "Very Good" performance for the Percent Bias (PBIAS) with a score of 4.50%. In assessing water availability, the PBIAS is the most critical indicator. It measures the model's ability to conserve mass and accurately simulate the total volume of water in the system over the long term. A "Very Good" PBIAS shows that the model's overall water balance is highly accurate (Adane et al., 2021). For a study aimed at quantifying long-term changes in water balance components like groundwater recharge and evapotranspiration, this accuracy in water volume is more important than perfectly simulating the hydrograph's shape (NSE). The strong KGE score further supports this conclusion, as it offers a balanced view of correlation, bias, and variability, confirming the model's overall reliability. Therefore, despite the inherent uncertainties of regionalization and the satisfactory NSE rating, the reliable performance in simulating the overall water balance gives high confidence that the model is a useful tool for assessing the possible impacts of climate change on water availability in the Hargeisa watershed.

5. CONCLUSIONS AND RECOMMENDATIONS

5.1 Conclusions

This research utilized the Soil and Water Assessment Tool plus (SWAT+) to simulate the impacts of climate change on water availability in the Hargeisa watershed. Due to the absence of local streamflow data, the regionalization approach was considered. First, calibrating (1992–1997) and later validating (1998–2000) in the gauged Dagahbur donor catchment. The model performance for the donor catchment was demonstrated to be reliable, achieving 'Satisfactory' to 'Very Good' ratings across key statistical metrics for the calibration period (NSE = 0.52, R^2 = 0.55, KGE = 0.65, PBIAS = 4.50%), providing a robust basis for the parameter transfer.

The analysis of historical (1995-2024) data for the Hargeisa watershed revealed a significant climatic shift, starting a widespread increasing trend in annual precipitation across all stations (ranging from +6.85 to +13.19 mm/year). This was accompanied by a pattern of asymmetric warming, with a statistically significant increase in minimum temperature.

Future climate forecasts for the set of three GCMs showed strong consensus for ongoing warming (up to +6.8°C by 2100 under SSP5-8.5). This projected warming is critical because it drives a substantial increase in evapotranspiration (+46.0% to +184.2%), which threatens to offset potential precipitation gains and increase agricultural water stress. Furthermore, the projections exhibited great uncertainty in future precipitation, ranging from a -5.1% reduction to an increase of +170.5%. This deep uncertainty implies that the watershed faces a 'dual-risk' scenario; consequently, future water infrastructure cannot be designed for a single 'average' condition but must be robust enough to withstand both intensified drought periods and extreme flooding events.

5.2 Recommendations

Based on the findings of this study, the following key recommendations are proposed for the Hargeisa watershed:

- ✓ **Adopt a Dual-Risk Adaptation Strategy**: Water managers should prepare for both droughts (through water conservation policies) and floods (through risk mapping and early-warning systems) to address the deep uncertainty in future surface runoff.

- ✓ **Establish a Local Hydrological Monitoring Network:** To address the primary challenge faced in this research, a permanent streamflow gauging station should be established to eliminate the uncertainties of regionalization and provide crucial local data for future models and water management.

5.3. Limitations and Future Research Directions

While this research provides a robust, quantitative assessment of climate change impacts on the Hargeisa watershed, it is important to acknowledge its limitations, which in turn provide clear directions for future research. The primary limitation of this study was the reliance on a regionalization approach due to the absence of historical streamflow records for the Hargeisa watershed. This is a standard method for ungauged basins, but it introduces uncertainty as the calibrated parameters from the donor catchment may not perfectly represent the unique hydrological characteristics of the target watershed.

To build upon the findings of this thesis, the following avenues for future research are recommended:

- ✓ **Expand the Climate Model Ensemble in Future Research**: Subsequent studies should utilize a larger ensemble of GCMs to better constrain the uncertainty in future precipitation projections and provide a clearer picture of the most likely climate scenarios.
- ✓ **Incorporate Land-Use Change Scenarios:** A critical next step is to investigate the combined impacts of both climate and land-use change (e.g., urban expansion, agricultural shifts) on the water balance. This would provide a more holistic and realistic assessment of the cumulative pressures facing the watershed's water resources.

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7. Appendix

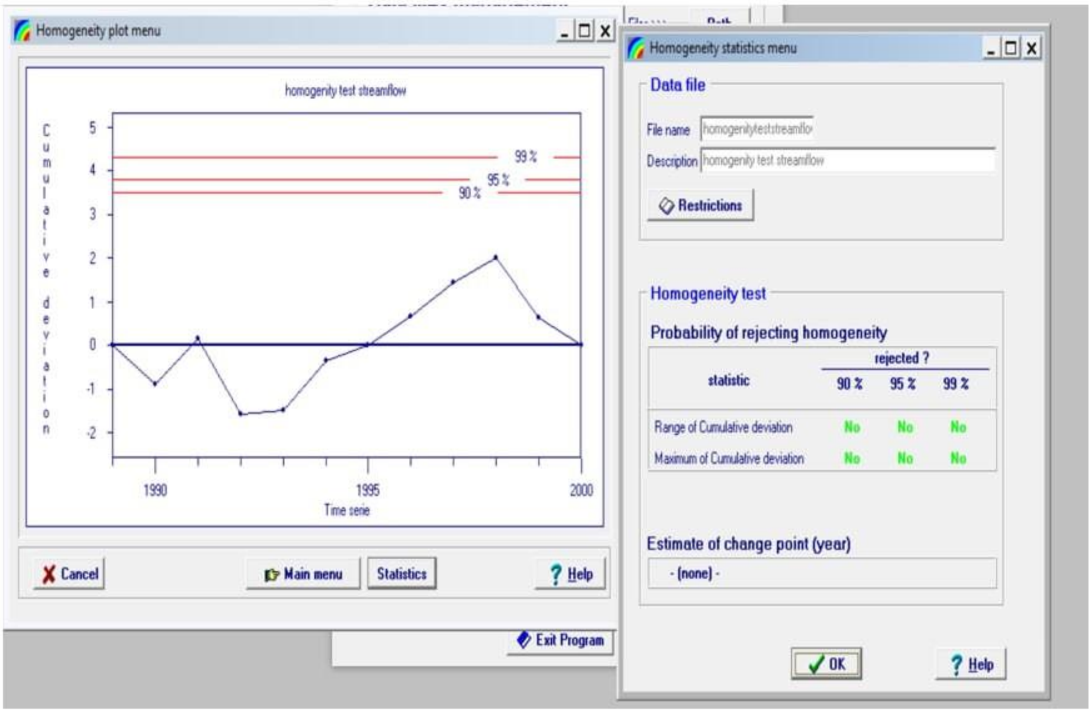

Figure 7. 1: Homogeneity Test

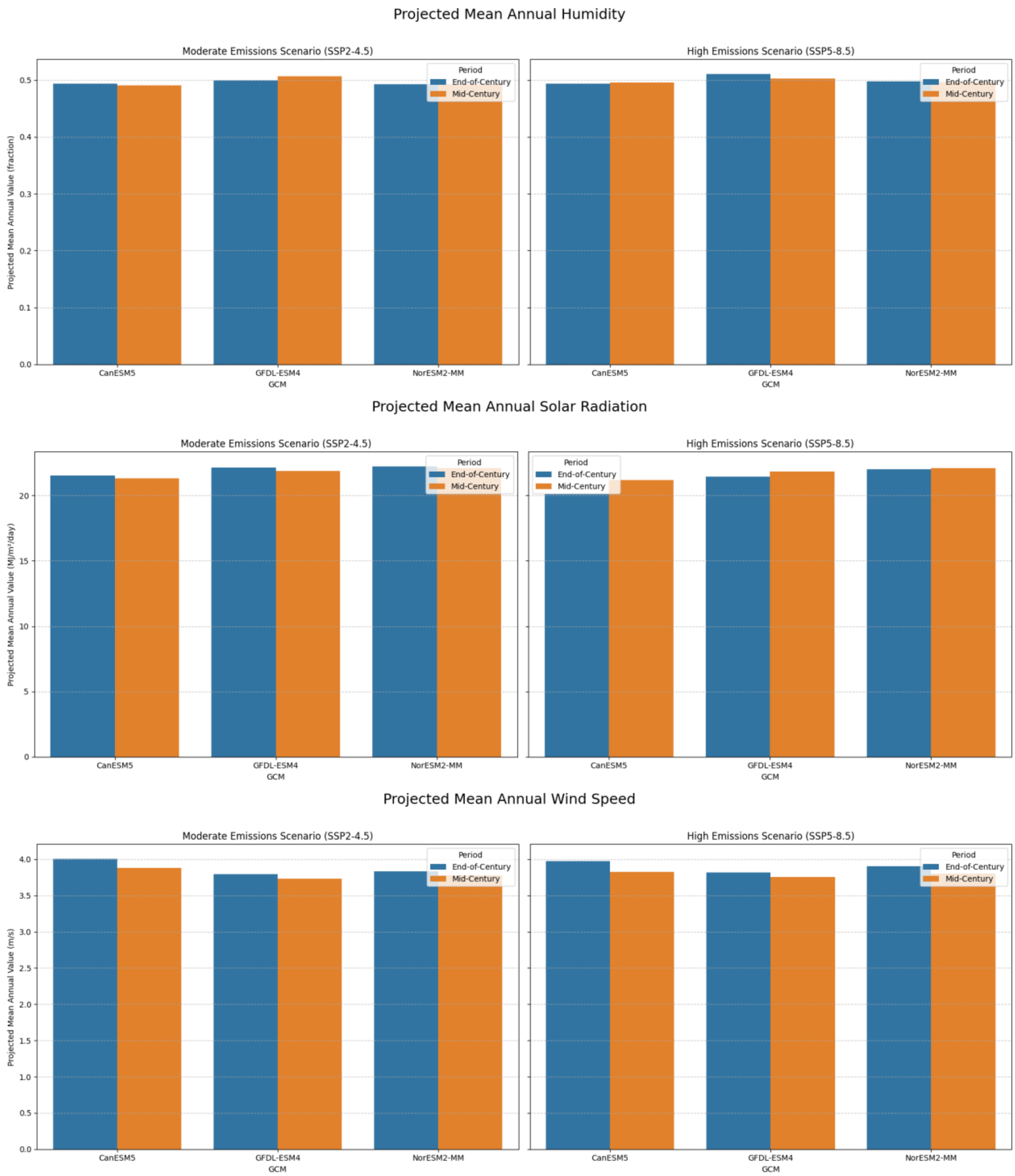

Figure 7. 2 : Projected Mean Annual Humidity, Solar and wind speed

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