IMPACT OF CLIMATE CHANGE ON THE GROUNDWATER RESOURCES OF SOUTHERN OMO BASIN, ETHIOPIA

PRESENTED IN PARTIAL FULFILLMENT OF THE REQUIREMENT FOR THE DEGREE OF MASTERS IN EARTH SCIENCES GEOLOGICAL ENGINEERING (HYDROGEOLOGY)

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Impact of Climate Change on The Groundwater Resources of Southern Omo Basin, Ethiopia

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GSR/8817/15

Presented in Partial Fulfillment of the Requirement for the Degree of Masters in Earth Sciences Geological Engineering (Hydrogeology)

College of Natural and Computational Sciences
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DECLARATION

I, Merga Leta, hereby declare that the thesis work, which I hereby submit for the partial fulfilment for the degree of Masters (M.Sc) of science in Geological Engineering (Hydrogeology) at the University of Addis Ababa, is my original work. To the best of my knowledge and belief, except as acknowledged in the text, the thesis does not contain any written work presented by other persons whether written, pictures, graphs or data or any other. I also declare that I have complied with the rules, requirements, procedures and policy of the university.

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A Thesis Submitted to

The School of Graduate Studies of Addis Ababa University in Partial Fulfillment of the Requirement for the Degree of Masters in Earth Sciences Geological Engineering (Hydrogeology)

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Abstract

In the present day context of Ethiopia, groundwater is the most economically feasible fresh water supply source used for public water supply, irrigation, and industrial purposes. With the growing demand for water supply, and current limited sources to enable community get access to safe and reliable water supply service, it will be wise to assess how the climate change impacts this precious resources in the arid climatic zone of Southern Omo Basin. To see how climate change impacts on the groundwater resources of Southern Omo Basin, two important steps were employed. Statistical Downscaling of Global Circulation Model on to six local meteorological stations (SDSM) and groundwater recharge estimation using the predicted climate variables up to the end of 2050. The predicted climate variables along with the study area Land use, Soil and DEM data served as input into the Arc SWAT model for annual groundwater recharge estimation up to the year 2050. In the climate variables prediction, it is observed that the temperature and precipitation generally increased which in turn gave rise to increased estimation of annual groundwater recharge. From the SWAT model output, locations with better groundwater recharge rate from available precipitation are identified for use in the development of artificial groundwater recharge. This research work is of utmost importance as it sheds light on the future groundwater recharge conditions in an area that is particularly susceptible to the impacts of climate change. One of the limitations of this work arises from the fact that the SWAT model was run using its own system simulated values due to the unavailability of certain climate variables, like relative humidity, wind speed, and sunshine hours at the local meteorological stations. Given its strategic location for border markets, tourism, and high-potential agro-investment opportunities, the study area is highly likely to be transformed into a bustling development corridor. Consequently, it becomes imperative to conduct additional research to comprehend the underlying reasons behind groundwater salinity and its pervasive spread, in order to devise effective mitigation measures.

Keywords: Climate change impacts · SDSM · Groundwater recharge. susceptible ·

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Acronyms

AET	Actual Evapotranspiration
AR5	Fifth Assessment Report
CDM	Clean Development Mechanism
CERs	Certified Emission Reductions
CMIP 6	Coupled Model Inter-comparison Project Phase 6
CMIP5	Coupled Model Inter-comparison Project, Phase 5
CUMC	Cubic Meter per second
DEM	Digital Elevation Model
DTM	Digital Terrain Model
GCM	Global Circulation Model
GHG	Green House Gases
GIS	Global Positioning System
GW	Groundwater
HRU	Hydrologic Response Unit
IPCC	Intergovernmental Panel on Climate Change
JI	Joint implementation
LULC	Land Use Land Cover
MCM	Million Cubic Meter
NDS	Nationally Determined Contribution
OGRB	Omo Gibe River Basin
PCP	Precipitation
PET	Potential Evapotranspiration
RCP	Representative Concentration Pathways
RGGI	Regional Greenhouse Gas Initiative
SDSM	Statistical Downscaling Method
SDSM	Statistical Downscaling Method
SQKM	Square kilometer
SRTM	Shuttle Radar Topography Mission
SSPs	Shared Socio-economic Pathways
SWAT	Soil and Water Assessment Tool
UNFCC	United Nations Framework Convention on Climate Change

CHAPTER ONE: INTRODUCTION

1. Background

In the present day context of Ethiopia, groundwater is the most economically feasible and safe source of fresh water supply for public water supply, irrigation, and industrial purposes. Groundwater source is directly or indirectly affected by climate variables based on its genesis and location in a given watershed. In view of this, the alluvial deposit of Southern Omo Basin is likely to be affected by the changing climate condition. With the growing demand for water supply, in connection with the population increment, it will be wise to assess how the climate change impact this precious resources for sustainable management.

Groundwater is beyond vital for life, especially in arid and semi-arid regions where there are no alternate water sources like the study area. Precipitation enabling environmental factors and availability of conducive geological material are reasons for groundwater to occur. Groundwater recharge is a critical process essential for maintaining the availability and sustainability of groundwater resources (Chow et al., 2019). It serves as a mechanism for replenishing underground aquifers, thereby determining the long-term viability of groundwater for various purposes such as household consumption, agricultural irrigation, and industrial use (Russo et al., 2018). Effective management of recharge is therefore imperative to ensure the sustainable utilization of groundwater resources (Allen et al., 2020).

Assessment of the impact of the climate change upon groundwater resources of the Southern Omo basin is crucially important because of the vulnerability of the source to the climate change. S. Kebede (2010) observed that the shallow alluvio-lacustrine aquifers with wadi bed recharge mechanism are highly vulnerable to the climate change and rainfall seasonality. According to the unpublished work of (A. Taddesse 2020) the hydro chemical evidences show that there is no significant signature of geochemical evolution that indicates the presence of continues or regional flow system along N-S and NE-SW hypothetical transects. The same study by A. Taddesse (2020) demonstrates the absence of flow continuity and the dominance of local recharge and flow systems of the study area through the comparison of the isotopic signature of the southern Omo alluvial deposit, which is relatively enriched, and the neighboring Hammer basement, which is relatively depleted. This study will contribute an invaluable information as to how the southern Omo alluvial deposit graben groundwater is impacted by the changing climate at least up to the year 2050. In the process of groundwater resource assessment under changing climate, many gaps have been identified that would serve as a background for the upcoming research works in the area.

The question of how the groundwater resource of southern Omo basin is going to be affected by the changing climate is the subject of this research. Considering that groundwater is the sole economically viable water source available for development, juxtaposed with the escalating demand for water supply, the assessment of climate change impact on this invaluable resource emerges as an imperative undertaking of unparalleled significance.

The purpose of this study is to extract forecasted climate variables influencing groundwater resources until the year 2050. By utilizing these projected climate variables, the research intends to assess their impact on groundwater resources. It will delve into evaluating the impacts of climate change on groundwater reservoirs and propose practical measures to mitigate adverse effects if any. Furthermore, the study will provide guiding principles for decision and policy makers to facilitate sustainable management of groundwater resources.

To address the purpose of this study, I preferred Statistical Downscaling Method (SDSM) to predict the climate variables that potentially influence the groundwater resources. This is because this method is proved to be robust in predicting climate variables and nowadays being used by different researchers. Statistical Downscaling Methods (SDSM) are widely used in climate science to bridge the gap between the coarse resolution of Global Climate Models (GCMs) and the finer spatial and temporal scales required for regional or local-scale climate assessments (Smith et al., 2009). The method offers valuable capabilities for generating high-resolution climate projections tailored to regional or local-scale applications (Wilby et al., 2002).

As far as the impact evaluation of these predicted climate variables on the groundwater resource is concerned, I used SWAT (Soil and Water Assessment Tool) to estimate the groundwater recharge. The SWAT (Soil and Water Assessment Tool) model is a distributed parameter, continuous simulation model designed to analyze the hydrologic and water quality response of agricultural watersheds (Arnold et al., 1998; Arrueta et al., 2022). It operates at a daily time step and incorporates various land management and climatic scenarios to simulate their effects on watershed processes. The model helps evaluate the impacts of land management practices and climate change on water resources, making it a valuable tool for watershed management and planning(Arnold et al., 1998; Arrueta et al., 2022). In the SWAT (Soil and Water Assessment Tool) model, watersheds are subdivided into sub-watersheds and hydrologic response units (HRUs). This division is based on information about land use, soil type, and slope (specifically for the Arc SWAT variant). The model produces outputs that can be evaluated at various spatial scales, ranging from individual HRUs to larger watersheds. This allows for a comprehensive assessment of hydrological and water quality processes at different levels of detail within the watershed.

1.1 Statement of Problem

The growing demand for water supply be it for domestic, agricultural and industrial, poses uncertainties in the future under the continued climate change. As the study area under consideration is devoid of flowing streams except one and only Omo river, and characterized by very sparse rainfall in all the arid expanse, groundwater resource stands the ultimate option for water supply source for the pastoral and agro-pastoral communities of the area. One factor of the growing demand stems from the population growth which according to UN, the African population is projected to double by the 2050s (United Nations, 2019). As part of Africa, the population of the study area is not different from this fact. The groundwater resource of the study area does not seem to be under pressure due to limited groundwater extraction in connection with the poor water supply infrastructure development level. In the subsequent endeavor of the government and partner organizations activity to realize the sustainable development goal (Target 6.1 specifically focusses on ensuring access to safe and affordable drinking water by all by 2030) the groundwater resources may be exposed to more pressure. This juxtaposed with the diversified water supply demand for example for irrigation development would put the groundwater resources of the study area under serious pressure.

Because of the vulnerability of groundwater resources in the study area due to reasons discussed earlier, it is imperative to conduct climate change impact assessment in order to devise mitigation measures and develop strategies to curb the impact of climate change on the groundwater resources. The author acknowledges the discrepancy in the SWAT model calibration using the Omo river flow with the nearly 10% area watershed of the study area.

1.2 Objectives of the study

1.2.1 General objective of the study

The general objective of this study is to assess climate change impact on the groundwater resources of Southern Omo basin through analysis of groundwater recharge based on the resulting climate variables under changing climate.

1.2.2 Specific objectives of the study

The specific objective of the study is:

- To downscale important climate variables from the Global Climate Model (GCM) using statistical downscaling technique upon the available local meteorological stations;
- Using the downscaled climate variables of appropriate scenario as an input together with other spatial data, estimate annual groundwater recharge from early 2020s through 2050s under the changing climate using Arc SWAT model.
- Comparison of the estimated groundwater recharge from 2020s through 2050s and analyze the impact of the climate change if any on the recharge to groundwater.
- Extract valuable information from the model output that are paramount important in devising groundwater resources management strategies and mitigation of undesired impact on the groundwater resources.

1.3 The research questions

The research questions include how is the limited resource (groundwater resources of southern Omo basin) connected with the climate change? How can the resource be wisely tapped without causing undesired impact on the resource availability and the environment under the inevitable climate change? With the growing population number, increased socioeconomic activities bringing about change in the dynamism of diversified resource utilization, juxtaposed with the climate change, how is the groundwater resource of the study area be affected? What strategies should be employed in the realization of the sustainable groundwater resource utilization.

From these points of view, it necessitates to know how the climate variables change in the future. How does the change in climate variables affect the groundwater? The identification of the inputs that derives the wheels of the impact would help to devise mitigation techniques or if not possible gives chance to think other way round to curb the impact through development of appropriate undesired impact curbing strategy/policy.

1.4 Significance of the study

The question how the groundwater resource of southern Omo basin is going to be affected by the changing climate is the subject of this research. Considering that groundwater is the sole economically viable water source available for development, juxtaposed with the escalating demand for water supply, the assessment of climate change impact on this invaluable resource emerges as an imperative undertaking of unparalleled significance.

If this study work is implemented successfully, it will come up with important findings that will assist the decision makers to develop strategies to mitigate undesired impacts on the groundwater resources. The findings of this study will help as a background for the planning and implementation of groundwater source for water supply system and further studies.

1.5 Limitations

Limitation of this research stems from the unavailability of sufficient input data that would critically improve the quality of the research. The unavailability of climate variables like relative humidity, wind speed and sunshine hours' data from the local meteorological stations forced the SWAT model run on the systems simulated variables in output generation. This could have affected the output of the model run in generating output data that may deviate from real time data. The distribution of meteorological stations by itself is the source of limitations. Out of the six meteorological stations used, only one station (Omorate station) is within the study area. The rest five stations are found widely and unevenly spaced around the study area. The larger the number of meteorological stations, the more they represent the study area, the better the output data. The unavailability of sufficient hydrological (measured stream flow data) is yet another serious limitation that would otherwise supported model calibration and validation.

1.6 Description of the study area

1.6.1 Location

The study area is bounded on the South by Kenya, and southwest by South Sudan, East by Hamer District and Borena zone of Oromia Region, and North by Kefa Zone. The are mainly lies within two zones, the Ari zone (Jinka main town) and the Pastoralist zone (Turmi main town). To reach the Study area, one can follow route from Addis Ababa – Arbaminch – Keyafer- Turmi Town (South Omo Pastoralist Zone). The road is asphalt all the way from Addis Ababa to Keyafer except few stretches from Keyafer to Turmi. The entry points to the study area are three. These are Turmi to Omorate, Turmi Gnangatom and Jinka Hana Salamago.

The study area currently lies amidst four zones Benchi Maji, Kefa, Ari zone and South Omo Pastoralist Zone. The study area is bounded between 4.4 and 6.5-degree north and 35.6 and 36.5 Degree east covering a total area of 8, 524 km^2 (see fig 1).

It is an enjoyment to go to south Omo because one crosses different and diversified cultures and living styles all the way from Addis to Omorate and to Hana Salamago. The study area is one of the most frequently visited Tourist site in which many western visitors frequent different sites in the study area.

1.6.2 Physiography of the study area

The study area lies on the lowest floor (graben) of South Omo constituting the western flank of the Ethiopian Rift. The south Omo graben as the other rift floor areas is the result the of the extensional movement of the major East African Rift. The study receives its run offs from the surrounding ridges located on the north, east and west. These ridges are also the source of sediments for its continued piling up in the study area.

The study area is characterized by semi-arid to arid climate with average monthly temperature ranging from 19.9 ^oC to 34 ^oC with the hottest spot at around Omorate town. It receives an average annual precipitation between 900-1000 mm in a bi modal rain fall system. The soil cover of the area is sand, silt and a few observable clay soils. The arid expanse is covered by short thorny bushes and thorny grasslands shallowly cut by north east south west aligned dry flow channels (wadi beds).

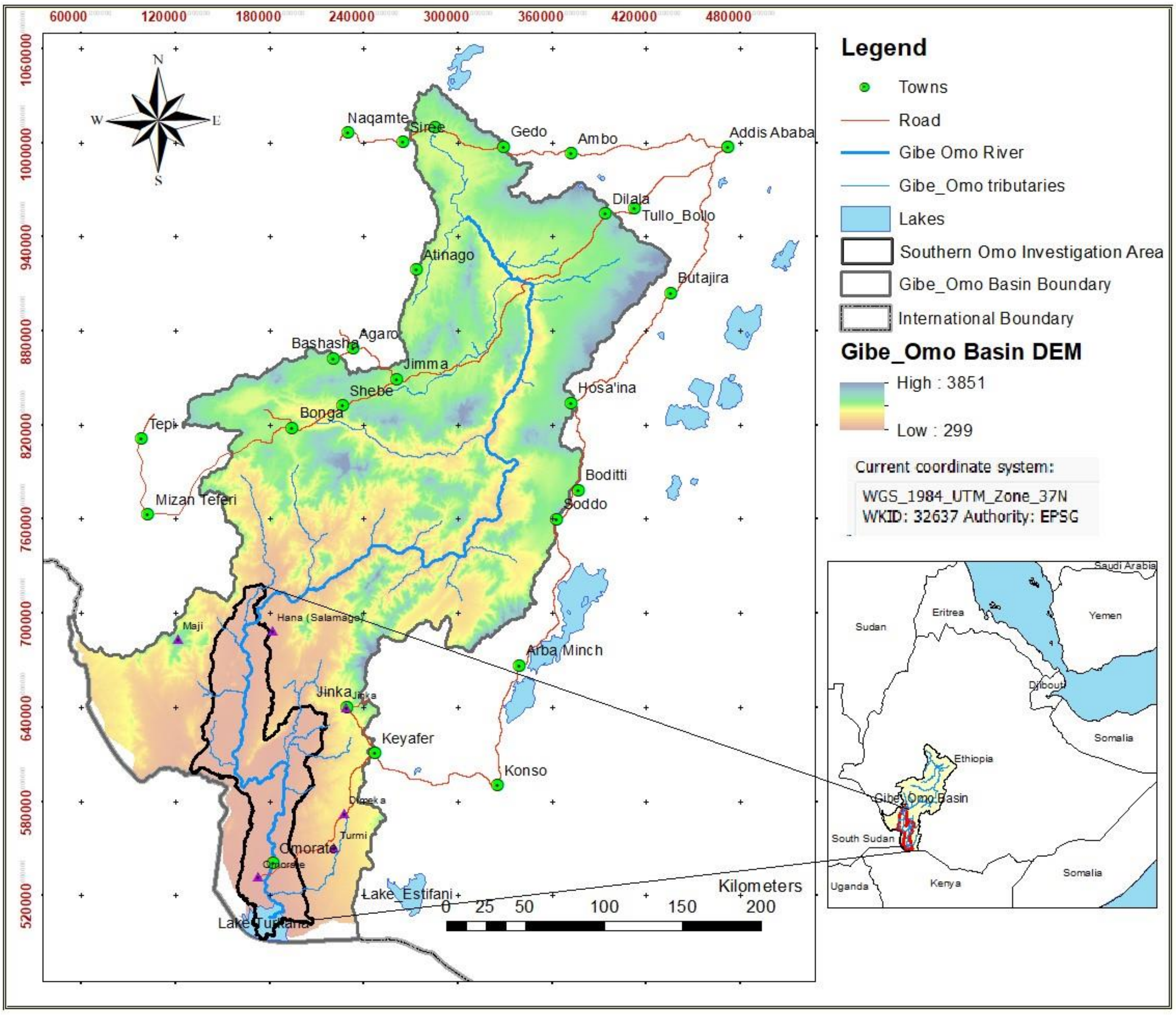


Figure 1: Location map of the study area

CHAPTER TWO: LITRATURE REVIEW

2. General

Literature review is an essential feature of academic study. Fundamentally, knowledge advancement must be built on prior existing work. To push the knowledge frontier, we must know where the frontier is. By reviewing relevant literature, we understand the breadth and depth of the existing body of work and identify gaps to explore. By summarizing, analyzing, and synthesizing a group of related literature, we can test a specific hypothesis and/or develop new theories. We can also evaluate the validity and quality of existing work against a criterion to reveal weaknesses, inconsistencies, and contradictions (Pare et al. 2015).

Therefore, the following basic data were collected and reviewed during office works.

- Literature review (Papers, technical reports, studies, well completion reports, design reports and the likes...)
- Review of geological and hydro-geological study reports and maps, topographic map of the area,
- Reviewing of all available information and data (climate data, well data including yield, water level, water quality, construction details, geological logs of boreholes in and the surrounding areas) and published and unpublished journals pertaining to the area,

The sources of data are:

- South OMO Zone Water Mineral and Energy Office
- District Water Mineral and Energy Office
- Ethiopian Water Resources Management Institute,
- International Water Resources Management,
- Ministry of Water, Irrigation and Energy,
- Ethiopian Meteorological Agency

The office work included collection of secondary data like previous geological and hydro-geological reports pertaining to the area and the collection of available water points, pumping test data and geophysical Surveying data and analyses in the locality in question.

2.1 Climate

The concept of climate refers to the long-term patterns and averages of its constituent variables like temperature, precipitation, humidity, wind and other atmospheric conditions in a particular region over time (IPCC, 2021). Climate is distinct from weather, which refers to short term variations in atmospheric condition (NASA, n.d). Understanding the concept of climate is essential for assessing the impacts of climate change (IPCC, 2021), developing effective strategies for mitigation and adaptation (UNFCCC, 2015), and promoting global cooperation to address this urgent and complex challenge (Paris Agreement, 2015).

Key elements of climate include:

- Temperature: The average temperature of a region or the planet over an extended period, such as a month, season, or year.
- Precipitation: The amount of rainfall, snowfall, or other forms of moisture that fall in a region over time.
- Humidity: The amount of moisture present in the air, which affects how hot or cold it feels.
- Wind Patterns: The direction and strength of prevailing winds in a region, which can influence weather and climate conditions.
- Atmospheric Pressure: The pressure exerted by the Earth's atmosphere, which can affect weather patterns and circulation systems.

Climate is distinct from weather, which refers to short-term atmospheric conditions at a specific time and place. While weather can change rapidly, climate represents the average of these conditions over longer periods, providing a broader understanding of the typical conditions experienced in a particular area. Climate is influenced by various factors, including geographic location, latitude, altitude, ocean currents, and human activities such as greenhouse gas emissions.

2.1.1 Climate Change

A change in the state of the climate that can be identified by changes in the mean or the variability of its properties, and that persists for an extended period, typically decades or longer (IPCC, 2021). Climate change may be due to natural internal processes or external forcings such as modulation of the solar cycles, volcanic eruptions, and persistent anthropogenic changes in the composition of the atmosphere or in land use (IPCC,2021).

Climate change impacts manifest in various ways across the globe, affecting ecosystems, economies, societies, and individuals (IPCC,2021). Observed increases in greenhouse gases (GHG) concentrations since around 1750are unequivocally caused by GHG emissions from human activities (IPCC,2021). Land and ocean sinks have taken up a near –constant proportion (globally about 56% per year of CO_2 emissions from human activities over the past six decades, with regional differences (IPCC,2021). In 2019 atmospheric CO_2 concentration reached 410 ppm, CH_4 reached 1886 ppb and nitrous oxide (N2O) reached 332 ppb (IPCC,2021).

Other major contributors to warming are tropospheric ozone (O3) and halogenated gases. Concentrations of CH4 and N2O have increased to levels unprecedented in at least 800,000 years, and the current CO2 concentrations are higher than at any time over at least the past two million years (IPCC,2021). Since 1750, increases in CO2 (47%) and CH4 (156%) concentrations far exceed increases in N2O (23%) are similar to the natural multi-millennial changes between glacial and interglacial periods over at least the past 800,000 years (IPCC,2021).

2.1.2 The Global Effort to counter the Climate Change

The world, ever after it came to notice and understand the consequence of climate change on mother earth, it seriously worked to counter the effect of climate change through establishing responsible organizations at government and expert level. Through its global organization like UNFCCC, IPCC, FAO and others has been exerting different measures and undertakings tailored with these same organizations to tackle this ever changing climate.

The Kyoto Protocol and the Paris Agreement, along with the other intermediary treaties and agreements, form part of the international frame work for addressing climate change (UNFCCC). They involve commitments, targets, and mechanisms to reduce greenhouse gas emissions, adapt to climate impacts, and provide support to vulnerable countries and communities (UNFCCC).

The Kyoto Protocol is an international agreement linked to the United Nations Framework Convention on Climate Change (UNFCCC). The Major feature of the Kyoto

Protocol is that it sets binding targets for 37 industrialized countries and the European community for reducing greenhouse gas (GHG) emissions (UNFCCC). These reduction amount to an average of five percent against 1990 levels over the five – year period 2008-2012 (UNFCCC).

The Kyoto Protocol established a frame work for emissions trading among participating countries (UNFCCC). It allowed countries to meet their emission reduction targets through various mechanism, including the Clean Development Mechanism (CDM), Joint Implementation (JI) and emission trading (UNFCCC). While the Kyoto Protocol is not universally ratified and its commitments have largely expired, it represented a significant international effort in carbon trading (UNFCCC).

The implementation of the Kyoto Protocol involves various mechanisms and strategies at national and international levels. Participating countries are required to develop and implement policies and measures to achieve their emission reduction targets. These may include energy efficiency improvement, renewable energy deployment, and regulatory measures to limit emissions from industrial sectors (UNFCCC).

The Paris Agreement, adopted in 2015, provides a framework of voluntarily pledge emission reduction targets (Nationally determined Contributions, or NDSs) for countries and encourages the use of market based mechanisms, including carbon trading, to achieve these targets (UNFCCC, 2015). Article 6 of the Paris Agreement outlines provisions for international cooperation, including the potential use of carbon market, although the operational details are still being negotiated (UNFCCC, 2015).

Additionally, various regional and national carbon trading schemes exist around the world, such as the European Union Emission Trading System (EU ETS) and the Regional Greenhouse Gas Initiative (RGGI) in the United States. While not part of a global treaty, these schemes contribute to global efforts to reduce greenhouse gas emissions through carbon trading mechanisms (UNFCCC, 2015).

The primary goal of the Paris Agreement on Climate Change is to limit global warming to well below 2 degrees Celsius over above pre industrial levels, and pursue efforts to limit the temperature increase to 1.5 degree Celsius. This is aimed at reducing the risk and impacts of climate change. To achieve this, countries that are parties to the agreement set their own national targets for reducing greenhouse gas emission and regularly report on their progress. The agreement also includes provision for international cooperation, support for developing countries. And mechanisms for transparency and accountability (UNFCCC, 2015).

2.1.3 Understanding Future Climate Scenarios

The scenario approach is used to characterize the range of plausible climate futures and to illustrate the consequences of different pathways (policy choices, technological changes, etc). They are chosen to span a wide range without any tie to likelihood; the scenarios serve as 'what if' cases. Over the past three decades, the approach to formulating the different 'scenarios' has evolved from a climate-centric to an increasingly societal development-centric concept, albeit with the same underlying goal of providing insight into a range of plausible climate outcomes. CMIP5 used *Representative Concentration Pathways(RCPs)* and CMIP6 introduces the *Shared Socio-economic Pathways (SSPs)*. To distinguish the magnitude of climate forcing, the numbering reflects a designated amount of radiative forcing (a measure of the extent to which GHGs in the atmosphere warm or cool the climate) measured in watts per square meter (W/m2) reached by 2100 (i.e., 2.6, 4.5, 6.0 and 8.5 W/m2 of change over pre-industrial, respectively). CMIP6 introduced forcing of 1.9 W/m2 to offer insight into the climate response that might be reflective of the Paris-Accord target.

For CMIP6, each SSP drives a corresponding future projection of greenhouse gas emissions and land-use change under the baseline SSP storyline. The SSPs were designed to function in combination with a new and improved version of RCPs. As such, different climate policy futures can be superimposed on SSPs to represent the influence of different climate policy choices (i.e. switching to renewable energy from fossil fuels) and the ease or difficulty in reaching the end-of-century radiative forcing goal specified by an RCP. The different policy scenarios lead to different levels of radiative forcing, with higher values representing stronger climate warming effects. The particular forcing values were chosen to allow easy comparison of the new scenarios to the RCPs used in the CMIP5 and IPCC AR5. Not all possible combinations of SSPs and forcing scenarios are viable and therefore, some do not have simulations. For example, SSP5 which prioritizes fossil-fuel development, thereby establishing a world with high emissions, is incompatible with a low forcing scenario (i.e. 1.9 W/m2), which would require stricter climate policy and strong mitigation, and therefore low greenhouse gas emissions.

The CMIP model results, as driven by scenarios, have become standard reference inputs for work concerning climate change science, impacts, vulnerability, adaptation, and mitigation. Scenarios should be used as tools to help understand the characteristics and magnitude of emerging climate signals to inform decisions. Focusing solely on end-of-century outcomes is an inadequate way to evaluate the usefulness of a given scenario. For purposes of informing societal decisions, shorter time horizons are highly relevant.

2.1.4 CMIP5

Representative Concentration Pathways (RCPs) are a method for capturing those assumptions within a set of scenarios. The conditions of each scenario are used in the process of modelling possible future climate evolution (IPCC web site). The Representative Concentration Pathways (RCPs), presented in CMIP5, describe four different 21st century pathways. The RCPs include a stringent mitigation scenario (RCP2.6), two intermediate scenarios (RCP4.5 and RCP6.0) and one scenario with high GHG emissions (RCP8.5). Scenarios without additional efforts to constrain emissions ('baseline scenarios') lead to pathways ranging between RCP6.0 and RCP8.5. Each RCP shows the planet trapping progressively higher amounts of energy from RCP2.6 (the lowest) to RCP8.5 (the highest). **Figure 2** shows the GHG emission pathways for each RCPs through to the end of the century.

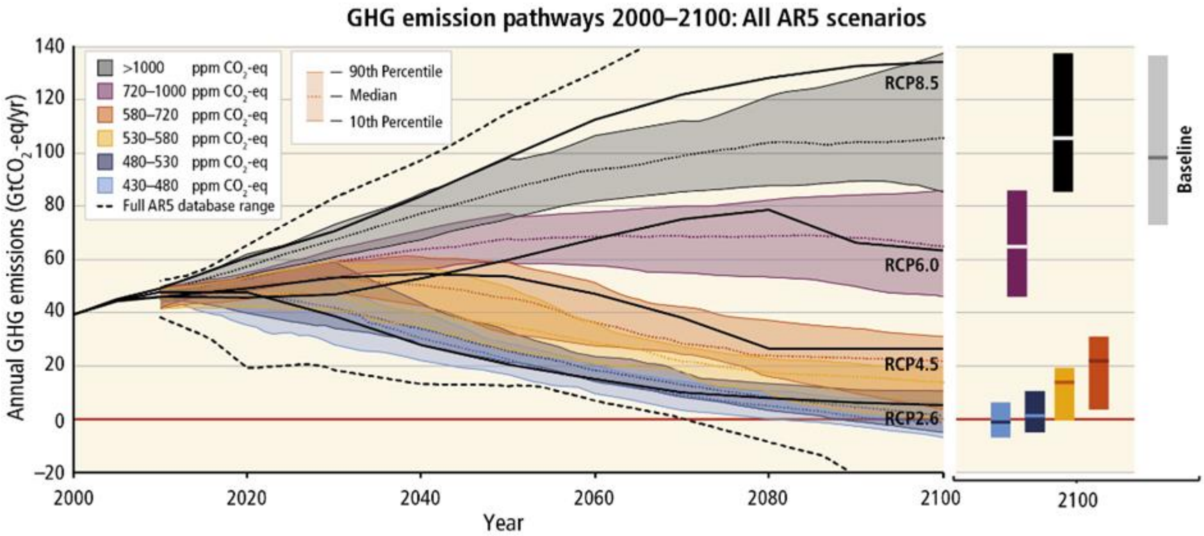


Figure 2: GHG Emission Pathways for each RCP from 2000-2100. Source, IPCC Working Group I, 2013 RCP scenarios

2.1.5 Global Circulation Model Future Projection Scenarios

The Representative Concentration Pathways (RCPs) are set of scenarios used in climate modeling to represent different possible trajectories of future greenhouse gas (GHG) concentration and associated radiative forcing levels (fig.2). Each RCP corresponding to a specific range of radiative forcing values by the year 2100, providing a framework for assessing climate change impacts and mitigation strategies (Moss et al., 2010). Here are the four RCPs along with their milestones.

i. RCP2.6: This pathway aims to keep global warming below 2^{o}C above pre-industrial levels, requiring significant reduction in GHG emissions.

ii. RCP4.5: This scenario stabilizes radiative forcing at 4.5W/m^2 by 2100 through the implementation of various mitigation measures.

iii. RCP6.0: This pathway envisions stabilization at 6W/m2 by 2100 with moderate emission reductions.

iv. RCP8.5: This is a high-emission scenario where radiative forcing reaches 8.5W/m^2 by 2100, assuming no significant reductions.

2.2 Geological and hydrogeological set up of the area

2.2.1 Geology

Considering the project area south Omo alluvial deposit (graben) many authors reported their geological works at regional level. Out of these authors, Mohr, Kazmin and Davidson are few of the documents reviewed.

A. V. Kazmin (1972) the first Compiled Geological Map of Ethiopia, Addis Ababa

V. Kazmin categorized and described the rock outcrops of the project area in to three major units. These are from oldest to youngest:

- Lower Complex
- Upper Complex
- Precambrian Granitoids
- Tertiary rocks

According to Kazmin (1971) the lower complex comprises various gneisses and migmatites, usually course grained, well foliated, and gray colored often banded. Transitions from foliated and banded rocks to massive varieties are common reflecting variation in the degree of granitization and mobilization. Generally the metamorphic grade is so high that no deduction as to the original composition of the rock can be made.

Most of the Precambrian rocks are relatively impermeable, and have been subjected to several orogenic episodes since their formation. This process combined with the rifting has resulted in considerable fracturing and shattering. Major water resources are associated with these fracture zones (Kazmine, 1975). Davidson (1983) Bulletin No.2, The OMO River Project, Reconnaissance Geology and Geochemistry of Parts of Ilubabore, Kefa, Gemu Gofa and Sidamo, Ethiopoa, Addis Ababa

According to the work of Davidson (1983), under the Omo project, at regional scale there are four major rock units that cover the project area. These rock units from oldest to youngest are:

- Crystalline basement rocks,
- Permian sediments,
- Pre-rift volcanic,
- Post rift sediments/volcanic.

A. Davidson continues explaining that, the biotite and hornblende gneisse covers a large part of crystalline basement in the Hamer domain. In the Hamer range and elevated plains particularly this unit is relatively uniform and poorly layered orthogenesis, representing deformed and metamorphosed plutonic rocks of diorite, quartz dioritic and tonalitic composition, although relict primary texture is rarely preserved. Contacts with the adjacent map units are gradational.

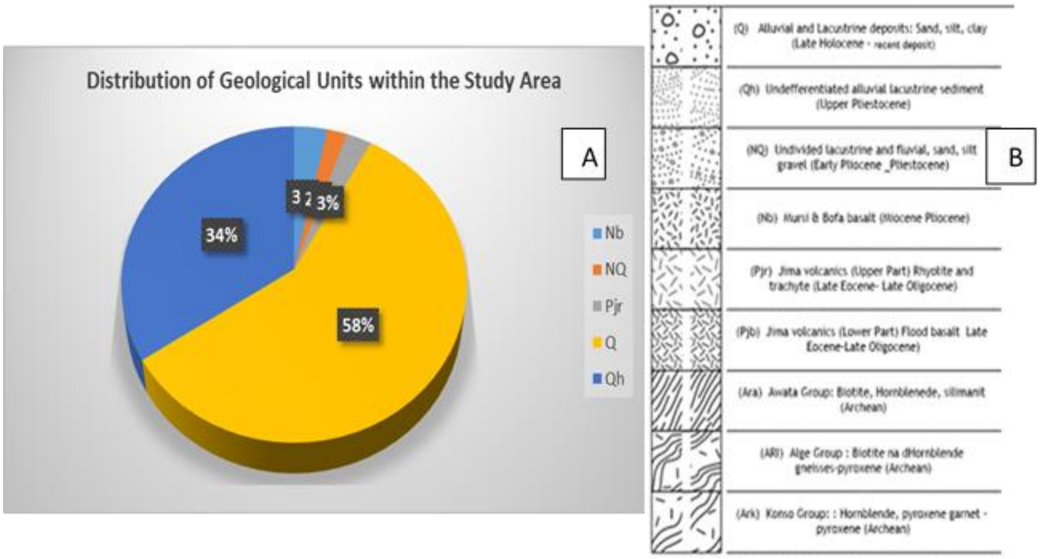


Figure 3: Stratigraphic Sequence of South Omo Basin

From the work of Davidson, (Davidson, 1983), it can be observed that 58% of the study area covered by the youngest alluvial and lacustrine deposit (Q) (fig. 3 A and B). This youngest deposit occupies the northern, southern and eastern margin of the study area. The second largest part of the study area covered by the second younger undifferentiated alluvial lacustrine sediment. This unit occupies the central and central western part of the study area.

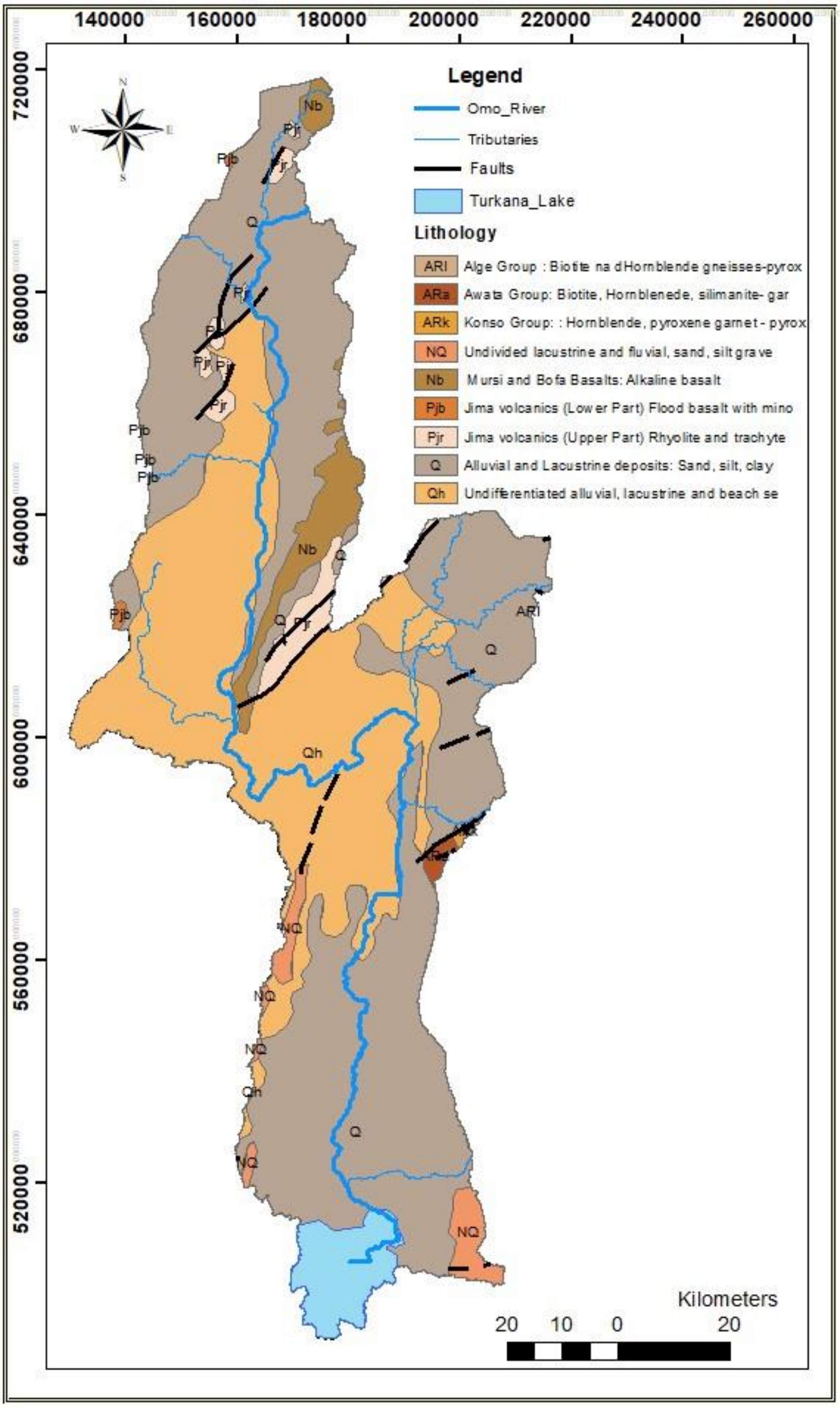


Figure 4: Geological map of the Southern Omo Alluvial Deposit Basin

The top most layer is covered up by recent alluvial and lacustrine deposits on the exit of the rift in southern tip of Ethiopia Between the alluvio-lacustrine deposit and the crystalline basement rock of south western Ethiopia lies volcanic rock cover with considerable extent in the north east of the study area (fig 3). This rock sample observation depicts that dark grey color basalt aphyric in texture and at places carrying plagioclase phenocryts. This rock according to (Davidson, 1983) is termed as Fejej Formation in Asille group and ranges in thickness from 20 to 150 m.

The metamorphic complex with its attendant plutonic rocks that makes up the crystalline basement of Ethiopia is part of the Mozambique Belt, itself part of the Pan African Orogenic System of late Precambrian to earliest Paleozoic age. The late Paleozoic ruminants of terrestrial sedimentary rocks were in part eroded before marine incursion from the east and north east, beginning in late Triassic continuing into Jurassic time. This succession was eroded at its margin before the advent of extensive volcanism in the early Tertiary that has continued to the present (Davidson, 1983)

Geological and Hydrogeological site observation is necessitated to confirm the information obtained in the desk review stage and to fill the gaps therein and to collect additional information on the groundwater resource of the study area for input in the impact assessment of Climate change impact groundwater resources southern Omo alluvial deposit graben. The alluvial deposit graben of south Omo graben can easily be recognized from the morphology and material covering the surface.

The flat expanse is covered by grass like thorns and lighter and darker gray silt, sand and clay material. The vegetation cover of the study area is sparsely distributed and sometimes clustered thorny bushes. While driving on the plain, it is common place to come across lighter pure sand beds (wadi beds) which are seasonal flow paths. This shallowly cutting seasonal run off flow paths are oriented east-west and flow to the Omo river.

2.1.2 Structure

The study area lies within the Omo plain. This plain is a graben created by the rifting process at the outlet of Ethiopia. It is covered by different undivided sediments. The graben plain is gently sloping down to south western direction. The major structure observed in the area is that the dry stream beds are aligned in conformity the Major Ethiopian Rift and drain to the Turkana Lake. The upstream part of the wadi beds passing through Omo plain for example the Keskie wadi bed is governed by the Major East African Rift structures. The Keskie wadi bed is partially aligned in conformity with the N-S oriented fault structure which gave rise to the rifting.

2.1.3 Drainage System

The Project area lies within the southern Omo River drainage basin. The drainage density is medium to high. The drainages are controlled by slopes and generally oriented in the southwesterly direction. The draining dry stream channels bear water only during sufficient rainfall or flood times when it rains in the upper north, eastern and western highlands. The gently general southwestern sloping landform governs the drainage pattern of the area. The dry stream beds (Wadi Beds) form intra-dendritic pattern and parallel flow patterns of the sub catchments are the sources of clay, silt, sand and gravel deposits that continually builds up at the delta mouth.

It can easily be observed that almost all waters from the sources of the sub catchment drains to the NS trending graben of South Omo alluvial basin (fig. 5). This drainage networks shallowly cuts the expanse plain with the run off during the precipitation in the surrounding highlands. The drainage networks are additional sources for the fresh water run off supply to the alluvial deposit plain of south Omo graben apart from the precipitation.

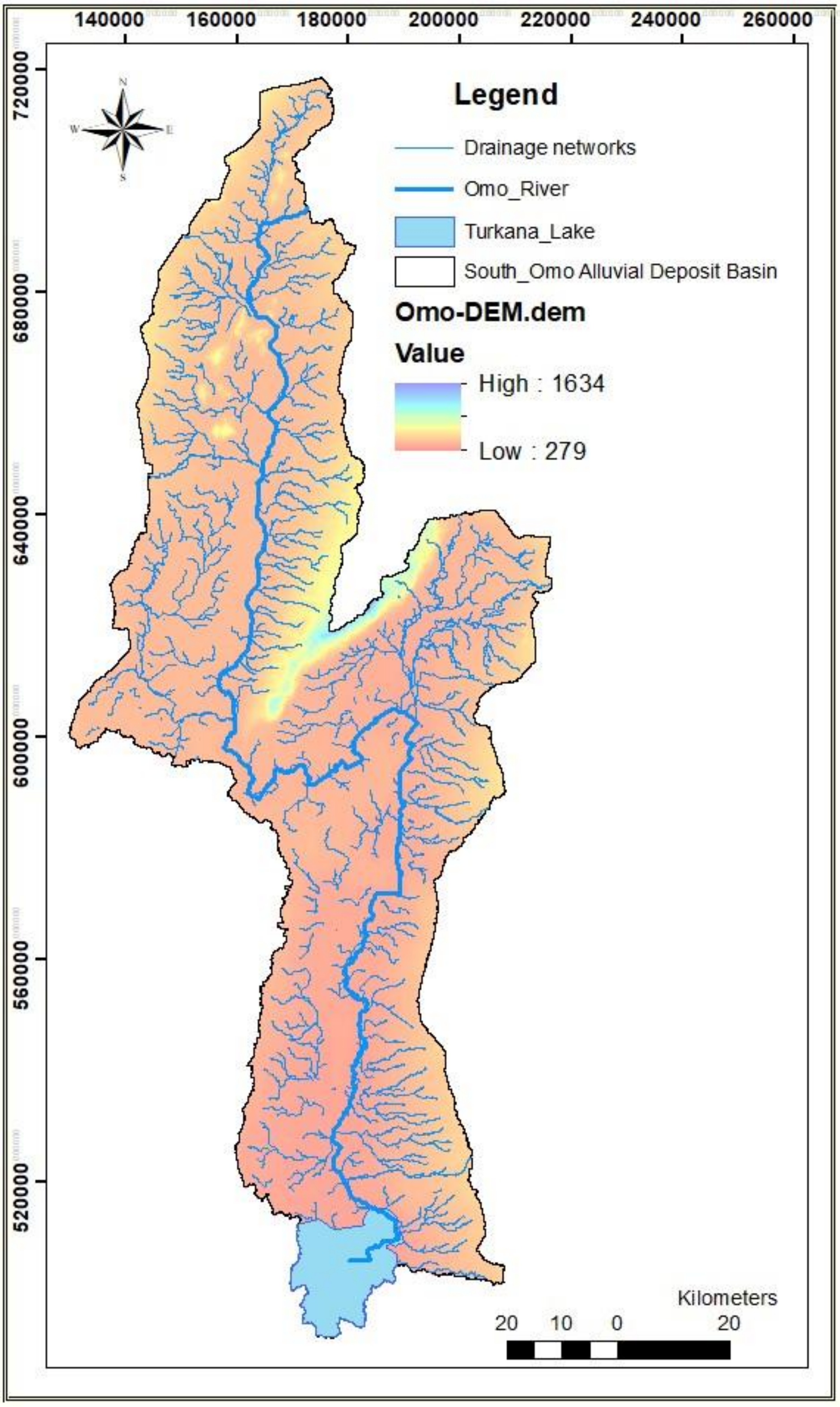


Figure 5: Drainage map of Omo Graben alluvial deposit

2.2.2 Hydrogeological Setup of the study area

In the hydrogeological review work of T. Cherinet (1993), the thickness of the weathered zone is usually small. Therefore, only the alluvial deposits along valleys can serve as sources for localized groundwater where the recharge to groundwater is sufficient. Tesfaye Cherinet continuous to explain that the grain size and sorting as well as the thickness of the alluvium determine the aquifer potential of the alluvium which generally have a low to moderate productivity.

According to S. Kebede (2010) shallow Alluvio Lacustrine Aquifers and the recharge mechanism of the aquifers in the area of interest is recharge to wadi beds through local wadi floods. The aquifers in the area are highly vulnerable to the climate change and rainfall seasonality.

In the hydrogeological assessment work of (Alemayehu 2006), unconsolidated sediments and lacustrine sediments of Genale, Dawa, Baro, Omo and Awash basins are recognized to produce productive aquifer. The assessment further describes that most of the time aquifers made of unconsolidated sediments and weathered profile can be exploited using hand-dug wells. In fact these unconsolidated sediments are being utilized as a source of water supply in the southern Omo through shallow bore wells fitted hand pumps and rudimentary hand-dug wells.

The comparison of annual precipitation, evapotranspiration, and streamflow for the baseline period, mid-term, and long-term for the South Omo-Gibe indicated increasing trends. The analysis revealed the impact of climate change on future annual streamflow to be directly and indirectly correlated with an annual change in precipitation and evaporation. (Shiferaw et al., 2022)

Substantial warming and erratic rainfall have made OGRB vulnerable to drought events. The intensification of droughts in the basin has also been recorded in humid parts of the basin which has a significant adverse effect on the water availability of down streams. This indicates that the observed drought intensity can increase the water deficit and other natural resources degradation. Therefore, this study provides essential information on drought characteristics for decision-makers to plan appropriate strategies for early warning systems to adapt and mitigate drought hazards in the basin (Regassa et al., 2022).

Carr and Carr (2017)described the Omo river to contribute 90% of the Lake Turkana water source which is the largest fresh water body in Kenya. The same author further described that the Omo's annual flood delivers a major 'pulse' of freshwater, sediment and nutrients to the Lake Turkana —vital contributions to the physical and biological integrity of otherwise saline waters.

2.2.3 Field Hydrogeological Observation

The southern Omo alluvial deposit is situated within the south western part of the country on the outlet of the Major Ethiopian Rift. Constituting the Omo basin, the south Omo alluvial deposit strip lies in a NNW-SSE starting a few kilometers north of Hana (Salamago) all the way to Omorate Town ending into Lake Turkana.

The alluvial deposit plain is bounded in the eastern by crystalline basement highland terrain and northern by volcanic rocks of different episodes. The south Omo strip is bounded on the western by highlands covered by volcanic rock and Crystalline basement rocks. The area lies on the northern plain surrounding Lake Turkana constituted of undivided sediments where the dry drainage streams beds very shallowly cut the plain. The area is characterized by blanket of sand covered by short thorny vegetation of the desert area. The dry stream beds are mostly covered by thick sand deposit transported from the up lands of Hammer district.

The geomorphology of the project area is expressed by low lying plain constituted by the recent sediments. The major Ethiopian rift bifurcates on its exit to the Kenya and our project area is part of the western flank of the Major Ethiopian Rift. Compared to the Chew Bahir Lake, Lake Turkana lies at an average elevation lower than the Chew Bahir Lake.

The seasonal river channels are sometimes covered up by pebble to cobble sized rounded rock pieces (fig 6 A). This indicate that there has been high intensity rainfall capable of plucking and rolling over pebble and coble sized fragments of rocks along its channel. These angular rock fragments at the beginning get rounded downstream due to wear and tear along the course. These kind of material transport are commonly observed along major wadi beds.

The silt and sand deposit along the flow channel indicates that there is low intensity rainfall which only capable of transporting silt and sand grains (fig 6 B).

These kind of channels are commonly observable everywhere across the study area. This is because the smaller stream channels acting as a sediment conveyor to the next longer channels. The density of these channels is much greater than the major ones (see fig 5).

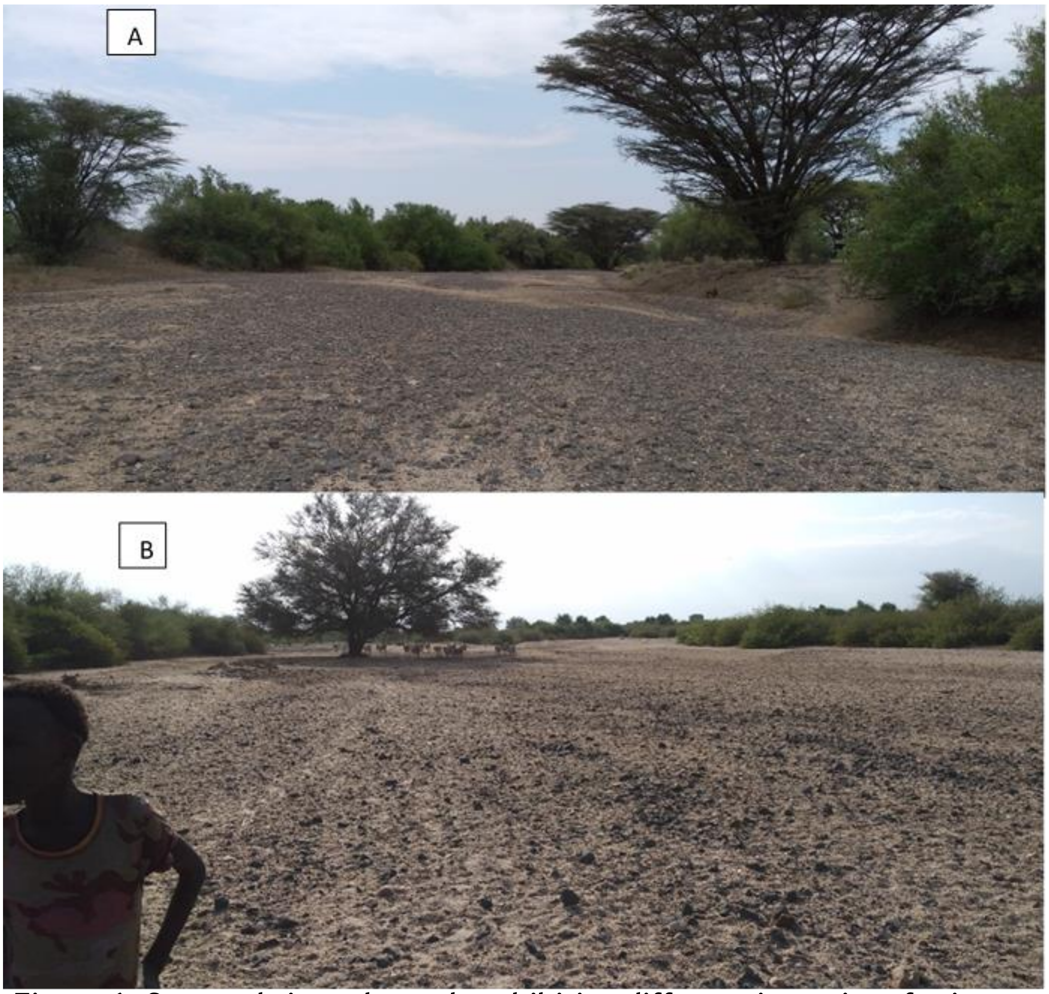


Figure 6: Seasonal river channels exhibiting different intensity of rain

The mode of deposition is directly related to the intensity of precipitation which generates flowing water capable of transporting depositing of pebble and coble sized fragments as can be observed in the above valley cut exposure. The pebble and coble sized fragments corresponds with the higher intensity precipitation followed by low intensity precipitation

Figure 7: Hand Dug well excavation and Valley cut exposures

From the comprehensive overview of the geological set of the study area, two important geological and hydrogeological units viz the very recent alluvial deposit and second youngest lacustrine deposit widely covering the study area.

Hydro-geological observation along selected traverse exhibited exposures along shallowly cutting wadi beds with alternating coarser and finer grain size fluvial deposit (fig. 7 B). These deposit are obviously unconsolidated. This unconsolidated nature of the deposit can be confirmed by the deeply cutting erosional flow marks on the seasonal flow banks. In addition, during site observation, efforts were made to collect groundwater resource data such as borehole depth, static water level, yield of the borehole and lithological logs in the Study area.

The suitable deposits for the occurrence of groundwater are prevalent on the rift floor with the detritus derived from the rift floor bounding escarpments and upstream area. These fluvial/alluvial deposits occur in along wadi beds (dry river channels) being drifted along the channel beds from upstream and from left and right channel banks. The wadi beds and streams if any flow to the Omo alluvial deposit graben and finally joins the Lake Turkana.

From the review of previous works, it is the work of T. Chernet (1993) that hints the recharge to the groundwater to range between 50mm/yr to or more than 150mm/yr. In this same work, Tesfaye categorized the aquifers of South Omo unconsolidated sediments to provide low to moderate yields (1-3 litres/sec)

In view of surface water, the south Omo alluvial deposit graben is characterized by having a single perennial river (Omo River) flowing from north to south (fig. 8). This River is a transboundary river tapping its water sources from the western and south western Showa, the Jima and Kefa highlands. This river carries sediments along with nutrients from the highlands and drains to Lake Turkana. Along its courses, the Omo river drops its sediment load and enriches the flood plains along the river course during its peak flow regimes.

With the work of (A. Tadesse, 2020), it has been detected through radon-222 that the Omo graben alluvial deposit recharges the Omo river. From this fact it can be concluded that the Omo river is a gaining river even as it flows along the study area (fig 7).

Figure 8: Omo River close to Omorate Town

2.2.4 Occurrence and productivity of groundwater resource of the study area

The ground water occurrence at regional level is very shallow to shallow basement aquifers and alluvio lacustrine aquifers. The recharge mechanism of these aquifers is recharge to wadi bed through local wadi floods and fast, selective recharge from heavy rainfall through fractures and unconsolidated sediments (Kebede, 2010).

Groundwater has been developed by shallow drilled bore wells and hand dug wells in the alluvio lacustrine deposit and in the alluvium along stream channels. These wadi beds are targets for the zonal experts to locate bore Wells for community water supply. These wadi beds are conveyors of runoff water, sand, silt and clay continually changes the morphology of the area. The run-off water is additional source of ground water recharge besides the direct precipitation. Since vertical permeability of soils is often higher in low rainfall regions than high rainfall areas. This factor may operate to induce a large vulnerability for aquifers from arid zones to pollution from the surface. The main problem of the study area is linked to poor quality groundwater resources existing side by side.

The suitable deposits for the occurrence of groundwater are prevalent on the rift floor with the detritus derived from the rift floor bounding escarpments and upstream area. Elsewhere these fluvial/alluvial deposits occur along wadi beds (dry river channels) being drifted along the channel beds from upstream and from left and right channel banks. The wadi beds and streams in the vicinity flow to the Omo River and finally joins the Lake Turkana.

The adjoining highlands in the northern, western and eastern part of Omo alluvial deposit graben contributes sediments and surface run off that continually enrich the sediment and fresh water recharge to the basin.

The small schemes (shallow wells and dug wells) are distributed surrounding the Omorate town and pastoral and semi pastoral settlements. These are indicatives of availability of shallow groundwater potential of the area under consideration. From the observation of two aquifers at Omorate, (T. Cherinet, 1993) describes that one with 20 m depth is fresh water whereas the second aquifer with 30 m depth is saline with a chloride content of 1000-1400 ppm. In this same work, Tesfaye describes that the more the depth of drilling the better productivity and possible risk of high salinity.

Hydraulic conductivity, often denoted as K, is a fundamental property in hydrogeology that describes the ability of a porous medium, such as soil or rock, to transmit water under the influence of a hydraulic gradient. In simpler terms, it measures how easily water can move through a material. Mathematically, hydraulic conductivity is defined as the proportionality constant between the flow rate of water through a unit cross-sectional area of the porous medium and the hydraulic gradient driving the flow. It is typically expressed in units of velocity per unit gradient, such as meters per day or centimeters per second (Todd, D. K. (1980). High hydraulic conductivity means that water can flow easily through the material, while low hydraulic conductivity indicates that the material restricts the movement of water. The value of hydraulic conductivity depends on various factors including the size and shape of the pores in the medium, the properties of the fluid, and the characteristics of the medium itself (such as grain size distribution and porosity). In groundwater flow, hydraulic conductivity plays a crucial role in determining the rate at which groundwater moves through the subsurface, influencing processes such as groundwater recharge, discharge, and contaminant transport. It is a key parameter used in groundwater modeling and is essential for understanding and managing groundwater resources. From the rare data that one can find in the study area, this writer could find one pumping test data around Fejeje locality southeastern tip of the study. From this data the Hydraulic conductivity (K) and transmissivity (T) of the aquifer matrix is respectively 0.2m/day and 17.8 m2/day with a constant discharge rate of 5.8 l/sec for aquifer thickness of 85m.

2.2.5 Water Points Inventory

The available water supply sources are collected from the regional office (Hawassa), zone and respective district offices. Though much efforts were exerted to exhaustively get access to the study area water points inventory, the author of this paper could inventory of water points location and status of the limited water points with respect to salinity.

From the water points distribution, one can easily observe that most of the drill wells were conducted along the wadi beds (fig. 9). This is not something done merely to intercept the seasonal waters that flow within the wadi beds. Because of the salinity problem within the south Omo basin groundwater sources, the wadi beds serves as seasonal fresh water flush thereby keeping the level of salinity at lower stage rendering the groundwater source in the drinking water quality range.

From the water points data collected from the regional office, zone and district offices and NGO offices operating in the study area, very few of them had necessary dataset. For the purpose of this study, data like water level records, discharge rates, aquifer characteristics like transmissivity, storativity are nonexistent. What is available at the offices is that location in most cases, type of bore well, year drilled, cost, source of budget and in some case their salinity (fig. 9).

This discrepancy created gap in the observation of groundwater resource impact assessment under the changing climate using groundwater flow modeling. This is because the groundwater flow modeling requires appropriate distribution of datasets that convey the model the information it requires to simulate the groundwater levels in response to the changing climate condition with respect to the given scenario.

Not only for groundwater flow modeling do the appropriate groundwater dataset are required but also equally these datasets are also required for the model calibration. Even though we try to simulate groundwater flow model using data sets derived from the standard values of similar geological material, it would finally necessitate those datasets to calibrate the groundwater flow model to see the model performance as related to real time values. This increase the level of confidence to convince stakeholders for the review of strategies and policies to curb the undesired predicted values for safe natural resources utilization

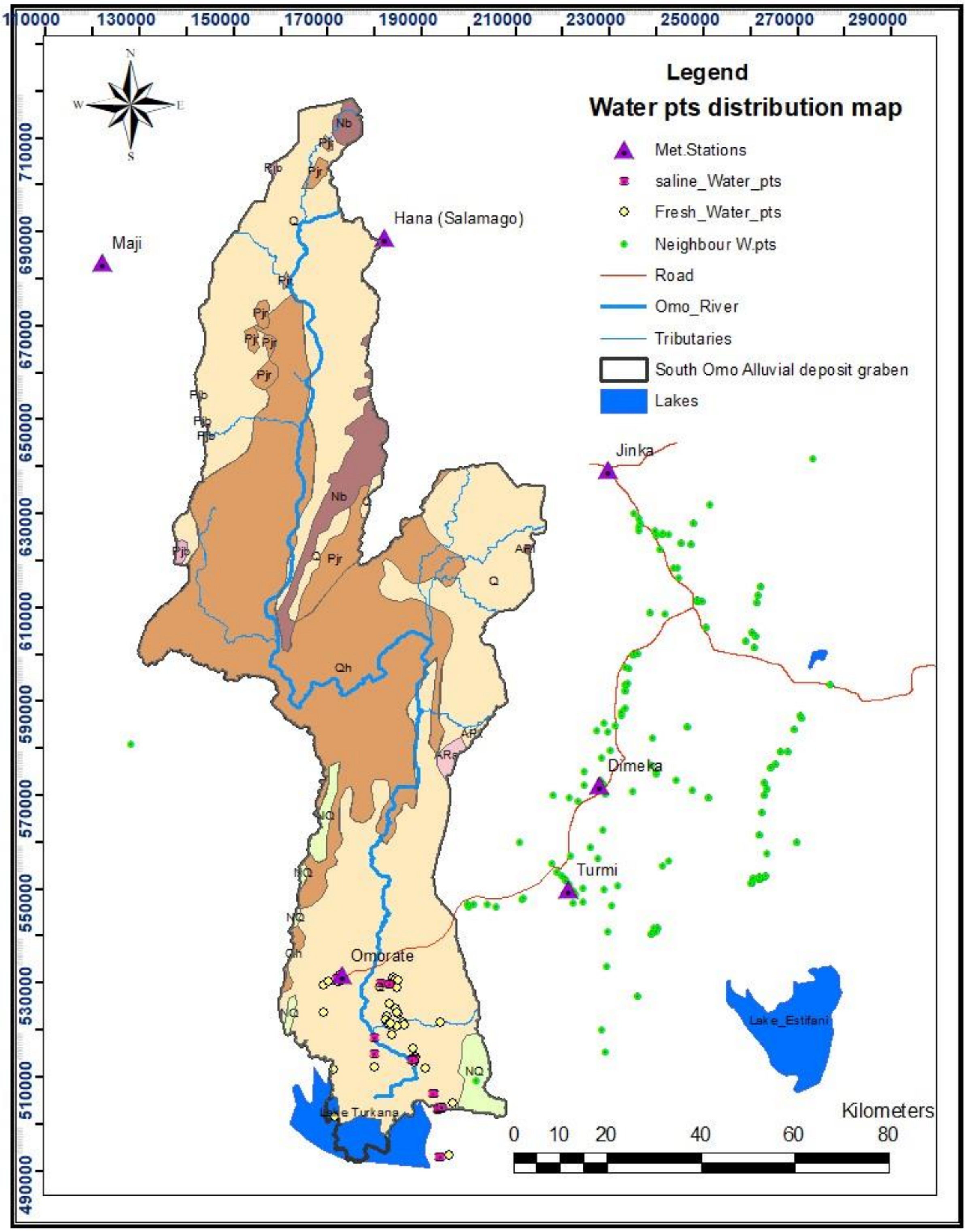


Figure 9: Water Points Distribution map

2.2.6 Groundwater Quality

In the context of the Omo Delta, the hydrogeological understanding is still in its infancy, as highlighted by Kebede's work in 2013. Kebede's study sheds light on the presence of both fresh and saline groundwater in the delta region, with a noted challenge in accessing fresh water due to the prevalence of salinity. This finding underscores the significance of further research to address the complexities of groundwater salinity and its implications for water resource management in the area.

Kebede's research also underscores the critical need for detailed investigations into the hydrochemical and isotopic composition of groundwater in the Omo Delta. Understanding the geochemical signatures and isotopic ratios can provide valuable insights into the origins of salinity, the mechanisms driving its distribution, and the factors influencing its lateral and vertical variations across different geomorphological settings within the delta.

Furthermore, the linkage between geomorphic processes and groundwater salinity remains poorly understood in the Omo Delta. Investigating how the delta's geomorphology influences the distribution of salt in groundwater is essential for unraveling the complex interactions between surface processes, subsurface flow dynamics, and groundwater quality.

Addressing key questions regarding the origin(s) of saline groundwater, the mechanisms governing its distribution, and its spatial variability requires a multidisciplinary approach that integrates hydrogeological, geochemical, and isotopic analyses. By gaining a sound understanding of these processes, researchers can better inform strategies for sustainable water resource management in the Omo Delta, mitigating the challenges associated with salinity and ensuring access to safe and reliable freshwater sources for local communities and ecosystems.

According to the unpublished work of (A. Taddesse 2020) the hydro chemical evidences show that there is no significant signature of geochemical evolution that indicates the presence of continues or regional flow system along N-S and NE-SW hypothetical transects. In this same assessment, it is described that the isotopic analysis shows that relatively depleted groundwater at Hammer basement and enriched groundwater at the alluvial deposits if the southern Omo graben reasonably indicates the absence of flow continuity between the two regions. Both hydro chemical and isotope techniques indicate the dominance of local recharge and flow system.

A.Taddesse further explains that from the converging evidence of geology, hydrogeology, hydrochemistry, and stable isotopes of water, three processes are responsible for the salinization of groundwater in Omo Delta: Salinity originated from water-rock interaction, evaporation at or near the surface and clay membrane filtration (A. Tadesse, 2020. Page 174).

This clay membrane filtration assumed in the work of A Tadesse, 2020, is best correlated with the elongated groundwater residence time due the clay lenses. This situation allow the groundwater undergo more extensive interactions with the aquifer matrix, leading to greater opportunities for the dissolution of minerals and the accumulation of salts Todd, D. K. (1980), Freeze, R. A., & Cherry, J. A. (1979), Fetter, C. W. (2001).

2.3 Important Findings of Document Review

The rain fall pattern of the study area is bi modal peaking in the months of October and April. Whereas the rainfall pattern of most of the upstream Gibe-Omo basin is single modal peaking in the months of July/August. This difference in monthly rainfall distribution within an interrelated watersheds give rise to different ground water recharge dynamism.

From the observation of documents, the alluvial deposit of southern Omo graben alluvial deposit is not connected to the upper Gibe Omo groundwater flow system. This implies that the southern Omo graben alluvial deposit groundwater system is characterized by local flow and local recharge system. Therefore, the southern Omo graben alluvial deposit gets its recharge from the local precipitation and local wadi beds flow. This means again the groundwater resource is highly dependent on the local precipitation and environmental factors for its recharge. The climate change is therefore highly affects the groundwater resource of the study area.

In terms of water quality, one can easily observe that the study area groundwater resource in certain localities is affected by salinity that renders the water unfit for drinking. The vertical and horizontal distribution of this salinity problem is not yet well understood.

CHAPTER THREE: MATERIALS and METHODS

3 General

The overall purpose of this section is to describe the materials and methods used in the research work. The climate data collected from the meteorological stations surrounding the study area were used as a predictand with the most correlable predictor variable. Thus the climate data are predicted using different scenario up to the year 2100.

These predicted climate variables were used as an input in the ArcSWAT together with spatial data like soil cover, land use land cover and topography. This with calibrated model run to produce outputs like groundwater recharge, evapotranspiration.

3.1 Materials

3.1.1 Primary data

The primary data mostly climate variables were collected from Ethiopian Meteorological Institute (EMI). In the study area most of the stations are records temperature and precipitation with only one Met. Station (Jinka) known to record all the climate variables including relative humidity, wind speed and sunshine hours.

There are six meteorological stations that can relatively better represent the study area. The list of these stations and their locations is provided in (Table 1) below. In all the six climate stations, there is no satisfactory and continuous records of data. The principal climate data that one can find is precipitation and temperature data. Additional climate data like wind speed, relative humidity and sun shine hours are not available in all the stations.

The Jinka station has got relative humidity, wind speed and sunshine hours' records. But these records are not continuous in years and highly missing. Because of this the writer of this paper couldn't use the data of these three variables in the statistical downscaling of the climate variables from the GCM.

Table 1: Meteorological Stations used in the study

No	Easting	Northing	Elevation	Station name
1	227966	572288	1115	Dimeka
2	182257	688728	586	Hana (Salamago)
3	229749	639434	1373	Jinka
4	122136	683560	2367	Maji
5	173157	531589	365	Omorate
6	221282	550053	934	Turmi

In addition to the meteorological stations data, hydrogeological and geological observation data were collected. These data were collected during site observation.

3.1.2 Secondary Data

Secondary data which constitute the foundation of this research like previous publications pertaining to South Omo, geological/hydrogeological maps and reports, water points inventory data were collected from different government and non-government institutions. Spatial data like LULC, soil and topography data were taken from open sources like USGS, FAO web sites. These secondary data were collected from different sources and analyzed and interpreted using tools listed (table 5)

3.2 Methods

3.2.1 Statistical Downscaling Method (SDSM)

Statistical Downscaling Methods (SDSM) are widely used in climate science to bridge the gap between the coarse resolution of Global Climate Models (GCMs) and the finer spatial and temporal scales required for regional or local-scale climate assessments (Smith et al., 2009). The method offers valuable capabilities for generating high-resolution climate projections tailored to regional or local-scale applications. However, they also have limitations and uncertainties that need to be addressed, including assumptions of stationarity, limitations in representing physical processes, uncertainty propagation, and potential scale mismatch issues. Careful consideration of these factors is essential for the accurate interpretation and utilization of downscaled climate information in climate change impact assessments and adaptation planning.

Green et al. (2011) discussed dynamic and statistical downscaling as alternatives for applying GCM results at the local scales of interest. Downscaled daily temperature generally compares well with observed data, but daily precipitation amounts often do not, particularly seasonal amounts and durations of wet and dry periods. Such discrepancies are important because of the highly nonlinear responses and sensitivities of dynamic vegetation growth and water use (transpiration) to precipitation regimes Green et al. (2007). Allen et al. (2010) used state-of-the-art downscaling methods to predict variations in recharge. They found that the variability in recharge predictions indicates that the seasonal performance of the downscaling tool is important, and that a range of GCMs should be considered for water management planning. Yang et al. (2005) noted that sufficient potential evaporation (PE) data are rarely available to identify long term trends. Thus, they made use of limited daily data to study sub-weekly structure, and used this information to downscale weekly sequences. In this way the dual objectives of downscaling weekly data and simulating daily PE sequences could both be achieved.

The Coupled Model Inter-comparison Project, Phase 5 (CMIP5), serves as a standardized experimental framework for evaluating coupled atmosphere-ocean general circulation models, enabling the assessment of model strengths and weaknesses (Taylor et al., 2012). Coupled Model Inter-comparison Project, Phase 5 (CMIP5) is a standard experimental framework for studying the output of coupled atmosphere-ocean general circulation models. This facilitates assessment of the strengths and weaknesses of climate models which can enhance and focus the development of future models. For example, if the models indicate a wide range of values either regionally or globally, then scientists may be able to determine the cause(s) of this uncertainty. CMIP5 is the most current and extensive of the CMIPs. It is defined by experiment suites divided into three categories: 1) Decadal Hindcasts and Predictions simulations; 2) "long-term" simulations; and 3) "atmosphere-only" (prescribed SST) simulations for especially computationally-demanding models. CMIP5 builds the database for the global climate change projections presented in the Fifth Assessment Report (AR5) of the Intergovernmental Panel on Climate Change (IPCC).

Figure 10: Downscaled GCM data extraction for statistical downscaling

3.2.2 GCM data Extraction and Procedures

Previously, I was thinking of using CMIP 6 _Coupled Model Inter-comparison Project Phase 6- organized by Shared Socioeconomic Pathways scenarios. Because of the limitation of accessing a robust CMIP6 data normalization for SDSM modeling, I resorted to use the CMIP 5 data for daily key variables extraction from the model.

I downloaded the GCM gridded data corresponding to my study area and downscaled to the Met stations surrounding my study area (fig 10). The GCM grid boxes are:

a. Longitude 36.57497, Latitude 7.4393

   X grid cell 14, Y grid cell 35

   Box longitude center: 36.5625, Box latitude center: 6.976

In this northern GCM grid box, three meteorological stations closer to my study area viz Jinka, Hana (Salamago) and Maji stations are included. Because of this, I downscaled the downloaded GCM using SDSM 4.2 downscaling model and extracted daily climate variables like precipitation, temp. max and temp. min. up to 12/31/2100 under the three representative concentration pathways of 2.6, 4.5 and 8.5.

b. Longitude 36.32887, Latitude 5.01353

   X grid cell 14, Y grid cell 34

   Box longitude center: 36.5625, Box latitude center: 4.185

In the southern GCM grid box, again three conventional meteorological stations are included. These are Dimeka, Omorate and Turmi stations. In the same way, the downloaded GCM is downscaled and daily data for the three variables are extracted under 2.6, 4.5 and 8.5 rcps up to 12/31/2100.

In the SDSM software there are 26 predictor variables designed to predicted climate variables. These predictor variables are screened and selected based on the correlation of the observed and historically modeled climate variables. Accordingly, out of the 26 predictor variables, 6 to 7 predictor variables were selected in order to predict the future climate variables under different scenarios.

3.2.3 SWAT Modeling

ArcSWAT (Soil and Water Assessment Tool) is a watershed-scale hydrological model developed by the United States Department of Agriculture (USDA) Agricultural Research Service (ARS) in collaboration with other organizations (arnole et al., 1998). It is an extension for ArcGIS , a geographic information system (GIS) software.

Using ArcSWAT for groundwater recharge estimation can be a useful approach, as SWAT is widely used hydrological model that can simulate various processes related to water resources (Neitsch et al., 2011). However, it is important to note that the accuracy of groundwater recharge estimation using any model, including SWAT, depends on numerous factors such as the input data quality, calibration, and validation of the model (Scannlon et al., 2002).

Before using ArcSWAT for groundwater recharge estimation, it is recommended to validate the model against observed groundwater recharge data if available. Additionally, sensitive analysis and calibration of the model parameters can help improve the accuracy of the estimation (Moriasi et al., 2007). Consulting with hydrology experts or researchers familiar with SWAT modeling can also provide valuable insights and guidance.

ArcSWAT is used to simulate the impact of land management practices on water, sediment and agricultural chemical yields in large, complex watersheds (Neitsch et al., 2011). It integrates hydrology, weather, land use, soil properties, and management practices to assess water quality and quantity, erosion, and sedimentation processes within a watershed (Arnold et al., 1998)

i. Key features and capabilities of ArcSWAT

a) Hydrological Modeling: ArcSWAT simulates the movement of water through a watershed, including processes such as precipitation, infiltration, evapotranspiration, surface runoff and groundwater flow (Arnold et al., 2012).
b) Water Quality Modeling: It can simulate the transport and fate of sediment, nutrients (such as nitrogen and phosphorous), pesticides, and other pollutants within a watershed, allowing for the assessment of water quality impacts (Neitsch et al., 2011).
c) Land Use and Management Analysis: ArcSWAT incorporates spatially distributed information on land use, soil properties, and management practices (such as tillage, crop ration, and chemical application to evaluate their impacts on hydrology and water quality (Gassman et al., 2007).
d) Scenario Analysis: User can silumate different land management scenarios to assess their potential impacts on water resources and make informed decision about watershed management (Arnold et al., 2012)
e) GIS Integration: ArcSWAT is seamlessly integrated with ArcGIS, allowing user to visualize model inputs and outputs, perform spatial analysis, and generate maps to support decision making (Olivera et al., 2006)

Overall, ArcSWAT is a powerful tool for watershed management, agricultural planning, conservation, and environmental assessment, providing valuable insights into the interactions betweene lan use, hydrology, and water quality within a watershed (Gassman et al., 2007)

3.2.4 Spatial data used in the SWAT Model

i. Land Use Land Cover of the study area

Land use and land cover play a critical role in the SWAT model's representation of hydrological processes and groundwater recharge. LULC categories define the spatial distribution of vegetation, impervious surfaces, agricultural land, forests, wetlands, and other land cover types within the watershed. These land cover types have distinct characteristics that influence the partitioning of rainfall, evapotranspiration rates, and surface runoff generation, ultimately affecting groundwater recharge rates.

SWAT utilizes land use and land cover data to parameterize various hydrological processes, such as the calculation of curve numbers for runoff estimation, determination of crop coefficients for evapotranspiration modeling, and identification of land management practices that impact soil erosion and water quality Neitsch et al. (2011). By incorporating LULC information at the watershed scale, SWAT enables users to assess the impacts of land use changes, urbanization, and agricultural practices on groundwater recharge dynamics.

Changes in land use and land cover can alter surface water runoff patterns, increase impervious surfaces, reduce vegetative cover, and modify soil properties, all of which can influence groundwater recharge rates. SWAT simulations can help quantify the effects of land use change scenarios on groundwater recharge and assess the sustainability of water resources in the context of changing land use patterns and climate conditions.

The study area is covered by short thorny bushes widely spread across the Omo grabe alluvial deposit. In most areas the south Omo graben basin is characterized by arid expanse covered by thorny bushes among grass land (fig 11). The greener and taller thorny bushes follow the shallowly cutting dry seasonal stream beds.

There are pockets of land distinctively covered by very short and thin grass and thorny shrub (fig. 19). The bushes are the source of food for shoats and the grasses for cattle grazing. Except the plots around Omorate and in the vicinity of Hana Salamago town (which is being irrigated from Omo River as water source, there is no observable practice of cropping in all the three kebeles and its vicinity.

From the land use and land cover map of the study, it can be observed that the grass land covers close to 79 % of the study area (fig 12 A and table 2 below). Following the grassland, the savannas covers 17% of the study area.

Table 2: Land Use Land Cover

No	Land-use and land-cover	Area (km^2)	Area (%)
1	Savannas	1456	17.1
2	Grassland	6707	78.7
3	Wetlands	191	2.2
4	Cropland	52	0.6
5	Barren or Sparsely vegetated	0.3	0.3
6	Waterbody	1	1

Figure 11: Widely observed Grassland of the Study Area

ii. Soil cover of the study area

Soil is a critical component of the SWAT model, as it directly influences the movement and distribution of water within the watershed Neitsch et al. (2011). Key aspects of soil that are considered in SWAT include texture, hydraulic conductivity, bulk density, organic matter content, and soil depth. These soil properties determine the capacity of the soil to store and transmit water, regulate infiltration rates, and affect the partitioning of rainfall into runoff and infiltration.

The SWAT model incorporates soil information at the hydrological response unit (HRU) level, which represents spatially homogeneous areas within the watershed with similar soil characteristics Arnold et al. (2012). By assigning soil properties to each HRU, SWAT accounts for spatial variability in soil properties and their impact on hydrological processes across the watershed.

SWAT utilizes empirical equations and process-based algorithms to simulate soil-water interactions, including the Green-Ampt infiltration model for estimating infiltration rates, curve number method for predicting surface runoff, and soil erosion equations for quantifying sediment yield. These algorithms rely on soil parameters to accurately represent the complex interactions between rainfall, soil, and vegetation within the watershed.

In addition to hydrological processes, soil properties also influence nutrient cycling, crop growth, and water quality in SWAT simulations. By integrating soil information into the model, SWAT enables users to assess the impacts of land management practices, climate variability, and land use changes on soil erosion, water availability, and water quality indicators within the watershed Abbaspour et al. (2015).

As far as the soil cover of the study is concerned, the majorly (37%) covered by a soil known as Vc26-3a-264 (Clay). Following this, the second most abundantly covers the study area is Jc6-2a-118 (Loam) which accounts for 32% coverage of the study area (fig. 12 B and table 3). These silty sand soil coverage acts as enabling environment for the precipitation and surface run off routing to the groundwater.

Table 3: Soil Cover of the study area

No.	Soil Name	Area Covered (SQ.Km)	% Cover
1	Be49-3c-20 (Clay)	214	2.5
2	Jc6-2a-118 (Loam)	2696	31.8
3	Vc26-3a-264 (Clay)	3120	36.8
4	Vc29-3a-268 (Clay)	953	11.2
5	Yh16-2-3c-348 (Clay Loam)	307	3.6
6	Yh17-2c-352 (Loam)	1127	13.3
7	WATER-1972 (Water)	62	0.7

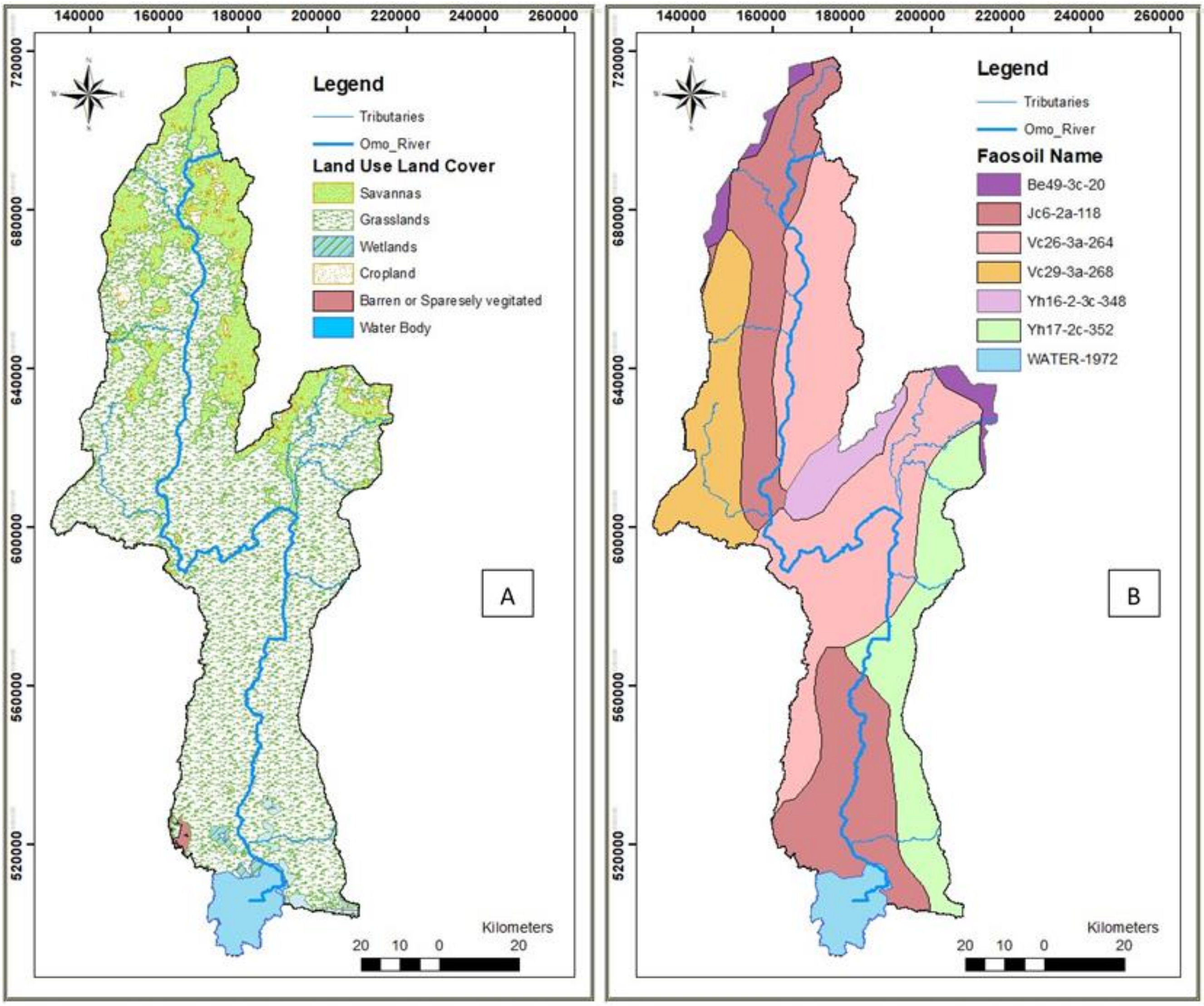


Figure 12: Land Use Land Cover and Soil map of the Study area

iii. Topography

Topography, represented by elevation, slope, aspect, and slope length, is a key driver of hydrological processes in the SWAT model, including groundwater recharge. The topographic characteristics of a watershed influence the spatial distribution of precipitation, the velocity and direction of surface runoff, and the rate of water infiltration into the soil profile.

In SWAT, elevation data are used to delineate watersheds and subbasins, defining the spatial boundaries of the modeling domain and facilitating the estimation of flow paths and accumulation of runoff within the watershed Arnold et al. (2012). Slope and aspect information determine the steepness and orientation of terrain, affecting the velocity of surface runoff and the direction of water flow across the landscape.

Slope length, combined with slope steepness, determines the length of overland flow paths and the potential for erosion and sediment transport. Longer slopes with steeper gradients tend to generate higher runoff velocities and greater erosion potential, impacting groundwater recharge rates through changes in soil erosion and sediment deposition patterns.

By incorporating topographic data into the SWAT model, users can assess the influence of terrain characteristics on groundwater recharge dynamics, such as preferential flow paths, recharge hotspots, and areas susceptible to erosion and sedimentation. SWAT simulations can help quantify the effects of topography on groundwater recharge and evaluate the vulnerability of aquifers to land use changes and climate variability.

Regarding the topography most of the study area is covered by an expanse of elevation within the range of 274- 465m a.s.l which constitutes 69% of the total study area. The second elevation range is 465- 611m.a.s.l (fig 13 A) constitutes 26% of the total area.

Table 4: Elevation range distribution across the study area

Elevation Range	% of Total Area
274 - 465	69.3
465 - 611	26.0
611 - 824	3.4
824 - 1105	1.1
1106 - 1647	0.2

In terms of the slope, the study are can be classified into five slope category. The slope range 0 -2.2% constitutes most of the area (fig. 13 B). This nearly flat topography again is another enabling environment for the groundwater recharge through reduced run off and increased stay time for the routing of either precipitation or arriving neighboring run off to the underlying soil formation. This is because the flatter the area the more time the water from either precipitation or runoff stays on the surface, the better chance of the water to take route down to the soil structure.

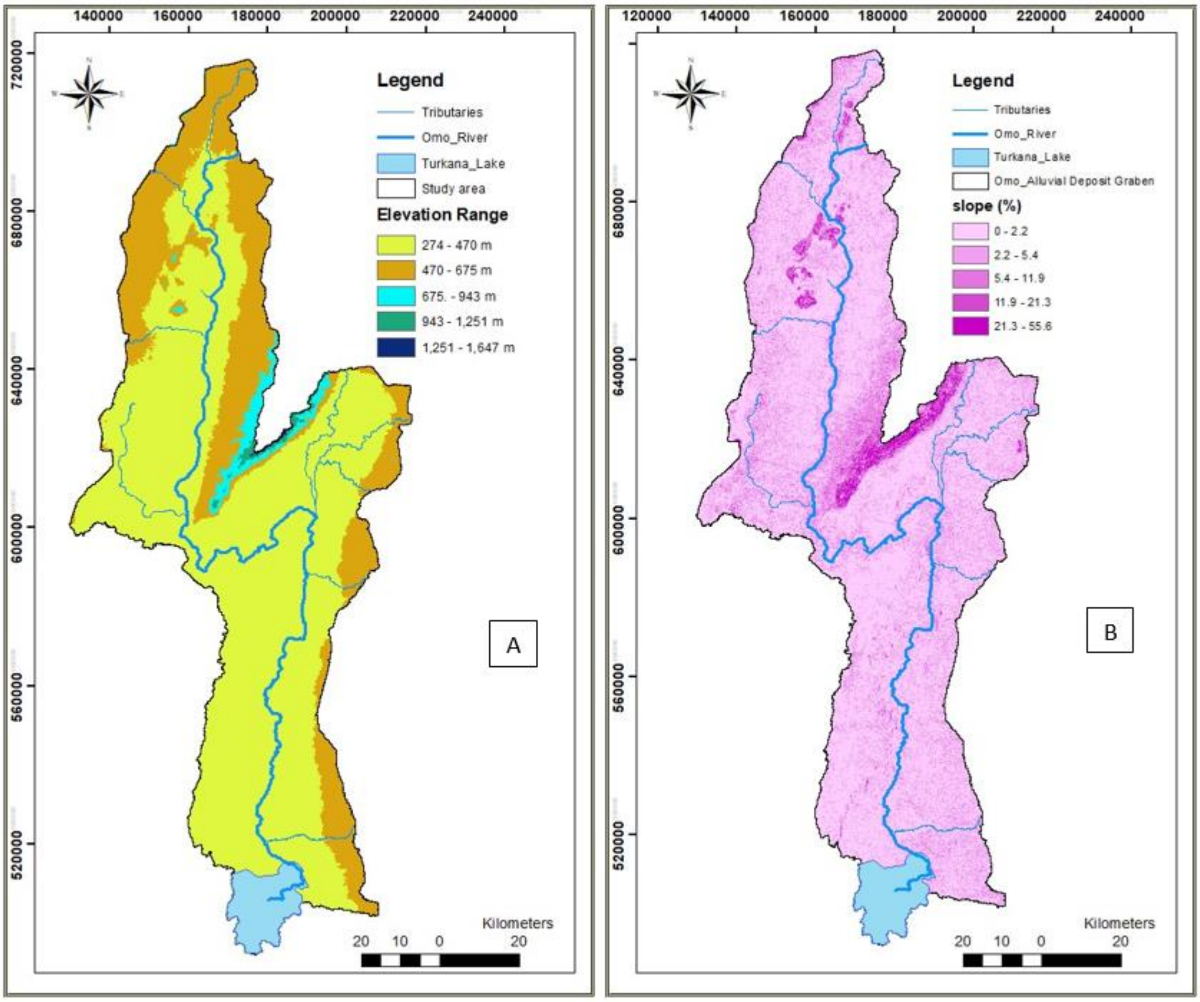


Figure 13: Surface Elevation Range and Slope map

SWAT is a physically based and continuous time semi-distributed spatiotemporal parameter model. SWAT2012 version of the model (Arnold et al. 2012), with an Arc-GIS-10.4 extension (Arc SWAT), was used for this study. The input data for the model are used as DEM, land use data, soils and slope classes (Spatial) for the delineation of Hydrologic Response Units (HRUs), climate, and hydrological data (fig.13). SWAT simulates the hydrology at each HRUs using the water balance equation, that include precipitation, runoff, percolation evapotranspiration and base flow components.

The model divides the basin into sub-basins HRUs. In this study, the South Omo basin is divided into 23 sub-basins (fig. 24). For each HRU, the model calculates the daily water balance and process the input as outflows such as surface runoff, interflow, and subsurface aquifer flow and then transmits downstream to the outlet of the catchment.

The SWAT model has been calibrated for the period 1995 to 2007 and validated for 2008 to 2015, including three years warm-up period, to initialize the model parameters.

The present study compared the simulated and measured discharges from gauging stations (Fig. 4). The Nash and Sutcliffe efficiency (NSE) criteria, the coefficient of determination (R2), and percent of bias (PBIAS) between the simulated and observed streamflow have been evaluated to assess the performance of the model (Rodda and Little 2015). NSE ranges from − ∞ to 1, and an efficiency of 1 indicates a perfect relationship between measured and calculated discharges. A value between 0.9 and 1 for NSE shows that the model performs very well. Values between 0.6 and 0.8 earmarks the model's performance as good (Abeyou 2008). The value < 0.0 specifies that the mean observed value out performs the simulated values, thereby rendering the model unacceptable.

SWAT is a widely used hydrological model that has been applied in various studies for simulating water flow and assessing water resources management strategies. When it comes to groundwater recharge estimation, SWAT has proven to be a valuable tool.

One study by Mishra et al. (2016) utilized SWAT to estimate groundwater recharge in a semi-arid watershed in India. The researchers incorporated various hydrological parameters such as soil characteristics, land use/land cover, and climate data to simulate the water balance components, including recharge. The SWAT model outputs were validated against observed groundwater levels, and the results showed a good agreement between the simulated and observed values (Mishra et al., 2016).

In another study conducted by Zhang et al. (2018), SWAT was employed to estimate groundwater recharge in a large-scale basin in China. The researchers integrated SWAT with a groundwater model to simulate the water balance and quantify the contributions of different recharge sources. The study demonstrated the capability of SWAT in estimating groundwater recharge and provided valuable insights into the spatial and temporal distribution of recharge processes (Zhang et al., 2018).

Furthermore, SWAT has also been applied in regional-scale studies for groundwater recharge assessment. For instance, a study by Li et al. (2019) used SWAT to estimate recharge in a large-scale watershed in the United States. The researchers considered land use/land cover changes, climate variability, and soil properties to simulate the water balance components. The SWAT-based recharge estimates were compared with other approaches, and the results indicated the reliability and accuracy of SWAT for regional-scale groundwater recharge assessment (Li et al., 2019).

In summary, SWAT modeling has proven to be effective for groundwater recharge estimation in various hydrological settings. The integration of hydrological parameters, land use/land cover, and climate data enables SWAT to simulate the water balance components and provide valuable insights into recharge processes. The studies conducted by Mishra et al. (2016), Zhang et al. (2018), and Li et al. (2019) highlight the successful applications of SWAT in groundwater recharge estimation.

For generalized conceptual understanding of the working methodology of this research and materials and tools used please observe (table 5 and fig. 14).

Table 5: Tools and Materials used for the research work

No	Material /Tools	Source
1	Garmin 12 channel GPS	Own source
2	Geological Map of Stefano's Hayk Sheet	Former GSE
3	Geological Map work of Davidson/1983/	Former GSE
4	Hydro geological Map of Stefano's Hayk Sheet	Former GSE
5	Geology and hydro geology map of Ethiopia	Former GSE
6	Topo Map of 1:50000	Ethiopian Mapping Agency
7	Spatial data/LULC/Soil/DEM	USGS/FAO Web sites
8	Computer Software	
9	Arc GIS	Open Source
10	Global Mapper	Open Source
11	Aquifer Test 3.5	Open Source
12	Starter	Open Source

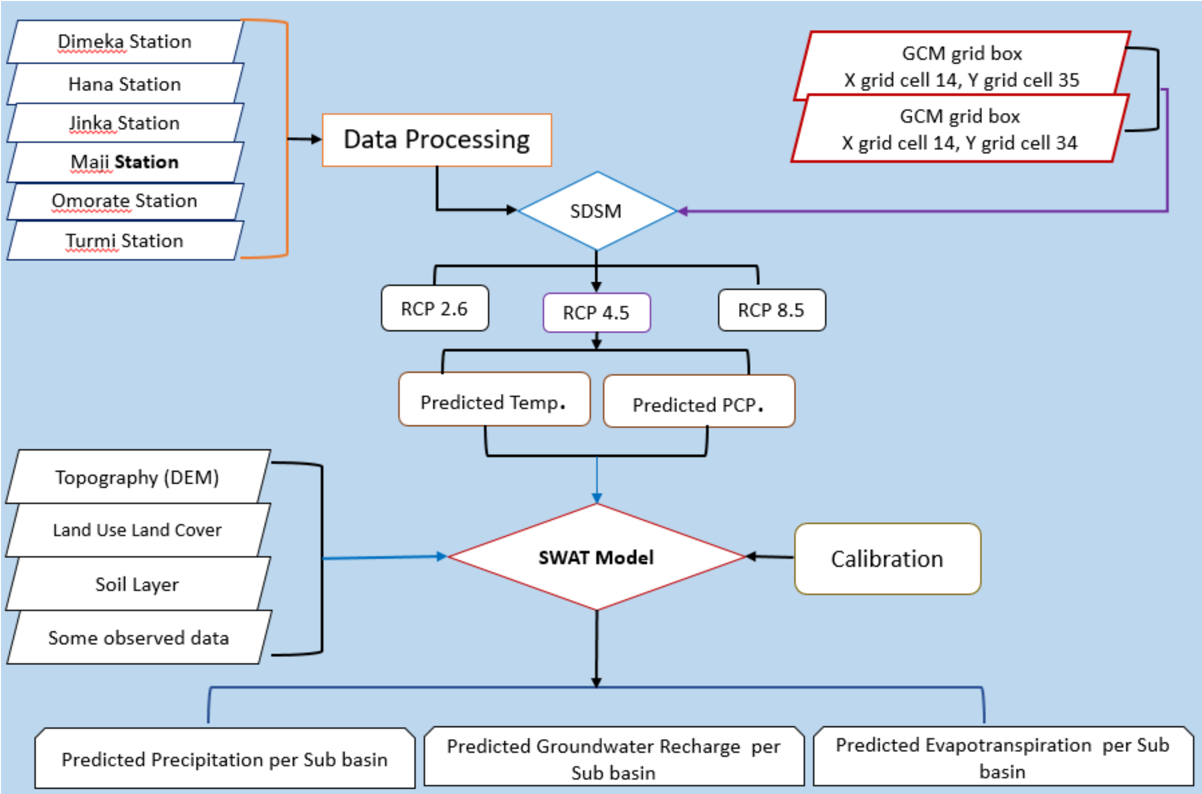


Figure 14: Generalized conceptual Flowchart of the Research Methodology

CHAPTER IV: RESULTS and DISCUSSION

4. General

The climate impact on groundwater resources assessment will be complete when there is full information on both the demand and supply side of the subject matter. The water demand side of the study area is poorly known. There is no clear information on the existing rate of groundwater extraction. The only available data are list of shallow wells with locations, and budget sources. There are of course few data that exhibits the salinity status of a certain bore-wells. In addition to the current water demand, it necessitates to have predicted water demand based on population growth and development plans. This together with the predicted impact of climate on the groundwater resources of the study area would have shown a clear relationship of the water demand and water supply sides. If both these situations are met, the balance or the disparity between the water demand and available supply source would show us clear relationship between the two game determining extremes.

From these relationships, devising the strategies to keep the proper balance between the two will be clear. In our case, though the demand side of the Omo graben alluvial deposit is not well understood, this paper tries to assess the impacts of the climate change upon the alluvial deposit from the point of view of the recharges generated from the resulting predicted climate variables.

The most recurrent water supply problem of the study area is the raised salinity and temperature of groundwater source. According to Kebede (2013), the groundwater of Omo Delta is characterized by the presence of fresh and saline groundwater side by side. He further explains that the success of having fresh water source is well below 50%. The vertical and lateral distribution of the saline and fresh groundwater is not yet understood. Because of this most of the drilled bore water wells turn out to be saline and unfit for drinking purpose. As a result, considerable number of drilled boreholes are abandoned.

4.1 Predicted climate variables Analysis

The climatic variables that are necessary for groundwater recharge determination are temperature, rainfall, relative humidity, sunshine hours and wind speed data.

The two common variables that are available at the meteorological stations surrounding the study area are temperature and precipitation. The remaining three variables vis relative humidity, sunshine hours and wind speed data are available at Jimka meteorological station. These available data are extremely missing. This situation led us to use the system simulated values for these variables.

4.1.1 Dimeka Station

The PCP mean observed is greater than the historically modeled in the months of November through February (fig 15 D). Whereas the predicted precipitation varies in accordance with the rcps. The rcp 8.5 prediction resulted in the higher precipitations amounts for the months of February, May, September, November and December. For the months of April, June and October, the precipitation amounts for the rcp 8.5 is unexpectedly lower than the remaining representative concentration pathways.

As far as the temperature prediction is concerned, all the forcing resulted in a relatively comparable amounts especially in the minimum temperature. As for the maximum temperature, months June through October the rcp 8.5 resulted in the higher values in the maximum temperature (fig 15 E & F).

4.1.2 Hana (Salamago) Station

The GCM downscaling and prediction at Hana (Salamago) Station is in harmony with the global climate change trend. The comparison between the observed and the historically modeled climate variables are strikingly similar both in the PCP and max and min temperatures (fig 15 A, B and C).

The PCP means exhibits higher values for the months of September, October and November for the 8.5 rcps. As for the mean max temperature, for the months January through June, the predicted data shows slightly higher values under rcp 8.5. For the remaining months, the predicted values show similarity under all the scenarios.

The mean minimum daily temperatures predictions are more similar with the global climate change trend.

4.1.3 Jinka Stations

The PCP prediction exhibits peculiar characteristics at Jinka Station. For the months of June and July, the values exhibit a reverse order with respect to the global trend. That means the recp 8.5 which was expected to result in Higher temperature and higher PCP, exhibited lower PCP and lower max temperature compared to the rcp 4.5 and rcp 2.6. The PCP under the rcp 8.5 shows exceptionally higher value for the month of August (fig 15 D, E and F).

4.1.4 Maji Station

Maji Station downscaled and predicted climate variables exhibits disparity in the historically modeled and observed data in all the months of the year specially for PCP (fig 16 A). The months January, February, November and December exhibits higher observed data compared to the historically modeled. Whereas the historically modeled data are higher for the rest the months compared to the observed data in PCP (fig 16 A).

As far as the temperature data are concerned, the observed and historically modeled max and mi temperatures are strikingly similar in all the months. The prediction under all the three scenarios does not show difference and even in most cases, the predicted values are nearly similar (fig 16 B, & C).

4.1.5 Omorate Station

In Omorate Climate station case the result of the SDSM has a striking similarity between the historically modeled and observed data in all the three variables viz. PCP, maximum and minimum temperature values (see fig 17 A, B, C). The predicted PCP mean daily values under rcp 8.5 gets higher than the other two scenarios in the months of May and October by mean daily PCP of nearly 1.7 mm (fig 16 A).

In the case of maximum daily temperature, the data exhibits similarity with the global trend. What is more striking is that the observed data and historically modeled including the predicted minimum temperature values under all the scenarios are similar. This in another word means that the daily mean minimum temperature until the turn of century would be the same and no change.

4.1.6 Turmi Station

At this station the SDSM output (historical modelled) and observed data in all the three variables are well correlated (see fig 17 D, E, F). In case of PCP, the predicted values show higher PCP under the rcp 8.5 scenario for the months of February, March May, August, September October and December. The December month mean daily PCP value exceeds the rcp 4.5 by nearly 2.5 mm (see fig 15 D).

In terms of temperature, the predicted max temperature shows no difference under the three scenarios, but in some months the predicted values exceed that of the current values. The minimum temperature in most months exhibit lower mean daily minimum temperature.

Figure 15: Statistical analysis of extracted climate variables (Rainfall, Temp. max and min) modeled up 12/31/2099 under three representative concentration ratio of 2.6, 4.5. and 8.5 for Hana Salamgo and Jinka Stations

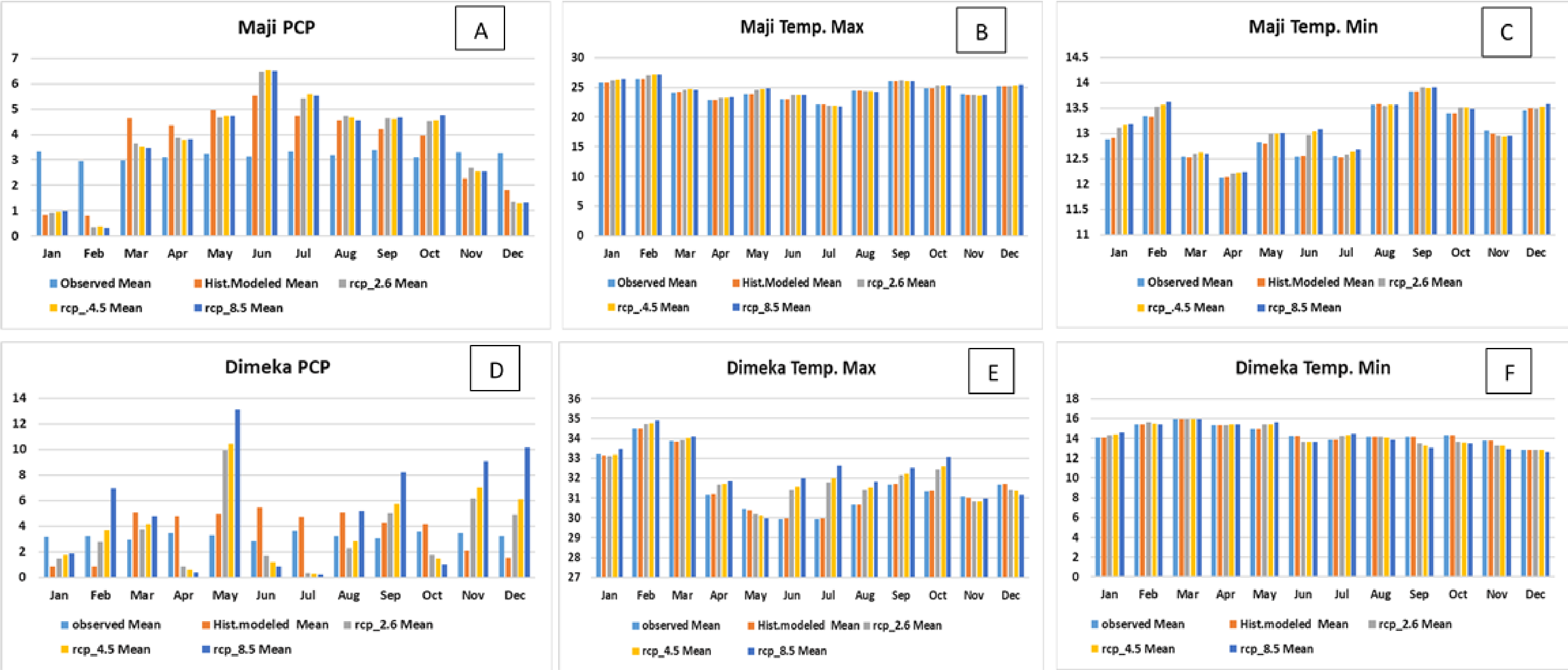


Figure 16: Statistical analysis of extracted climate variables (Rainfall, Temp. max and min) modeled up 12/31/2099 under three representative concentration ratio of 2.6, 4.5. and 8.5 for Maji and Dimeka Stations

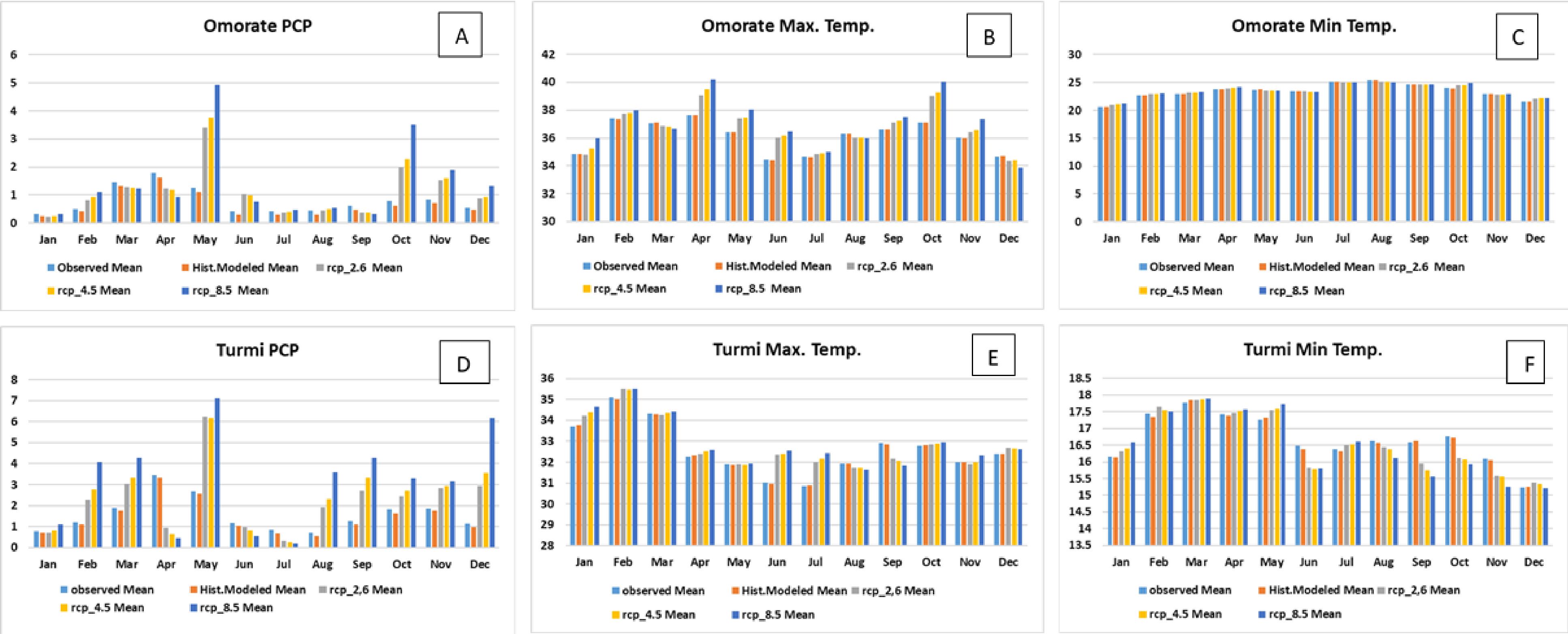


Figure 17: Statistical analysis of extracted climate variables (Rainfall, Temp. max and min) modeled up 12/31/2100 under three representative concentration ratio of 2.6, 4.5. and 8.5 for Omorate and Turmi Station

4.2 Climate variables Trend Analysis

At the beginning, I thought that there would be all the climate variables at least in two meteorological stations. The Jinka Station has got all the climate variables to be predicted. But the data like wind speed, Solar radiation and relative humidity are highly missing. Even there are many years of missing data. Due to this discrepancy, I used the PCP and temperature data.

In order to see the temperature change trend across the predicted years, the writer of this paper used the average of maximum and minimum daily temperatures. This average daily temperature per year is taken from the mean of the daily average temperature. The daily average temperatures were converted to mean monthly temperature, and the mean monthly temperature is converted to mean yearly temperature.

Unlike the temperature, the daily precipitation is usually aggregated to monthly, and the monthly values summed up to yearly to express the annual precipitation. In terms of the expression of the annual precipitation, what is usually required is to aggregate the daily precipitation values to yearly.

4.2.1 Dimeka Station

At this station the predicted average yearly temperature under all the scenarios until late 2050s shows undifferentiated prediction values. The average temperature increments up to the late 2050 is nearly from 23.1^{o}C at 2023 to 23.3 ^{o}C at nearly 2059. After the 2060, the segregation in accordance with the global temperature change trend starts under the three scenarios. The maximum average temperature predicted is 24OC under the rcp 8.5 and 23.36 ^{o}C under the rcp 4.5 and rcp 2.6.

As for the PCP, the annual value about 1200 mm at 2023, steadily increases without segregation with respect all the three scenarios until late 2050s to nearly 1500mm. From the 2060 afterwards, the predicted annual PCP values starts segregating per the scenarios in accordance with the global trend. The rcp 8.5 shows a remarkable higher PCP values up to 4000 mm annual which has not yet been observed value in Ethiopia. Under the rcp 4.5 which is the most likely case, the annual PCP values ranges between 1500 to 2000 mm per annum starting from early 2070s up to the 2100.

Under the rcp 2.6, the PCP annual value hits its climax of 2000mm at the end of 2050s. The predicted values under this scenario ranges between 1500 and 2000mm and gets exceptionally lower that 1000mm at the year 2095.

4.2.2 Hana (Salamago) Station

At this station, the average daily temperature predicted values ranges between 27.5°C and 27.9°C up to the 2050 without making difference between the three scenarios. From the 2050 onwards, each forcing starts exhibiting its own distinctive trend. The rcp 8.5 gets higher ranges between 27.7 °C and 28.3 °C, whereas the rcp 4.5 and rcp 2.6 showing no significant changes up to 2100.

What is more attractive at this station is that the striking similarity between the timings and the rate of change average temperature and PCP under similar representative concentration pathways. Like in the case of average temperature, there has been no segregation between rcps up to the 2050. Of course the annual PCP values increases up to 3200mm under the rcp 8.5 close to 2090s. We can imagine how catastrophic this value is compared to the currently observed to peak floods that resulted in the damage of infrastructures and dislocation of settlements, while the annual PCP is less that 1500mm.

4.2.3 Jinka Station

The predicted average temperature values show no distinct variation under the three scenarios up to early 2050s. From the early 2050s onwards, the predicted temperature values under rcp 8.5 shows slightly higher values compared to the other scenarios. The temperature change at this station does not significant change as observed in the other stations. On the contrary, the temperature changes under scenario 2.6 shows a negative trend, i.e the average temperature decreases up to 20.85°C in the future.

When the PCP trend is observed, the undifferentiated trend under the three scenarios continues up to the early 2070s. From this point forward, the graph of rcp 8.5 starts raising slightly higher the remaining two scenarios swinging between 1000mm-1320mm. The rcp 2.6 and rcp 4.5 graph intertwines exhibiting no separate trend ranging between 780mm and 1110mm.

4.2.4 Maji Station

In terms of temperature and precipitations, the downscaled climate variables at Maji station exhibit peculiar trend in disparity with the global trend under the scenarios. Up to the year 2100, the average annual temperature and precipitation does not show and increasing trend. In both temperature and precipitation, there is a horizontal trend under the 2.6, 4.5 and 8.5 representative concentration pathways (rcps) see fig .15 A and B.

The predicted average temperature values show no distinct variation under the three scenarios up to 2100. The Maji station exhibits peculiar graph in which the three lines representing three different scenarios with maximum amplitude along a horizontal direction. Of course the rcp 8.5 line runs mostly on the upper maximum limit and goes down to the minimum values because of the high amplitude. The three scenarios play average temperature between 18.7 ^{o}C and 19.2 ^{o}C. This implies that at Maji station, the temperature change is not significant up to the 2100 GC compared to other stations (fig. 15 A).

When the PCP trend is observed, the undifferentiated trend under the three scenarios continues up to the year 2100. The rcp 4.5 line touches the maximum limit of PCP 1673mm at the year 2068. This situation indicates a rare instance whereby the maximum precipitation is exhibited by the rcp 4.5 instead of the rcp 8.5. The reason behind this situation is not the scope of this work (fig 15 B).

4.2.5 Omorate Station

The predicted average temperature values show no distinct variation under the three scenarios up to 2060. From the 2060 onwards, the rcp 8.5 line starts to rise and ends up to the 31 ^{o}C average temperature at the 2100 GC.

When the PCP trend is observed, the undifferentiated trend under the three scenarios continues up to the year 2060. The rcp 8.5 line starts rising and ends to 835mm per annum at 2100 GC. The precipitation under the rcp 4.5 and rcp 8.5 continues with nearly close to zero slope causing no significant change in precipitation increment.

4.2.6 Turmi Station

The predicted average temperature values show no distinct variation under the three scenarios throughout the predicted period. In considerable instances, the graph lines of the three scenarios strikingly coincides. This coincidence stands in contrary to the global trend. This instance avails ground for the review of the SDSM software and the algorithms there in.

Observation of the PCP trend shows the undifferentiated trend under the three scenarios continues up to the mid-2060s. The rcp 8.5 line starts rising progressively and ends at close to 3000mm per annum at 2100 GC. The precipitation under the rcp 4.5 and rcp 8.5 continues with nearly flat slope causing no significant change in precipitation increment. At this station, there is an anomaly of 1720mm annual precipitation caused by the rcp 4.5 at 2069.

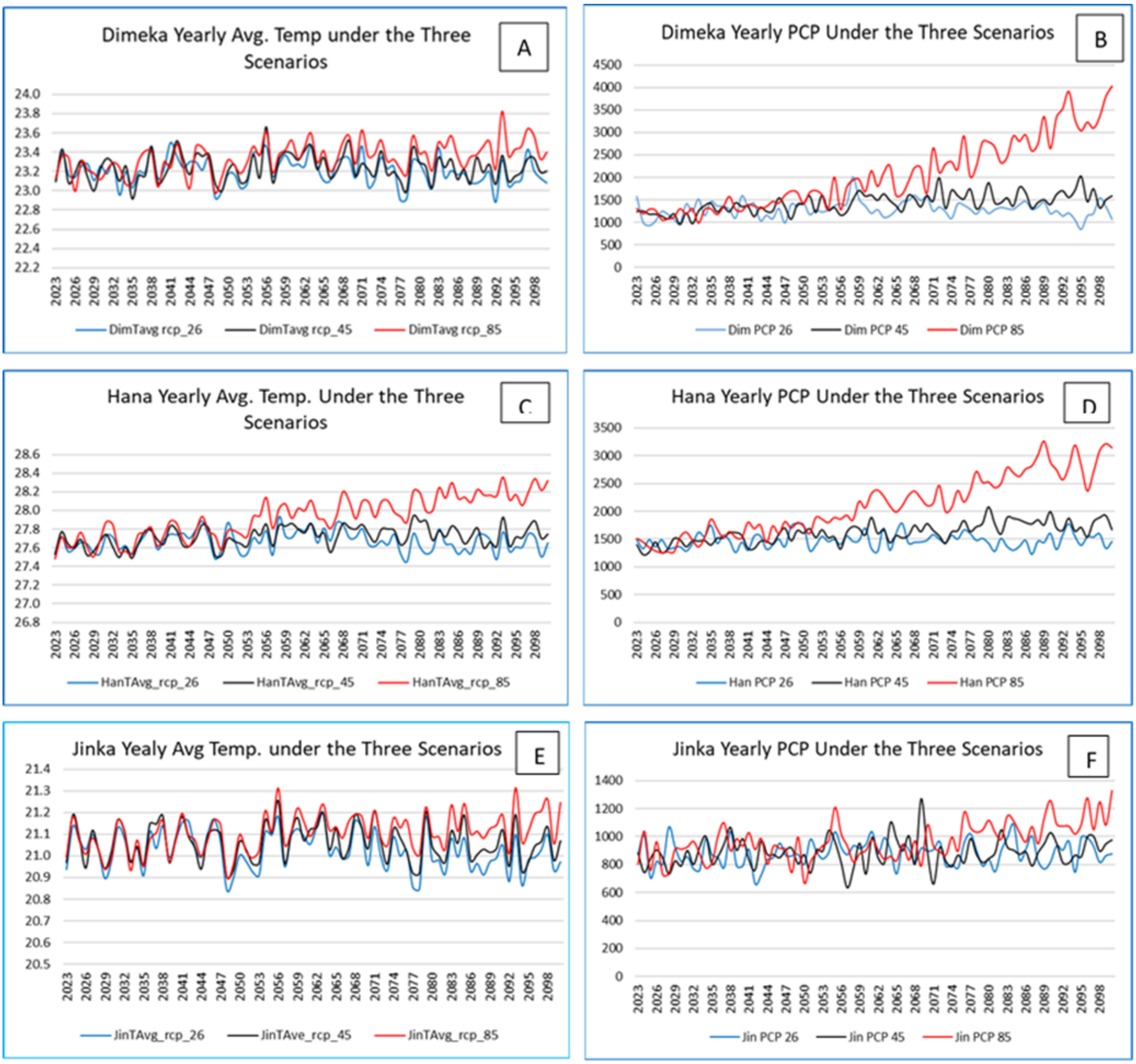


Figure 18: Comparison of Predicted Temperature and Precipitation under the Three Scenarios

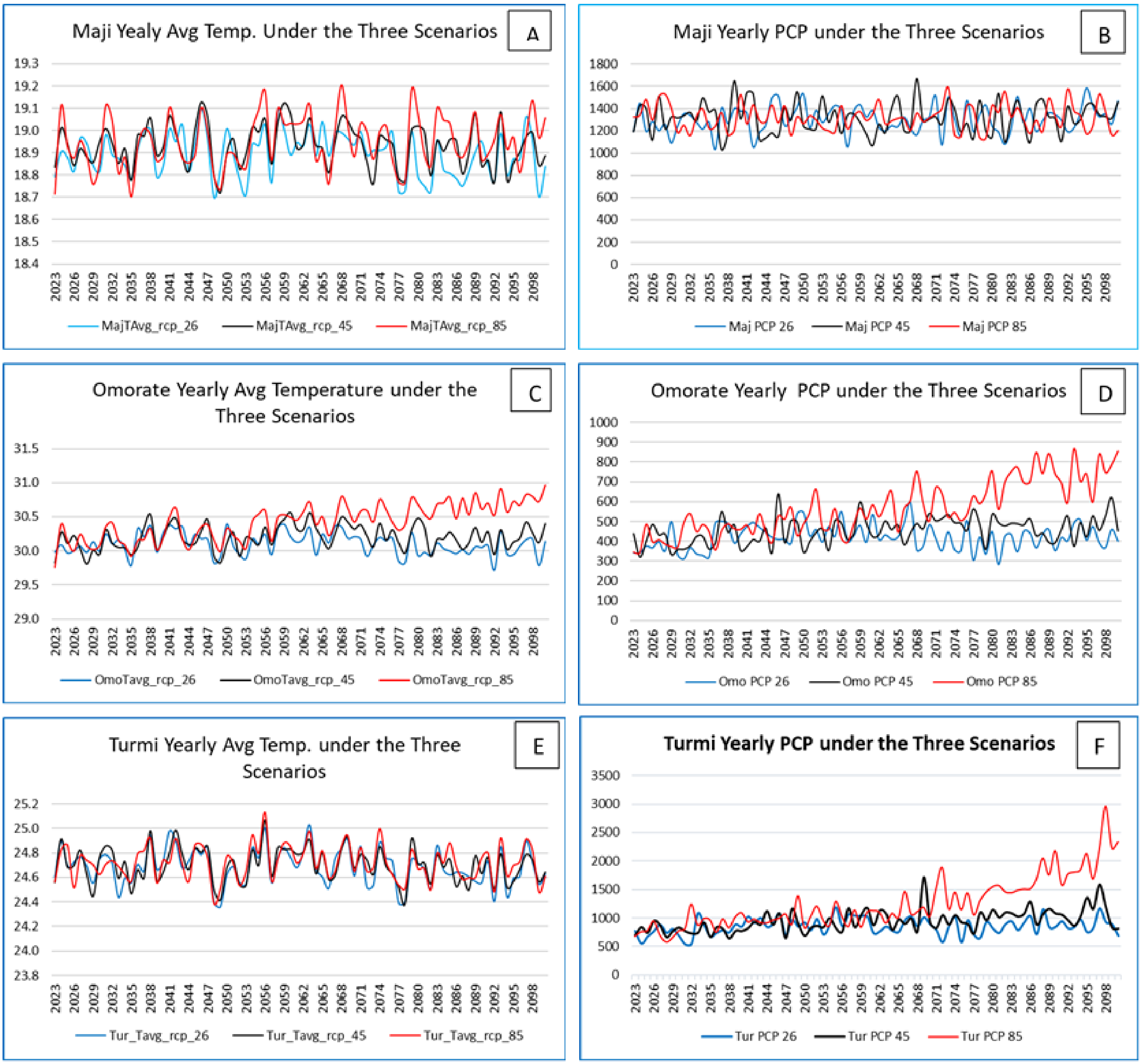


Figure 19: Comparison of Predicted Temperature and Precipitation under the Three Scenarios

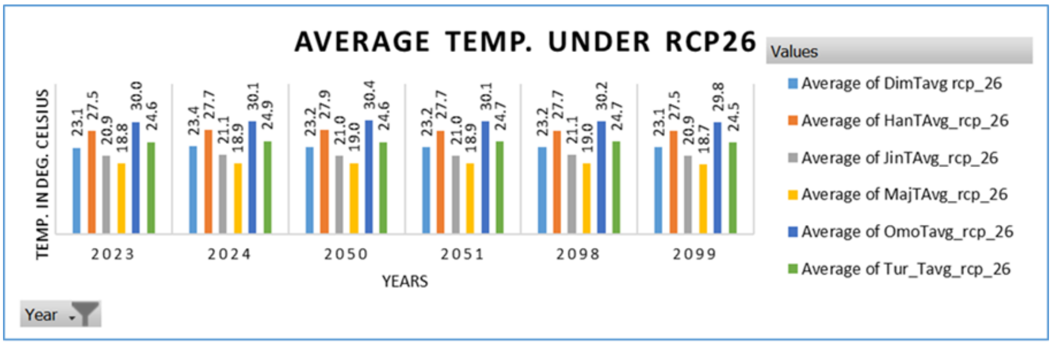
4.3 Summary of Climate Variables

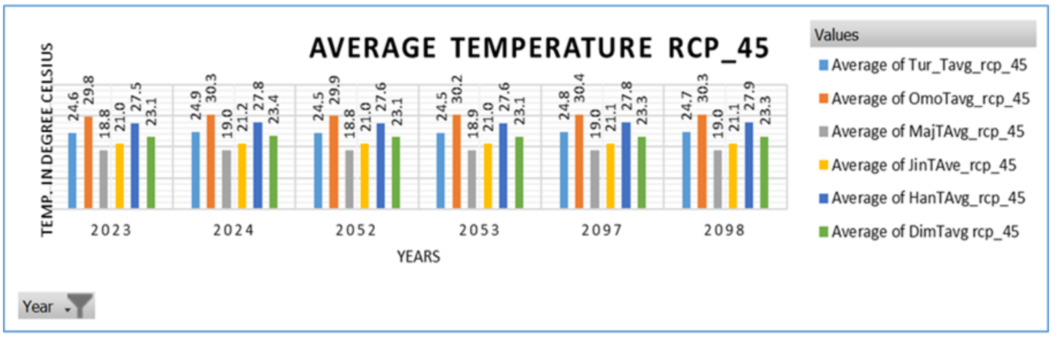
4.3.1 Temperature

Temperature variables are observed to have an increasing trend at two stations (Hana Salamago and Omorate stations). At three stations (Dimeka, Jinka and Maji), the predicted temperature showed no variation by showing horizontal trend line. What is more striking is that the temperature trend line at Turmi station shows a decreasing attitude resulting in a decreased temperature. Therefore, the temp. change at two stations (Hana Salamago and Omorate) as compared with the (base years 2022 and 2023) shows 0.1°C increment at early 2050s. Whereas there is no observed change in temperature at Dimeka, Jinka and Maji meteorological stations. At Turmi station, the opposite of the global trend in temperature is observed. At this station, the temperature decrease by 0.1°C at early 2050s compared with the base years (2022,2023). This opposite trend is beyond the scope of this work (fig. 20).

4.3.2 Precipitation

Precipitation is the major input for the groundwater resource. The predicted precipitation shows an increasing trend in all the stations except the Maji meteorological station. The Maji station exhibits unexpected horizontal trend showing no increment in precipitation (fig. 21). The average precipitation across the study area at the base years is 1120mm. This precipitation is the model averaged precipitation across the study area. This average precipitation increased to 1299 mm by the year 2050. Therefore, the precipitation change across the study area shows an increased average precipitation of 179mm per annum. This can be best expressed as compared to the base years, the precipitation across the study area increased by about 16%.





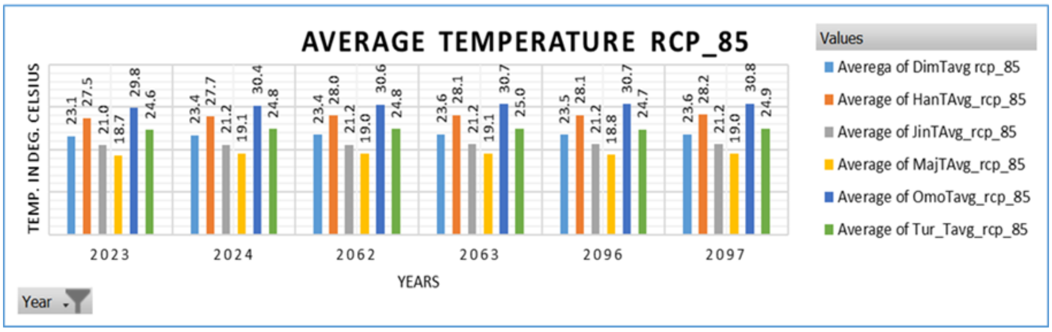


Figure 20: Comparison Project Temperatures under all Scenario at each Station

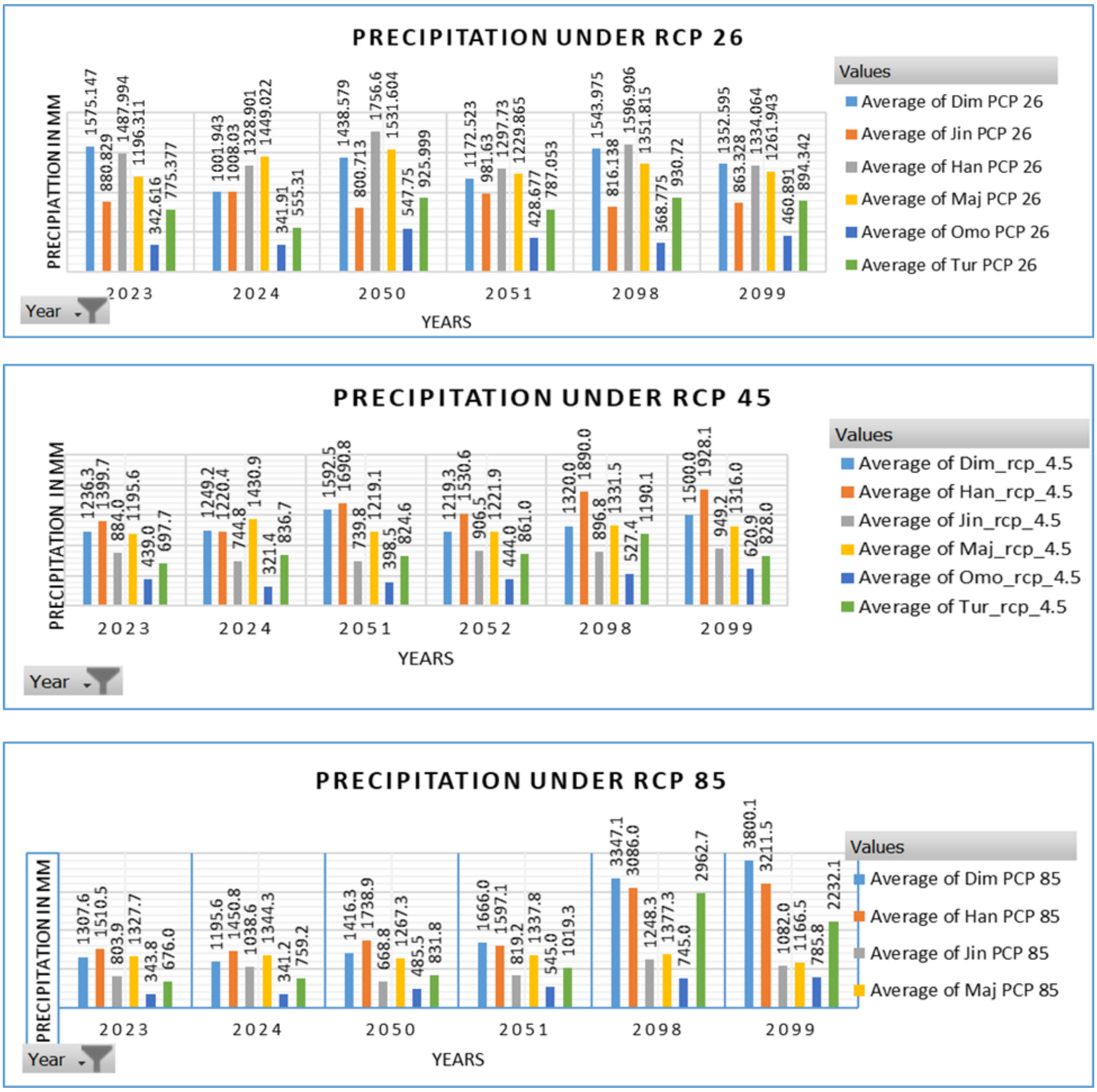


Figure 21: Comparison Project Temperatures under all Scenarios at each Station

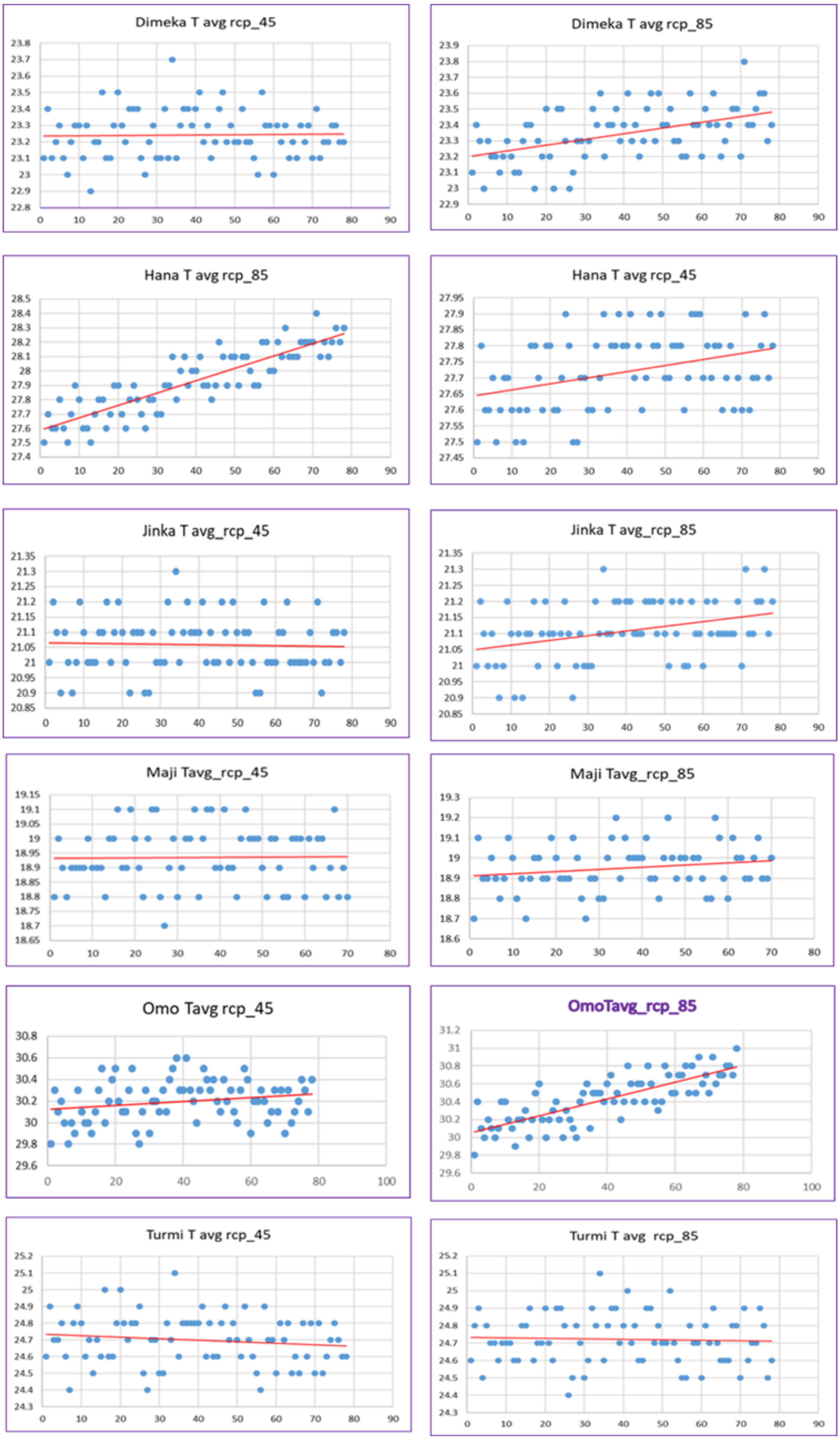


Figure 22: Predicted average annual Temperature trends per station under rcp_45 and rcp_85

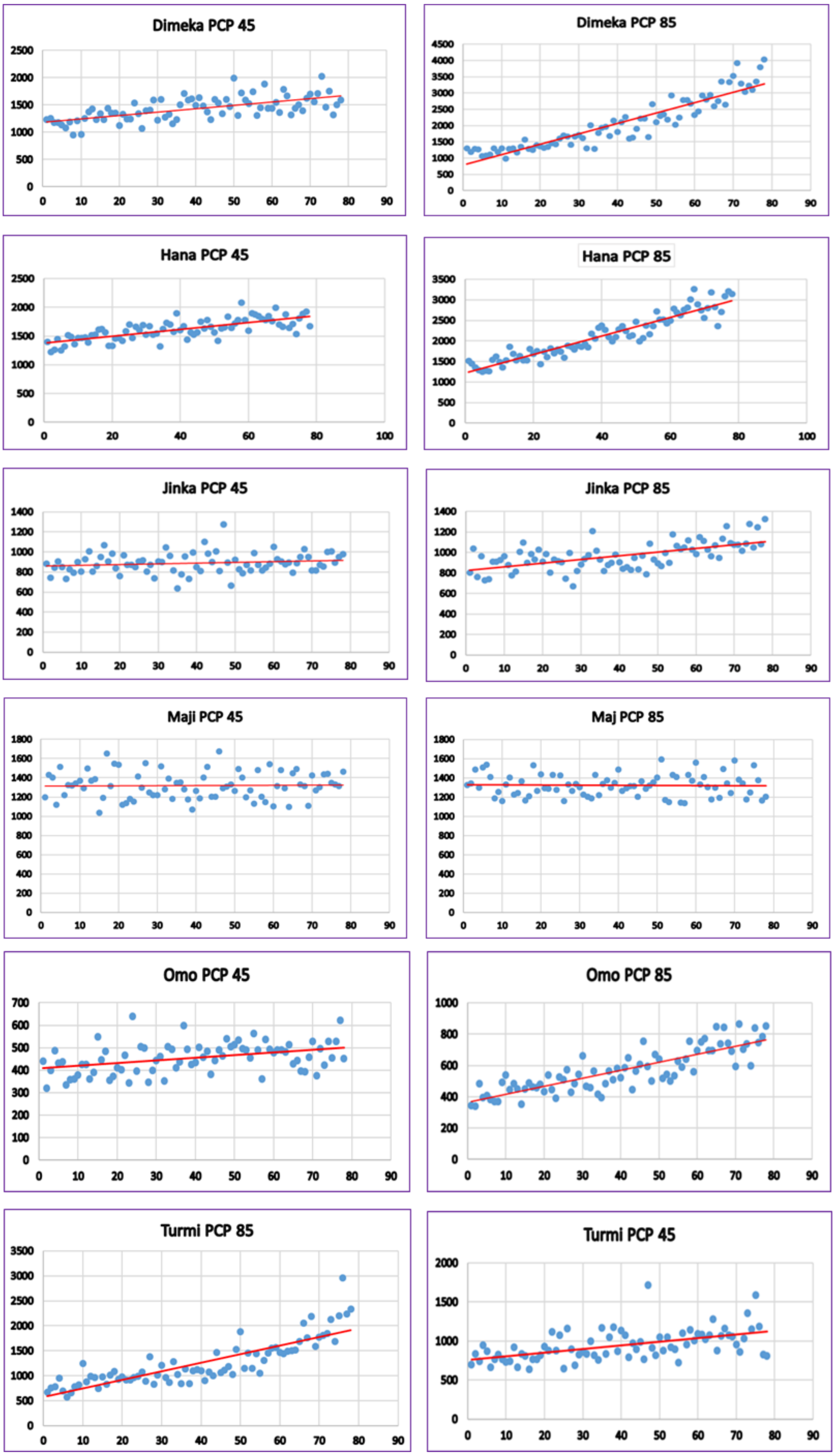
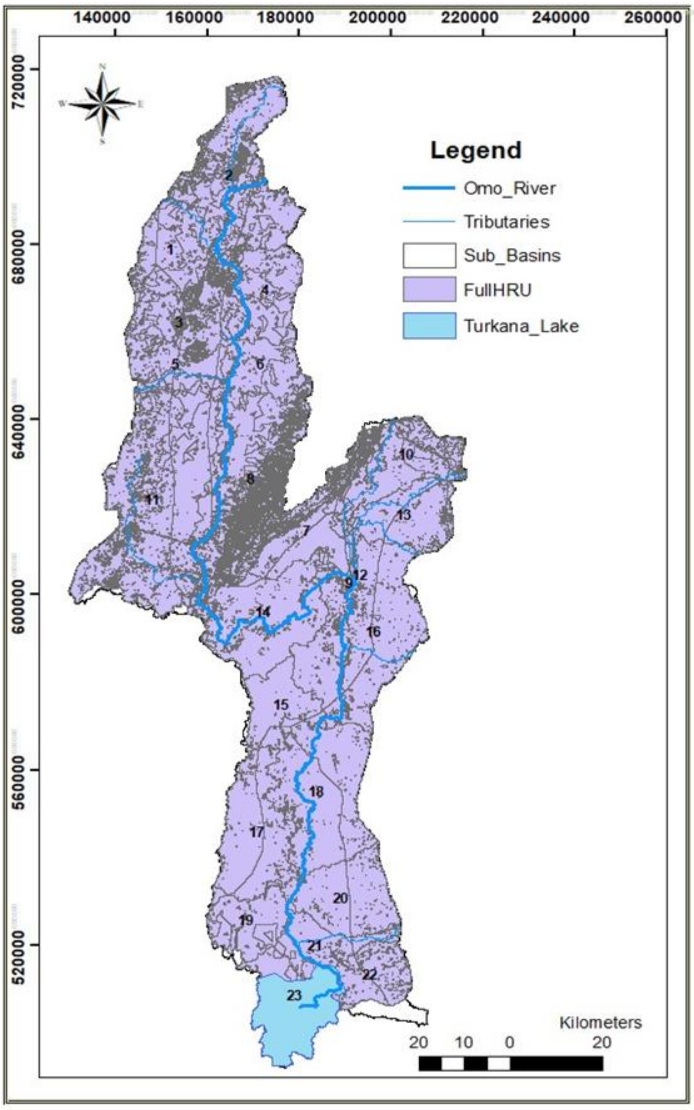


Figure 23: Predicted Annual Precipitation trends per station under rcp 45 and 85

4.4 Groundwater Recharge Estimation using Arc SWAT Modeling

4.4.1 Model Set up

The use of Arc SWAT modeling for groundwater recharge estimation is a widely practiced research with focus on understanding the factors influencing groundwater recharge rates, such as land use, soil cover, climate variability, and hydrological processes Singh et al., 2018. The Arc SWAT model divides the study area into 23 sub basins and 103 hydrological response units (HRUs).



No	Sub-Basin	Area (km2)	HRU	HRU ID
1	1	280.8	7	1 _ 7
2	2	626.4	8	8_15
3	3	290.9	13	16_28
4	4	320.7	5	29_33
5	5	205.6	7	34_40
6	6	220.3	2	41-42
7	7	286.3	8	43-50
8	8	706.9	9	51-59
9	9	3.7	3	60-62
10	10	400.3	10	63-72
11	11	971.5	2	73-74
12	12	1.0	2	75-76
13	13	273.4	2	77-78
14	14	550.6	1	79
15	15	206.1	2	80-81
16	16	767.3	2	82-83
17	17	400.9	2	84-85
18	18	586.0	2	86-87
19	19	217.0	2	88-89
20	20	325.8	2	90-91
21	21	202.7	3	92-94
22	22	215.6	2	95-96
23	23	205.8	7	97-103
Total		8265.5	103	

Figure 24: Hydrologic Response Units distribution map

Sub basin cluster (7,8,10 and 13) are identified as spots receiving the highest rainfall, followed by sub basins (15,17,18,19,20,21,22) which receives the second highest rainfall (fig. 22).

The amount of rainfall of course determines the groundwater recharge. It is not only the amount rainfall, but also other factors like soil cover, LULC, and slope that contributes to the GW recharge. Because of this, in most cases, the comparison of rainfall distribution and gw recharge maps are not similar. Regions identified to receive similar rainfall exhibited different groundwater recharge amounts due to factors like soil cover, LULC and slope.

In Accordance to the SWAT model output, the study area is divided into 23 sub basin. Within these 23 sub basins, there are 103 hydrologic response units (HRUs). The number of HRUs per sub basin ranges from 1 to 13. The sub basin identified as no 14 is comprised of one HRU while the sub basin no. 3 is comprised of 13 HRUs.

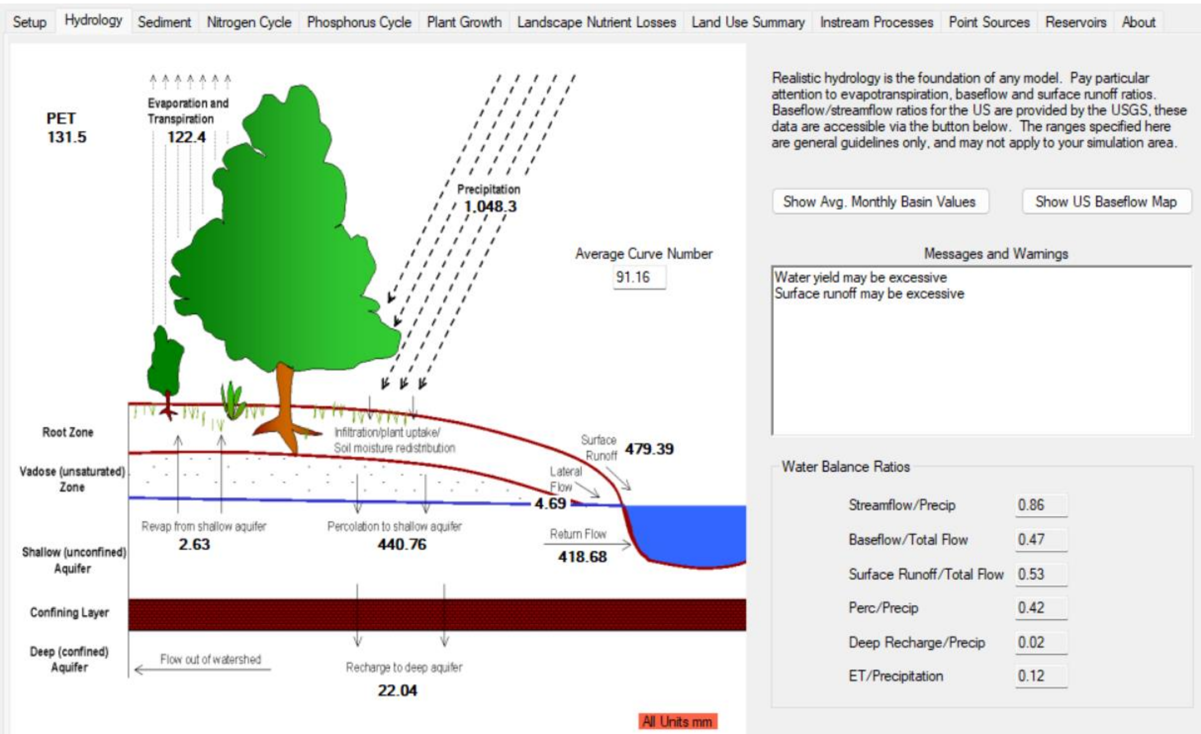


Figure 25: The simulated Water balance ratio

4.1.1 Model Calibration

Calibration is an important step in SWAT modeling to ensure accurate estimation of groundwater recharge. Calibration involves adjusting model parameters to minimize the differences between simulated and observed values of key hydrological variables. A study by Abbaspour et al. (2004) focused on the calibration of the SWAT model for groundwater recharge estimation. The researchers calibrated the model using observed streamflow and groundwater level data. They optimized parameters related to soil properties, land use, and groundwater characteristics to improve the simulation of water balance components, including recharge. The calibrated SWAT model showed improved agreement with the observed groundwater recharge values, demonstrating the effectiveness of calibration in enhancing recharge estimation (Abbaspour et al., 2004).

In another study by Zhang et al. (2016), SWAT model calibration was performed for groundwater recharge estimation in a watershed. The researchers utilized observed streamflow and groundwater level data to calibrate the model parameters. They adjusted parameters related to soil properties, land use, and hydrological processes to improve the accuracy of the simulated recharge values. The calibrated SWAT model successfully reproduced the observed groundwater recharge, indicating the importance of calibration for reliable estimation (Zhang et al., 2016).

Furthermore, a study by Wu et al. (2019) conducted SWAT model calibration for groundwater recharge estimation in an agricultural watershed. The researchers used observed streamflow and groundwater level data to calibrate the model parameters, including soil properties, land use, and aquifer properties. The calibration process involved multiple iterations to improve the agreement between simulated and observed recharge values. The calibrated SWAT model exhibited improved performance in estimating groundwater recharge, emphasizing the significance of calibration in enhancing estimation accuracy (Wu et al., 2019).

In summary, SWAT model calibration plays a crucial role in improving the accuracy of groundwater recharge estimation. The studies conducted by Abbaspour et al. (2004), Zhang et al. (2016), and Wu et al. (2019) highlight the effectiveness of calibration in adjusting parameters related to soil properties, land use, and hydrological processes to enhance the agreement between simulated and observed recharge values. These findings underscore the importance of careful calibration to ensure reliable groundwater recharge estimation using the SWAT model.

I used about eleven parameters to calibrate the model performance. The list of parameters and with their ranges is given in (table 6) below.

Table 6: Parameters and their range of values used in the Calibration

No	Parameter	File ext.	Method	Min	Max	Layer/column
1	CN2	.mgt	r Relative	-0.2	0.2	
2	ALPH_BF	.gw	V Replace	0	0.6	
3	GW-DELAY	.gw	V Replace	80	150	
4	GWQMN	.gw	V Replace	0	2	
5	GW_REVAP	.gw	r Relative	0	0.2	
6	REVAPMN	.gw	r Relative	0	1	
7	CH_N2	.rte	r Relative	0	1	
8	CH_K2	.rte	r Relative	0	500	
9	SOL_AWC	.sol	r Relative	0	1	all
10	SOL_K	.sol	r Relative	0	2000	all
11	SURLAG	.hru	r Relative	0.5	24	

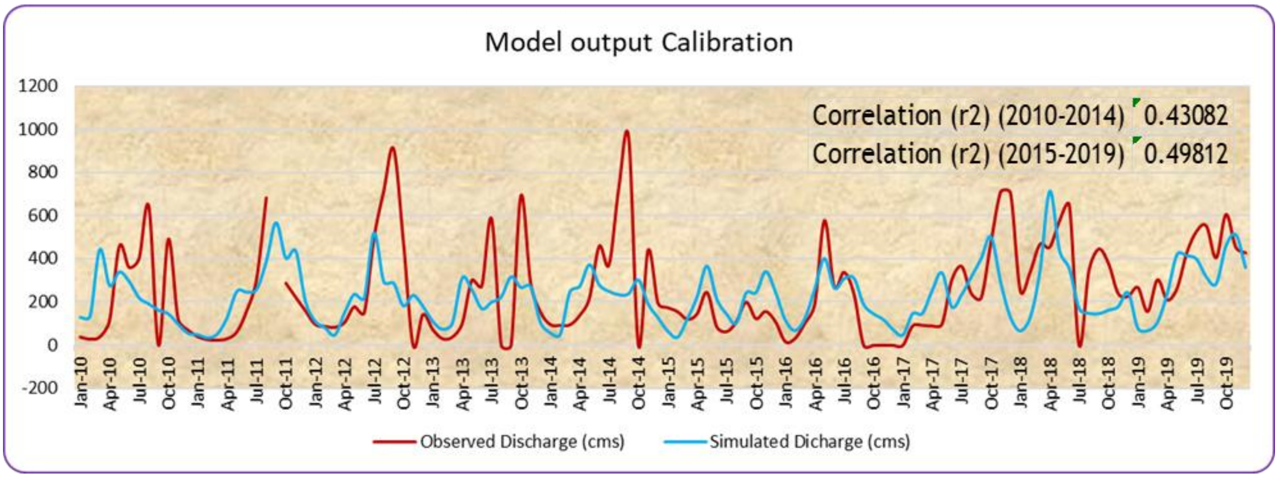


Figure 26: Discharge hydrograph of Measured and Simulated

Because of the differences between the whole Gibe –Omo basin upstream volcanic and other varied aquifers, that contribute much of the Omo River water, in their groundwater flow properties compared with the south graben alluvial deposit, the measured flow at Omo River located close to Omorate town, and the Arc SWAT simulated flow does not well correlate. The whole Gibe –Omo River basin accounts for a total of 79,822 km^2 while the south Omo graben alluvial deposit (study area) accounts for 8,524 km^2.

The Omorate flow gage station measures the out flow of the whole Gibe_Omo basin. The simulated flow characterizes the out flow from the south Omo graben Arc SWAT simulated which accounts only 10.7% of the total Gibe_Omo River basin.

The discrepancy of the two systems is not only in terms of areal extent (fig. 1). The upstream subsurface hydraulic properties of the Gibe_Omo river basin is quite different from that of the study area. The upstream mainly volcanics and other varied aquifer characteristics are different from the Omo graben alluvial deposit. The volcanic aquifers hydraulic conductivity, transitivity, amount of rainfall, groundwater recharge, and annual rainfall distribution of the upstream environment is quite different from the study area.

Because of all these factors, the measured flow and the simulated flow corresponding the gauging station (out let at the 19th sub basin) of the Arc SWAT model could not obviously correlate well.

4.1.2 Sensitivity Analysis

Sensitivity analysis is a crucial step in understanding the behavior and reliability of hydrological models like SWAT, particularly when it comes to groundwater recharge estimation, Abbaspour et al. (2007). It helps identify the most influential parameters and their impact on model outputs. Due to the limited observation data availability, it is difficult to run the sensitivity analysis.

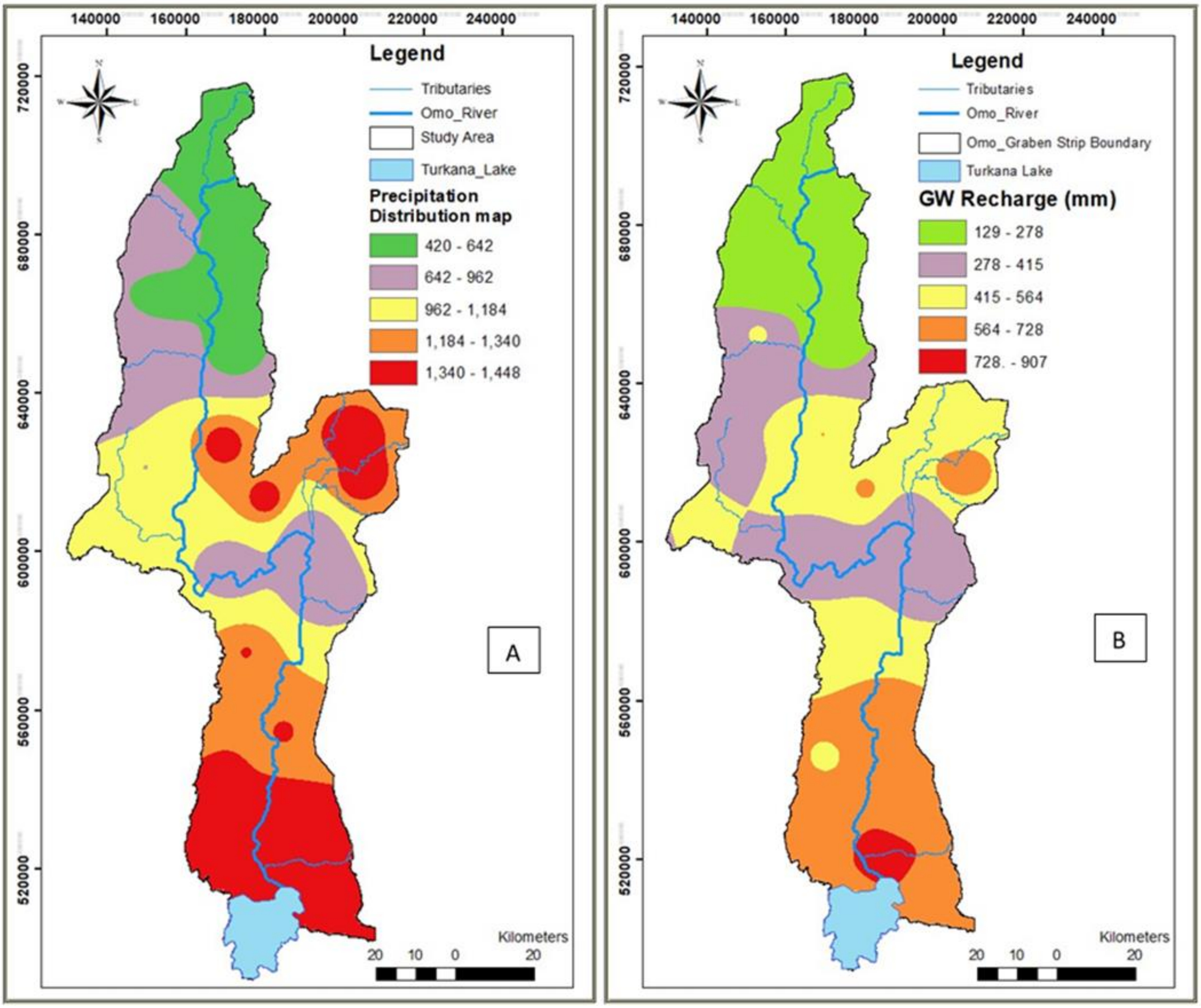


Figure 27: Rainfall and GW Recharge Distribution map

The SWAT model rainfall distribution and groundwater recharge distribution shows slight similarity in the northern and southern part of the study area (fig. 27 A & B). There are considerable differences in the distribution of the two parameters as a function of the the soil, LULC and topography of the surface.

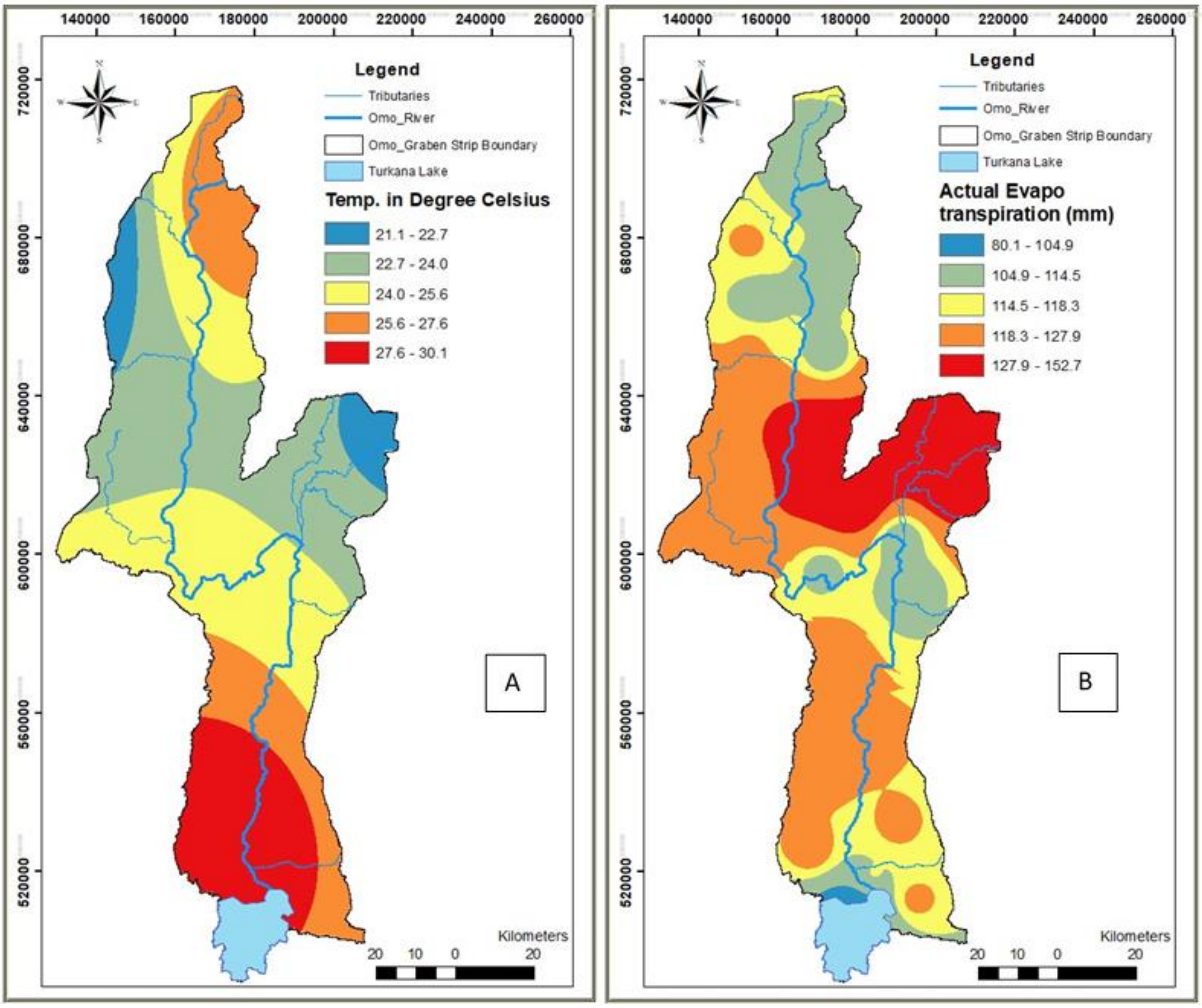


Figure 28: Temperature and Actual Evapotranspiration Distribution across the study area

According to the output of the model, the temperature and actual evapotranspiration does not correlate i.e higher temperature of a given area does not necessarily result in the higher evapotranspiration. This is because there are much more parameters like wind speed, sun shine hour, land use land cover and relative humidity that together with temperature derives the evapotranspiration. The south western tip and northeastern tip of the study area receives relatively higher temperature (fig. 28 A). The estern tip and north western part receives the lowest tepaerature. In contarary to the hifger temperature distribution, the central, and the southern part are known to have higher evapotranspiration value (fig 28 B).

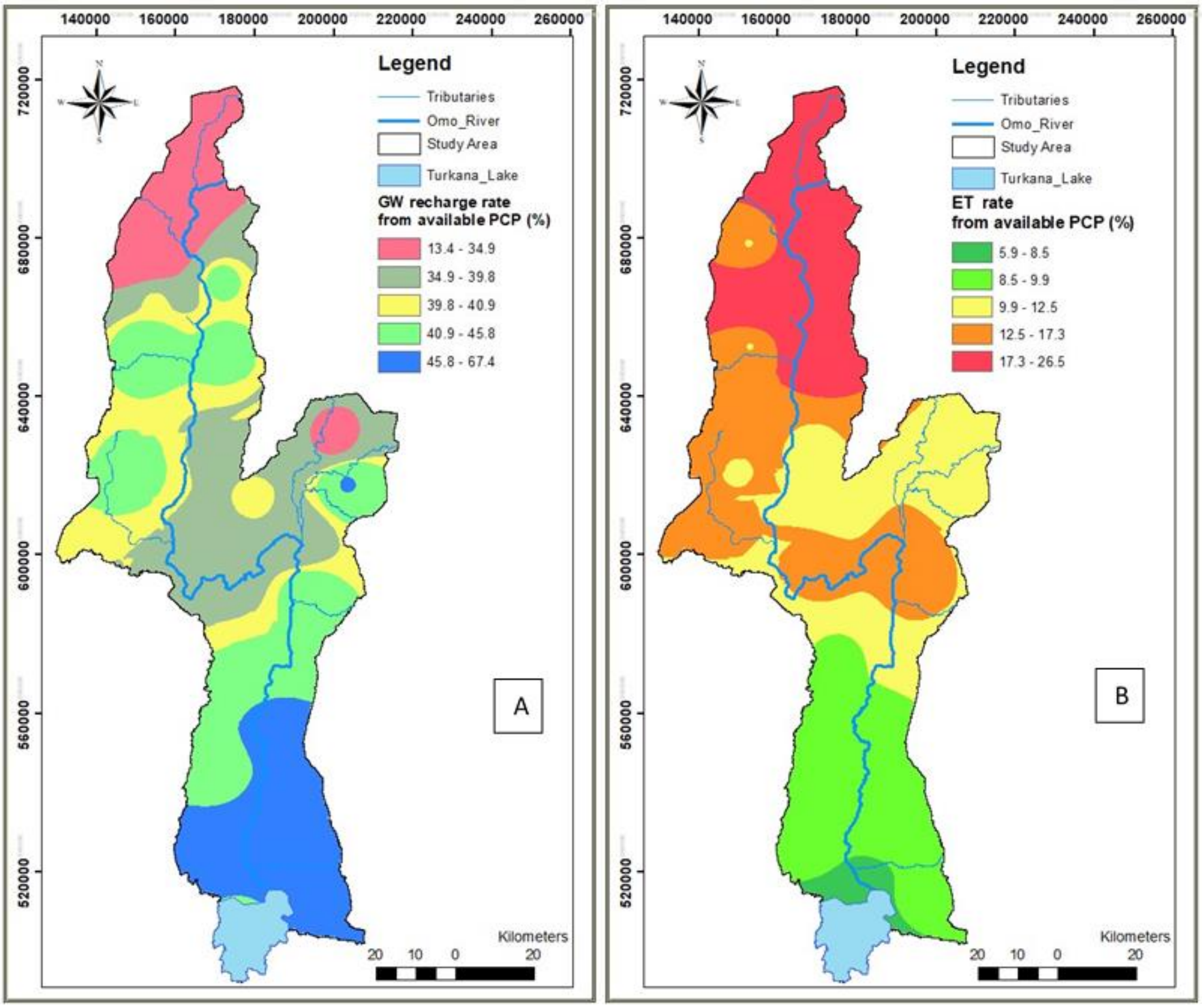


Figure 29: GW recharge and ETo hot spots distribution across the study area.

The two maps (fig. 29 A and B) important maps from groundwater managmenet point of view in light of sustainable use of groundwater sources. Thr groundwater rechrge rate from the available precipitation helps in the decision of artificial groundwater recharge infrastructures development. The most suitable areas for artificial groundwater recharge infrastructure development are the southern part and and a few area in the central northern part (fig. 29 A)

The evapotranspiration hot spot area conveys important information as to where to intervene in the improvement of LULC (fig. 29 B). The identification of the ETo hot spots paves way for the necessary groundwater management measures.

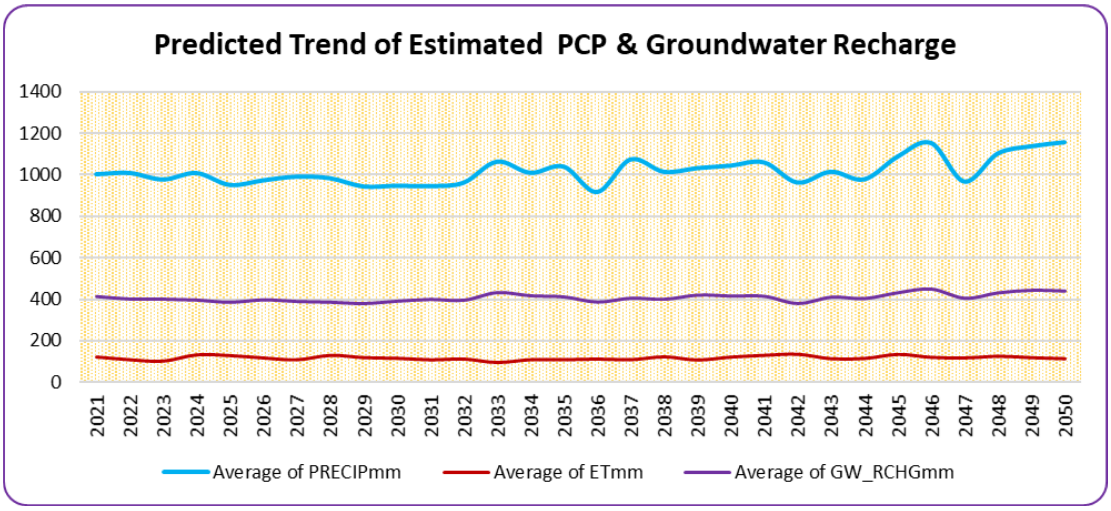


Figure 30: Average Yearly Predicted PCP, GW Recharge and Actual Evapotranspiration

The monthly distribution of groundwater recharge exhibits a peculiar relationship with the precipitation (fig. 30). The precipiattion of the study area peaks twice a year. The major episod of precipitation ranges from February to June and peaks in the month of May. The minor episod of precipitation ranges from August to Decemmber and peaks at the end of October.

The monthly distribution of groundwater recharge of the study area is represented by a peculiar graph in relation to the monthly precipitation distribution. The precipitation graph line peaks twice per annum, while the groundwater rechrge graph line peaks thrice per annum. The two peaks of the groundwater recharge corresponds to the two peaks of the precipitation (fig. 31) . The middle peak of the groundwater recharge graph line is generated by the wadi beds recharge in addition to the direct precipitation recharge. Because of the wadi beds recharge out of the direct precipitation recharge, the groundwater recharge graphline gets higher than the precipitation graphline in the period starting from end of June to the end of September.

The actual evapotranspiration of the study area does not significantly vary within the prediction period. The graph line for the evapotranspiration slightly replicates the precipitation graphline showing two slight peaks corresponding to the precipitation graphline.

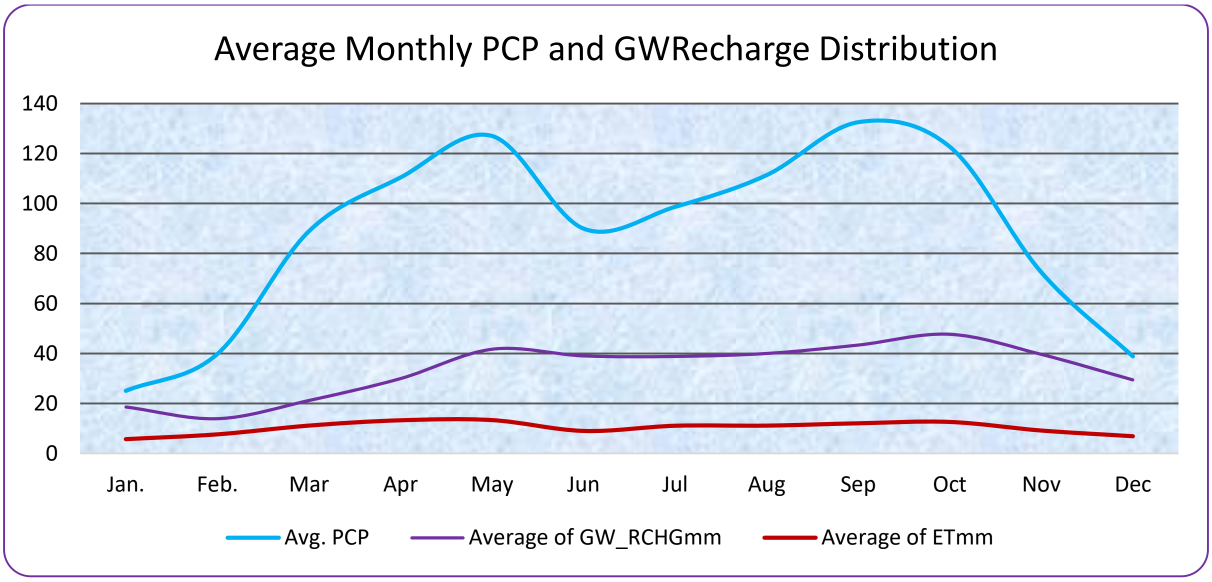


Figure 31: Average Monthly PCP, GW Recharge and Actual Evapotranspiration

From the average monthly disribution of PCP (fig. 27), GW recharge and Actual evapotranspiration, one can understand that the precipitation peaks twice in a year. This is typical patter of rainfall to the study area whereby many researchers described it as bimodal precipitation pattern. The first pttern ranges from February to June peaking peaking at the mid of May. The second patter ranges from August to November peaking at the beginning of October.

The groundwater recharge graph shows nearly similar patter as the precipitation graph. The groundwater recharge graph peaks twice a year corresponding to the precipitation graph. The groundwater recharge is not as prominent as the PCP graph. While the PCP graph remarkably lowers between the two peaks, the groundwater recharge graph maintains horizontal trend as opposed to the PCP graph. This can be attibuted to the runoff recharge to the groundwater.

4.4.1 Groundwater Quality

The change in groundwater recharge (increment) would positively impact the groundwater quality of the study area. The existing raised salinity of the groudwater would be desalinized by the inreased grounwater recharge. Of courrse the degree to which the increased groundwater recharge would improve the groundwater quality would require further assessment of the distribution salinity zones and groundwater extraction trends.

4.5 Summary of Results

4.5.1 Climate Variables (SDSM)

As far as the change in temperature is concerned, the average temperature at early 2020s increased by an average 0.23oC under the working scenario (4.5 W/m2) The average Precipitation at early 2020s which is nearly 1000 mm increased to 1158mm by the year 2050.

4.5.2 Groundwater Recharge

The average net groundwater recharge was closely 403mm at early 2020s, this value gradually increased to 437mm by the close of the 2050s. There is no pronounced change in actual evapotranspiration. It remains on average at 116mm.

4.5.3 Groundwater quality

The increment in groundwater recharge would positively impact the groundwater. One of the positive impacts of increased groundwater recharge is improvement in groundwater quality (qualitatively).

4.5.4 Important areas identified for groundwater management

High groundwater recharge rate areas used for probable artificial groundwater recharge infrastructure development are identified (fig 28 A). High evapotranspiration rate areas identified for treatment in the groundwater management (fig 28 B).

CHAPTER 5: CONCLUSION and RECOMMENDATION

5.1 Conclusion

5.1.1 Vulnerability of the Groundwater system of the study area

From the observation we have gone through, the alluvial deposit of southern Omo graben alluvial deposit is not connected to the upper Gibe Omo groundwater flow system. This implies that the southern Omo graben alluvial deposit groundwater system is characterized by local flow and local recharge system. Therefore, the southern Omo graben alluvial deposit gets its recharge from the local precipitation and local wadi beds flow. This means again the groundwater resource is highly dependent on the local precipitation and environmental factors for its recharge. The groundwater resource of the study the area is highly affected by the climate change.

5.1.2 Climate Variables

The change in the climate variables for example temperature upon all the meteorological stations varies. The change in average temperature upon all the stations under representative concentration pathway (rcp) 4.5W/m2 between the 2023 and 2050 is 0.23^{o}C. Whereas the change in average temperature under the representative concentration pathway (rcp 8.5W/m2) between the 2023 and 2050 is 0.26^{o}C.

The precipitation changes between 2023 and 2050 exhibit varied behavior. The maximum precipitation change is observed at Dimeka station. Two meteorological stations Jinka and Omorate showed decrease in precipitation amount. Whereas the four other station showed increment in precipitation at different rates under representative concentration pathway (rcp) 4.5W/m2. Under the representative concentration pathway (rcp) 8.5W/m2, again there an increment in precipitation upon the four meteorological stations. Bu the two stations Jinka and Maji stations showed decrease in precipitation between 2023 and 2050. The average increment in precipitation under rcp 8.5 is greater than that of under rcp 4.5.

From the downscaled data, one can observe that there is an increase both in average temperature and precipitation under the working scenario (rcp 4.5). From the SWAT output, it can be observed that the precipitation across the study area which was closely 1000 mm at the early years of 2020s, is increased to 1158mm at the year

2050. This trend clearly shows that the precipitation is in the increasing trend under the rcp 4.5. Though the annual precipitation showed steadily increments, the seasonal distribution of precipitation did not deviate from its current bi-modal pattern.

The average change in climate variables is less under rcp 4.5 compared to the rcp 8.5. The change in climate variables specifically precipitation gets catastrophic level with grave consequences at 2100. The precipitation at the three stations vis Dimeka, Omorate and Turmi which surrounds Omorate town shows a catastrophic level by the close of 2100 under the rcp 8.5. This situation poses a serious threat to the Omorate town to the extent of putting the town under water.

5.1.3 Groundwater Recharge

Groundwater recharge primarily hinges on factors such as temperature, precipitation, and spatial data including soil cover, Land Use Land Cover, and topography. With climate variables showing an upward trajectory, groundwater recharge similarly demonstrated an increasing trend.

During the early 2020s, the average net groundwater recharge was closely 403mm, gradually rising to 437mm by the close of the 2050s. This upward trend in groundwater recharge demonstrates a positive impact brought about by the changing climate. However, this incremental rise alone does not ensure sustainable groundwater availability, as understanding the demand side of groundwater resources within the area is crucial.

5.1.4 Groundwater Quality

From the increased groundwater recharge, it can be observed that based on the status quo, the ground water quality improves because of the additional fresh water recharge to the groundwater. This conclusion is valid as long as the annual groundwater abstraction rate is lower that than annual groundwater recharge rate.

5.1.5 Identification of hot spots for groundwater recharge and actual evapo-transpiration

Hot spot areas for high rate of evapotranspiration and high rate of groundwater recharge sites are identified for use in future groundwater resource management.

These hot spots were identified from the output of parameters per sub basin from the SWAT model.

5.2 Recommendations

5.2.1 Demand Side

The groundwater recharge depends mainly on variables like temperature, precipitation, and spatial data like soil cover, Land Use Land Cover and topography. Since the temporal variables are in the increasing trend, the resulting groundwater recharge similarly found in the increasing trend.

The amount of net groundwater recharge which at the early 2020s was 403mm on average keeps increasing to grow to 437mm close to 2050s. This groundwater recharge increasing trend shows a positive impact under the changing climate. However, this mere increment in groundwater recharge under the changing climate does guarantee the sustainable groundwater availability. This is because the demand side of the groundwater resources of the study area needs to be clearly known.

To exhaustively understand the demand side of the equation of sustainable groundwater management, it is imperative to:

a) Keep records of documents related to groundwater development infrastructure
b) Establish monitory system that continually keep records of groundwater level under pumping condition
c) Develop the groundwater supply demand plan probably using the Sustainable development goal "Target 6.1: By 2030, achieve universal and equitable access to safe and affordable drinking water for all". The water demand plan can also be developed in collaboration with investment office.
d) Promote and apply water conservation practices for efficient water use. These can reduce water demand and ease pressure on groundwater resources. Engaging local communities and stakeholders in awareness campaigns, education programs, and participatory decision-making processes to foster a collective responsibility for sustainable groundwater management.

5.2.2 Supply Side

The supply side measures for sustainable groundwater management requires action plan and implementation that aims at ensuring long-term availability and quality groundwater resource. Practices may include one or combinations of the following:

a) Aquifer recharge: Develop artificial aquifer recharge structures to replenish groundwater levels. This activity involves capturing and directing runoff water or storm water, at the area identified as groundwater recharge hot spots.
b) Monitor Groundwater Extraction: Develop regulation and guidelines for groundwater pumping limits to avoid over exploitation. Use water allocation mechanisms that would help manage groundwater extraction rates to maintain aquifer sustainability.
c) Adopt integrated water resources management approaches: Integrate the use of both surface water and groundwater sources using infrastructures such as surface water storage reservoirs, boreholes and water transfer systems to optimize water allocation and reduce dependence on a single source.
d) Establish Groundwater Monitoring and Data Management System: Establishing groundwater monitoring networks, and data management systems will assist in analyzing data to access status of aquifers, identify trends and helps develop sound sustainable management strategies.

Appendices

Predicted PCP and Average Temperature under Scenario 2.6 (W/m^2)

Year	Dim PCP	Jin PCP	Han PCP	Maj PCP	Omo PCP	Tur PCP	Dim Tavg	Han Tavg	Jin Tavg	Maj Tavg	Omo Tavg	Tur Tavg
2023	1575.1	880.8	1488.0	1196.3	342.6	775.4	23.1	27.5	20.9	18.8	30.0	24.6
2024	1001.9	1008.0	1328.9	1449.0	341.9	555.3	23.4	27.7	21.1	18.9	30.1	24.9
2025	927.5	704.9	1491.5	1197.1	376.8	678.5	23.2	27.6	21.1	18.9	30.0	24.7
2026	1028.8	823.9	1360.7	1287.1	367.9	772.7	23.1	27.6	21.0	18.8	30.0	24.7
2027	1241.1	800.6	1489.3	1202.0	399.0	885.0	23.3	27.7	21.1	19.0	30.1	24.8
2028	1179.9	1069.6	1332.8	1258.3	352.6	745.4	23.3	27.6	21.0	18.9	30.0	24.7
2029	1063.4	927.2	1345.8	1094.6	500.5	809.9	23.1	27.5	20.9	18.8	30.1	24.6
2030	976.6	822.1	1363.3	1245.8	332.5	687.7	23.3	27.5	21.0	18.8	30.0	24.8
2031	1409.6	855.5	1285.0	1354.4	311.6	540.2	23.2	27.7	21.1	19.0	30.2	24.8
2032	1234.5	769.1	1417.6	1339.4	367.5	553.7	23.3	27.7	21.1	18.9	30.1	24.7
2033	1517.4	759.7	1627.0	1278.6	337.0	1085.2	23.0	27.6	21.0	18.9	30.2	24.4
2034	1148.6	986.3	1550.3	1216.5	329.4	878.2	23.2	27.6	21.0	18.8	30.0	24.6
2035	1463.1	869.9	1754.2	1279.1	319.6	677.1	23.0	27.5	20.9	18.8	29.8	24.6
2036	1365.6	848.1	1427.3	1035.8	493.3	741.6	23.2	27.6	21.1	18.9	30.3	24.7
2037	1357.0	779.7	1574.8	1405.4	501.9	788.5	23.2	27.7	21.0	19.0	30.2	24.7
2038	1293.8	1039.9	1477.8	1265.6	488.6	749.5	23.4	27.8	21.1	19.0	30.4	24.9
2039	1094.3	790.5	1258.9	1400.3	392.2	891.4	23.1	27.6	21.0	18.8	30.0	24.7
2040	1586.4	789.8	1446.2	1377.3	438.0	850.4	23.2	27.7	21.1	18.8	30.3	24.7
2041	1365.9	909.3	1298.7	1361.5	475.4	1029.9	23.5	27.7	21.2	19.0	30.4	25.0
2042	1421.5	662.2	1555.7	1058.2	495.9	916.8	23.4	27.7	21.2	19.0	30.3	24.9
2043	1039.1	724.5	1561.5	1186.8	470.9	1003.5	23.2	27.8	21.0	19.0	30.4	24.7
2044	1157.5	833.1	1318.8	1253.2	446.2	845.1	23.3	27.7	21.0	18.8	30.1	24.7
2045	1078.1	852.0	1391.5	1496.1	421.3	904.2	23.3	27.8	21.1	18.9	30.2	24.8
2046	1310.8	953.7	1501.5	1513.6	410.6	1083.2	23.2	27.9	21.2	19.1	30.2	24.8
2047	986.2	864.6	1363.9	1250.2	412.0	704.1	23.3	27.7	21.1	19.0	30.2	24.8
2048	1401.9	862.9	1737.3	1315.9	389.7	968.5	22.9	27.5	20.8	18.7	29.8	24.4
2049	1356.4	872.2	1784.1	1410.4	540.1	852.0	23.0	27.6	20.9	18.8	29.9	24.4
2050	1438.6	800.7	1756.6	1531.6	547.8	926.0	23.2	27.9	21.0	19.0	30.4	24.6
2051	1172.5	981.6	1297.7	1229.9	428.7	787.1	23.2	27.7	21.0	18.9	30.1	24.7
2052	1277.4	889.8	1391.1	1384.4	460.7	982.4	23.0	27.5	20.9	18.8	29.9	24.6
2053	1229.0	840.8	1552.1	1275.0	396.8	713.6	23.1	27.5	20.9	18.7	29.9	24.5
2054	1274.3	888.6	1459.2	1353.3	475.1	882.5	23.4	27.7	21.1	18.9	30.2	24.8
2055	1367.4	1034.8	1497.4	1427.2	425.4	1193.9	23.4	27.6	21.1	18.9	30.1	24.8
2056	1415.5	922.1	1407.1	1392.1	552.0	857.4	23.5	27.8	21.2	19.0	30.2	25.0
2057	1399.6	871.0	1559.0	1058.1	402.4	1067.0	23.1	27.5	21.0	18.8	29.9	24.6
2058	2011.7	935.3	1461.3	1379.2	430.3	1045.5	23.3	27.9	21.1	19.1	30.3	24.8
2059	1520.7	917.6	1475.6	1435.5	482.4	1037.1	23.4	27.7	21.1	19.0	30.4	24.8
2060	1366.8	943.6	1702.3	1325.1	396.2	1027.5	23.3	27.7	21.1	18.9	30.2	24.8
2061	1201.2	1035.7	1333.1	1383.3	537.0	738.5	23.3	27.8	21.1	18.9	30.1	24.7

2062	1282.4	879.1	1274.1	1233.5	410.3	769.6	23.3	27.8	21.1	18.9	30.2	24.8
2063	1112.1	992.2	1700.8	1201.8	433.7	852.1	23.5	27.9	21.2	19.0	30.3	25.0
2064	1146.4	903.9	1299.5	1247.1	412.1	780.7	23.2	27.7	21.0	18.9	29.9	24.7
2065	1274.3	732.7	1605.0	1237.8	421.4	759.6	23.1	27.8	21.0	19.0	30.2	24.6
2066	1456.6	938.0	1788.4	1324.5	491.0	963.6	23.1	27.7	21.0	18.9	30.1	24.5
2067	1482.7	905.9	1431.0	1225.7	597.4	1030.5	23.3	27.9	21.0	19.0	30.4	24.8
2068	1601.8	813.1	1444.5	1164.3	357.7	854.6	23.3	27.8	21.2	19.0	30.4	24.8
2069	1485.6	917.1	1449.8	1294.8	374.9	1016.9	23.3	27.7	21.1	19.0	30.2	24.9
2070	1566.8	897.9	1480.1	1326.9	485.7	890.5	23.1	27.7	21.0	18.9	30.2	24.6
2071	1250.6	906.8	1583.8	1515.5	417.7	791.6	23.5	27.8	21.1	19.0	30.2	24.9
2072	1341.1	964.9	1501.8	1076.0	352.5	576.7	23.0	27.6	21.0	18.9	29.9	24.5
2073	1237.3	788.6	1436.7	1502.5	448.0	858.5	23.1	27.6	20.9	18.9	30.1	24.5
2074	1084.8	799.5	1571.6	1311.2	359.3	1015.1	23.3	27.7	21.1	18.9	30.2	24.9
2075	1413.0	775.6	1503.4	1161.3	351.7	577.1	23.2	27.6	21.0	18.9	30.1	24.8
2076	1380.4	959.1	1667.8	1472.3	505.5	962.4	23.3	27.7	21.0	19.0	30.2	24.7
2077	1295.8	1021.6	1605.4	1195.5	305.1	708.4	22.9	27.5	20.9	18.7	29.8	24.4
2078	1185.0	897.1	1479.2	1344.0	422.7	655.3	22.9	27.5	20.8	18.7	29.8	24.4
2079	1320.7	788.8	1514.5	1430.9	336.2	935.8	23.3	27.8	21.2	19.0	30.3	24.7
2080	1199.1	836.4	1427.1	1244.0	451.0	820.6	23.3	27.6	21.0	18.8	29.9	24.7
2081	1284.1	747.7	1280.0	1190.5	283.1	741.0	23.2	27.5	21.0	18.8	30.0	24.7
2082	1331.1	900.8	1513.2	1083.3	425.1	891.9	23.0	27.6	20.9	18.7	29.9	24.5
2083	1305.7	992.6	1367.3	1215.7	436.5	946.3	23.5	27.8	21.1	19.0	30.1	24.9
2084	1288.8	1088.7	1300.0	1507.3	348.3	790.0	23.1	27.6	21.0	18.8	30.0	24.7
2085	1392.6	831.7	1371.1	1276.1	450.7	924.2	23.2	27.6	21.1	18.8	30.0	24.6
2086	1467.4	911.4	1478.4	1400.5	443.7	1037.3	23.2	27.5	20.9	18.8	30.0	24.6
2087	1282.8	1004.9	1227.2	1196.8	368.3	719.8	23.2	27.6	21.0	18.8	30.0	24.6
2088	1341.7	822.6	1463.8	1289.9	435.2	1156.9	23.1	27.5	20.9	18.8	29.9	24.6
2089	1446.3	767.5	1440.7	1361.7	461.4	840.8	23.1	27.7	21.0	18.9	30.1	24.6
2090	1194.8	818.2	1605.9	1346.2	354.0	846.6	23.1	27.7	21.0	19.0	30.0	24.6
2091	1254.9	934.0	1312.9	1297.7	419.5	945.1	23.2	27.7	21.1	18.8	30.1	24.7
2092	1142.1	902.8	1574.7	1192.9	403.6	820.8	22.9	27.5	20.9	18.8	29.7	24.4
2093	1204.9	966.5	1779.1	1228.9	493.7	845.9	23.3	27.8	21.1	19.0	30.3	24.9
2094	1054.6	744.7	1551.4	1362.0	510.5	976.5	23.0	27.6	20.9	18.8	29.9	24.4
2095	843.3	994.7	1389.9	1583.8	406.2	756.6	23.1	27.6	21.0	18.9	29.9	24.6
2096	1144.1	992.7	1541.6	1420.7	476.1	825.9	23.1	27.6	21.0	18.9	30.1	24.6
2097	1196.7	931.4	1539.2	1327.5	394.2	1172.3	23.4	27.8	21.0	19.1	30.2	24.9
2098	1544.0	816.1	1596.9	1351.8	368.8	930.7	23.2	27.7	21.1	19.0	30.2	24.7
2099	1352.6	863.3	1334.1	1261.9	460.9	894.3	23.1	27.5	20.9	18.7	29.8	24.5
2100	1068.6	875.9	1459.3	1468.0	402.2	689.1	23.1	27.7	21.0	18.8	30.1	24.6

Predicted PCP and Average Temperature under Scenario 4.5 (W/m^2)

Year	Dim PCP	Han PCP	Jin PCP	Maj PCP	Omo PCP	Tur PCP	Dim Tavg	Han Tavg	Jin Tavg	Maj Tavg	Omo Tavg	Tur Tavg
2023	1236.3	1399.7	884.0	1195.6	439.0	697.7	23.1	27.5	21.0	18.8	29.8	24.6
2024	1249.2	1220.4	744.8	1430.9	321.4	836.7	23.4	27.8	21.2	19.0	30.3	24.9
2025	1180.1	1266.0	842.8	1403.2	400.4	739.6	23.1	27.6	21.1	18.9	30.1	24.7
2026	1179.8	1449.4	906.0	1118.6	486.1	950.2	23.2	27.6	20.9	18.8	30.2	24.7
2027	1137.9	1255.1	849.1	1514.8	432.2	867.4	23.3	27.7	21.1	18.9	30.0	24.8
2028	1076.5	1320.8	733.4	1222.1	436.8	660.8	23.1	27.5	21.0	18.9	29.8	24.6
2029	1187.0	1512.1	827.3	1327.2	333.3	766.8	23.0	27.6	20.9	18.9	30.0	24.4
2030	948.2	1487.3	791.7	1320.1	359.3	829.9	23.2	27.7	21.0	18.9	29.9	24.8
2031	1207.1	1363.1	901.9	1339.9	360.6	765.4	23.3	27.7	21.2	19.0	30.3	24.9
2032	965.8	1470.6	802.8	1369.0	377.9	728.7	23.3	27.6	21.1	18.9	30.1	24.8
2033	1253.2	1464.0	926.4	1292.2	425.0	739.5	23.1	27.5	21.0	18.9	30.0	24.6
2034	1372.4	1475.9	1003.5	1499.0	425.6	919.7	23.3	27.6	21.0	18.9	30.0	24.7
2035	1425.5	1392.9	807.1	1371.7	361.7	663.8	22.9	27.5	21.0	18.8	29.9	24.5
2036	1231.7	1516.9	861.0	1388.7	391.0	837.3	23.2	27.6	21.1	19.0	30.1	24.7
2037	1343.7	1521.2	951.5	1033.8	549.9	807.7	23.2	27.8	21.1	19.0	30.3	24.6
2038	1233.1	1614.9	1068.0	1191.7	446.7	638.7	23.5	27.8	21.2	19.1	30.5	25.0
2039	1436.4	1621.1	904.3	1653.3	483.5	771.4	23.1	27.7	21.0	18.9	30.0	24.6
2040	1350.1	1569.2	985.0	1311.7	355.0	770.7	23.1	27.6	21.1	18.9	30.2	24.6
2041	1355.5	1334.3	837.0	1547.3	373.5	819.4	23.3	27.8	21.2	19.1	30.4	24.8
2042	1126.0	1328.2	762.4	1537.2	409.7	933.1	23.5	27.8	21.1	19.0	30.5	25.0
2043	1334.3	1460.5	969.6	1122.5	400.8	881.5	23.3	27.6	21.0	18.9	30.2	24.8
2044	1242.4	1464.8	872.8	1139.0	467.2	1121.0	23.2	27.6	20.9	18.8	30.1	24.7
2045	1246.9	1415.4	872.5	1183.3	342.2	879.1	23.4	27.7	21.1	19.0	30.1	24.8
2046	1542.3	1585.4	850.9	1151.0	639.7	1078.3	23.4	27.9	21.1	19.1	30.3	24.8
2047	1345.1	1701.6	905.9	1413.2	395.3	643.7	23.4	27.8	21.1	19.1	30.5	24.9
2048	1065.3	1470.9	917.1	1297.5	504.1	1161.8	23.1	27.5	20.9	18.8	29.9	24.5
2049	1397.9	1658.5	806.9	1554.5	497.6	892.9	23.0	27.5	20.9	18.7	29.8	24.4
2050	1408.2	1607.9	871.9	1248.6	345.3	686.9	23.2	27.7	21.1	18.9	30.1	24.7
2051	1592.5	1690.8	739.8	1219.1	398.5	824.6	23.3	27.7	21.0	19.0	30.3	24.7
2052	1219.3	1530.6	906.5	1221.9	444.0	861.0	23.1	27.6	21.0	18.8	29.9	24.5
2053	1607.3	1670.1	897.7	1517.4	461.4	835.5	23.1	27.6	21.0	18.9	30.2	24.5
2054	1273.9	1526.8	1047.1	1281.7	353.5	997.6	23.4	27.8	21.2	19.0	30.2	24.8
2055	1330.6	1540.6	962.1	1390.0	504.6	821.2	23.1	27.7	21.1	19.0	30.1	24.7
2056	1156.5	1321.4	813.0	1179.1	492.5	759.3	23.7	27.9	21.3	19.1	30.3	25.1
2057	1231.5	1622.2	635.7	1345.0	410.7	1173.3	23.1	27.6	21.0	18.8	30.1	24.6
2058	1502.9	1729.1	775.0	1355.1	438.3	834.2	23.3	27.8	21.1	19.0	30.4	24.8
2059	1712.4	1696.7	954.4	1278.9	598.4	1048.7	23.4	27.8	21.2	19.1	30.5	24.8
2060	1586.0	1574.3	733.6	1175.1	493.2	1175.1	23.4	27.9	21.1	19.1	30.6	24.8
2061	1608.1	1893.4	995.2	1070.3	424.5	870.5	23.3	27.8	21.1	18.9	30.3	24.8
2062	1491.4	1604.8	848.4	1261.2	433.2	1132.2	23.4	27.8	21.1	18.9	30.3	24.8

2063	1635.0	1671.7	811.2	1183.8	503.2	1074.3	23.5	27.9	21.2	19.1	30.6	24.9
2064	1483.6	1435.9	1102.1	1400.5	459.0	789.1	23.2	27.7	21.0	18.9	30.3	24.6
2065	1370.5	1565.0	984.3	1515.4	483.6	974.2	23.3	27.8	21.1	18.9	30.2	24.8
2066	1234.8	1524.4	900.6	1205.5	382.5	892.2	23.1	27.6	21.0	18.8	30.0	24.6
2067	1600.5	1564.6	1006.8	1204.5	441.8	991.5	23.2	27.7	21.0	19.0	30.3	24.6
2068	1536.2	1752.5	807.3	1673.3	490.3	768.2	23.4	27.9	21.2	19.1	30.5	24.8
2069	1345.0	1635.9	1272.2	1291.8	462.7	1721.0	23.5	27.8	21.1	19.0	30.4	24.9
2070	1600.1	1781.1	892.6	1310.2	541.1	916.2	23.2	27.8	21.0	19.0	30.3	24.7
2071	1472.1	1659.5	662.1	1329.0	504.0	820.6	23.3	27.9	21.2	19.0	30.4	24.8
2072	1997.1	1560.1	923.9	1261.9	514.5	1051.3	23.2	27.7	21.1	18.9	30.2	24.7
2073	1306.2	1422.9	824.8	1492.4	534.7	880.6	23.2	27.7	21.0	18.8	30.1	24.6
2074	1717.6	1630.6	787.5	1401.7	494.9	1049.7	23.4	27.8	21.1	19.0	30.4	24.9
2075	1591.8	1654.8	870.7	1195.7	491.5	922.7	23.2	27.8	21.1	19.0	30.2	24.7
2076	1522.0	1838.5	814.6	1271.0	454.1	892.1	23.2	27.8	21.0	18.9	30.3	24.6
2077	1746.8	1639.5	987.0	1128.1	563.8	721.4	23.1	27.6	20.9	18.8	30.1	24.5
2078	1304.0	1724.5	871.6	1478.6	488.9	1097.0	23.0	27.7	20.9	18.8	30.0	24.4
2079	1449.1	1781.9	816.0	1200.6	359.9	956.9	23.5	27.9	21.2	19.0	30.3	24.9
2080	1885.4	2084.8	845.5	1147.8	535.5	1145.9	23.3	27.9	21.0	19.0	30.5	24.7
2081	1434.0	1781.6	885.2	1540.7	494.5	1008.2	23.3	27.9	21.0	19.0	30.4	24.7
2082	1434.4	1589.5	1049.1	1104.9	478.3	1096.0	23.0	27.7	21.0	18.8	29.9	24.5
2083	1544.3	1892.7	925.8	1314.8	490.9	1081.8	23.3	27.8	21.1	19.0	30.2	24.8
2084	1361.3	1876.4	905.0	1478.0	489.1	1025.9	23.2	27.7	21.1	18.9	30.2	24.7
2085	1785.9	1851.8	875.0	1289.6	482.4	1075.7	23.3	27.8	21.2	19.0	30.3	24.8
2086	1665.1	1800.7	892.4	1099.7	514.2	1283.6	23.1	27.8	21.0	19.0	30.2	24.5
2087	1316.9	1775.4	791.3	1445.8	429.3	880.0	23.2	27.6	21.0	18.8	30.0	24.6
2088	1441.6	1849.7	887.8	1489.9	441.7	1070.6	23.1	27.7	21.0	18.9	30.1	24.5
2089	1504.4	1755.9	951.3	1331.1	395.6	1160.4	23.3	27.8	21.0	19.1	30.3	24.8
2090	1397.3	1998.6	1029.5	1315.5	392.9	1078.9	23.2	27.6	21.0	18.8	30.1	24.6
2091	1620.9	1703.1	952.1	1108.3	459.0	1058.0	23.3	27.7	21.1	18.9	30.3	24.8
2092	1704.9	1659.5	815.0	1423.1	528.1	957.1	23.1	27.6	21.0	18.8	29.9	24.5
2093	1555.0	1879.3	813.0	1269.5	375.3	862.2	23.4	27.9	21.2	19.1	30.3	24.8
2094	1715.5	1646.0	869.1	1302.7	494.8	1035.6	23.1	27.6	20.9	18.8	30.0	24.5
2095	2031.3	1713.5	856.7	1433.8	422.2	1358.7	23.2	27.7	21.0	18.9	30.1	24.6
2096	1461.5	1538.6	1000.7	1444.2	529.0	1155.8	23.2	27.7	21.0	18.9	30.2	24.7
2097	1749.8	1813.5	1003.3	1348.2	455.2	1591.6	23.3	27.8	21.1	19.0	30.4	24.8
2098	1320.0	1890.0	896.8	1331.5	527.4	1190.1	23.3	27.9	21.1	19.0	30.3	24.7
2099	1500.0	1928.1	949.2	1316.0	620.9	828.0	23.2	27.7	21.0	18.8	30.1	24.6
2100	1589.2	1672.2	977.4	1462.2	453.1	812.5	23.2	27.8	21.1	18.9	30.4	24.6

Predicted PCP and Average Temperature under Scenario 8.5 (W/m^2)

Year	Dim PCP	Han PCP	Jin PCP	Maj PCP	Omo PCP	Tur PCP	Dim Tavg	Han Tavg	Jin Tavg	Maj Tavg	Omo Tavg	Tur Tavg
2023	1307.6	1510.5	803.9	1327.7	343.8	676.0	23.1	27.5	21.0	18.7	29.8	24.6
2024	1195.6	1450.8	1038.6	1344.3	341.2	759.2	23.4	27.7	21.2	19.1	30.4	24.8
2025	1290.7	1350.8	760.3	1486.0	485.1	776.2	23.3	27.6	21.1	18.9	30.1	24.9
2026	1272.5	1287.8	963.7	1299.5	395.8	947.3	23.0	27.6	21.0	18.9	30.0	24.5
2027	1060.8	1255.4	729.9	1511.8	406.6	697.0	23.3	27.8	21.1	19.0	30.2	24.8
2028	1074.0	1274.0	738.1	1534.5	384.3	577.9	23.2	27.6	21.0	18.9	30.1	24.7
2029	1115.1	1268.9	909.9	1407.4	371.9	653.7	23.2	27.5	20.9	18.8	30.0	24.7
2030	1303.0	1536.5	910.3	1188.0	369.0	777.0	23.1	27.7	21.0	18.9	30.1	24.6
2031	1184.0	1624.2	925.3	1253.6	493.6	814.5	23.2	27.9	21.2	19.1	30.4	24.7
2032	1308.3	1483.5	965.8	1160.1	538.5	1240.7	23.3	27.8	21.1	19.0	30.4	24.7
2033	986.3	1361.7	876.0	1330.3	448.0	875.7	23.2	27.6	20.9	18.8	30.2	24.7
2034	1290.4	1533.8	776.2	1401.6	484.1	986.0	23.1	27.6	21.1	18.9	30.1	24.6
2035	1300.6	1858.6	812.7	1227.4	448.6	961.8	23.1	27.5	20.9	18.7	29.9	24.6
2036	1175.8	1685.8	1006.6	1244.5	354.6	747.3	23.3	27.7	21.1	18.9	30.2	24.8
2037	1343.9	1524.0	1096.2	1366.7	452.3	981.8	23.4	27.8	21.1	19.0	30.2	24.8
2038	1574.7	1635.3	899.1	1166.5	487.8	827.5	23.4	27.8	21.2	19.0	30.3	24.9
2039	1285.9	1533.3	985.3	1208.7	461.8	1019.1	23.0	27.6	21.0	18.9	30.0	24.6
2040	1254.6	1523.7	933.3	1531.1	458.6	1089.2	23.3	27.7	21.1	18.9	30.2	24.7
2041	1392.0	1801.5	1028.4	1265.1	480.9	931.7	23.2	27.9	21.2	19.1	30.5	24.7
2042	1368.1	1686.9	907.8	1437.7	434.8	977.7	23.5	27.9	21.1	19.0	30.6	24.9
2043	1312.2	1756.2	986.0	1295.4	538.2	918.2	23.2	27.7	21.1	18.9	30.2	24.7
2044	1351.3	1437.8	803.6	1285.7	445.8	912.3	23.0	27.6	21.0	18.9	30.0	24.6
2045	1465.4	1736.8	932.8	1434.5	391.8	962.1	23.5	27.8	21.1	18.9	30.2	24.9
2046	1429.3	1601.2	915.9	1275.8	527.8	993.7	23.5	27.9	21.2	19.1	30.3	24.9
2047	1605.5	1814.9	906.6	1427.9	510.1	1069.8	23.3	27.8	21.1	19.0	30.4	24.8
2048	1696.0	1698.6	744.3	1161.2	571.7	885.8	23.0	27.7	20.9	18.8	30.2	24.4
2049	1668.8	1796.5	996.9	1331.2	428.4	1386.7	23.1	27.6	21.0	18.7	30.0	24.5
2050	1416.3	1738.9	668.8	1267.3	485.5	831.8	23.3	27.8	21.1	18.9	30.3	24.8
2051	1666.0	1597.1	819.2	1337.8	545.0	1019.3	23.3	27.8	21.0	18.9	30.2	24.7
2052	1708.3	1889.4	881.5	1303.0	662.2	1207.3	23.2	27.7	21.0	18.8	30.1	24.5
2053	1610.4	1859.0	936.1	1228.2	466.4	960.4	23.3	27.7	21.0	18.8	30.0	24.6
2054	1295.6	1795.3	973.3	1203.4	458.0	862.3	23.5	27.9	21.2	19.0	30.4	24.9
2055	2007.6	1888.2	1209.9	1190.4	564.2	1288.6	23.4	27.9	21.1	19.1	30.5	24.8
2056	1282.7	1859.5	1018.9	1429.3	416.1	1024.3	23.6	28.1	21.3	19.2	30.6	25.1
2057	1779.0	1929.7	932.1	1220.9	393.5	847.0	23.2	27.8	21.1	18.9	30.1	24.6
2058	1936.7	1841.6	818.0	1336.0	484.9	1138.7	23.4	28.0	21.1	19.1	30.5	24.8
2059	1958.3	2177.9	879.0	1376.9	566.5	838.2	23.4	28.1	21.2	19.0	30.5	24.9
2060	1683.3	2060.3	900.5	1298.5	510.9	1098.4	23.5	27.9	21.2	19.0	30.5	24.9
2061	2148.6	2316.7	981.0	1350.0	583.2	1129.4	23.3	28.0	21.1	19.0	30.4	24.7
2062	1800.9	2381.3	903.9	1485.9	522.6	1096.5	23.4	28.0	21.2	19.0	30.6	24.8

2063	2104.1	2269.7	838.4	1267.5	586.2	909.4	23.6	28.1	21.2	19.1	30.7	25.0
2064	2264.7	2097.4	858.7	1292.8	651.1	1080.6	23.3	27.9	21.1	18.9	30.4	24.7
2065	1600.0	1986.9	828.3	1315.3	446.8	1005.4	23.4	27.9	21.1	18.9	30.5	24.8
2066	1626.0	2098.8	946.1	1315.0	564.4	1467.4	23.2	27.8	21.1	18.8	30.2	24.6
2067	1901.0	2283.2	833.3	1205.3	606.3	1068.8	23.3	27.9	21.2	19.0	30.4	24.6
2068	2218.9	2360.9	970.5	1363.1	753.2	1107.1	23.5	28.2	21.2	19.2	30.8	24.9
2069	2217.8	2238.0	789.5	1285.7	592.6	1187.9	23.6	28.1	21.2	19.0	30.6	24.9
2070	1644.5	2105.1	1083.9	1319.8	500.9	1027.1	23.3	27.9	21.1	18.9	30.4	24.7
2071	2652.2	2138.4	930.8	1355.1	669.2	1525.5	23.6	28.1	21.2	19.0	30.6	24.8
2072	2108.0	2464.1	894.4	1403.6	642.0	1882.2	23.4	28.1	21.1	19.0	30.6	24.7
2073	2297.2	1997.0	868.0	1594.6	520.0	1154.5	23.4	27.9	21.0	18.9	30.4	24.7
2074	2350.9	2064.9	997.4	1170.1	544.3	1453.0	23.5	28.1	21.2	19.0	30.8	25.0
2075	2183.8	2371.8	898.2	1149.0	503.1	1144.5	23.3	28.1	21.1	19.0	30.6	24.7
2076	2926.5	2166.2	1175.7	1431.6	533.8	1439.5	23.3	28.0	21.2	18.9	30.4	24.6
2077	2026.0	2361.4	1063.5	1407.5	627.8	1054.0	23.2	27.9	21.0	18.8	30.3	24.5
2078	2245.5	2714.7	1031.4	1144.2	588.6	1302.5	23.2	27.9	21.0	18.8	30.4	24.5
2079	2790.7	2520.6	1049.6	1137.9	639.8	1456.8	23.6	28.2	21.2	19.2	30.8	24.8
2080	2790.7	2524.8	1116.3	1430.9	754.0	1548.3	23.4	28.2	21.1	19.1	30.7	24.7
2081	2678.9	2424.1	1029.4	1370.4	560.3	1570.0	23.4	28.0	21.1	18.9	30.5	24.7
2082	2327.4	2496.6	982.3	1559.4	694.3	1461.0	23.2	28.0	21.0	18.8	30.5	24.5
2083	2445.1	2787.6	1147.6	1329.9	748.9	1442.1	23.5	28.2	21.2	19.1	30.7	24.8
2084	2923.1	2691.5	1111.4	1411.5	773.3	1487.2	23.4	28.1	21.1	19.0	30.7	24.7
2085	2808.1	2624.6	1027.7	1302.0	694.6	1508.4	23.6	28.3	21.2	19.0	30.8	24.9
2086	2949.3	2759.6	961.5	1178.4	698.0	1514.6	23.4	28.1	21.1	18.9	30.5	24.7
2087	2588.9	2814.2	1071.3	1298.8	847.5	1683.5	23.2	28.1	21.1	18.9	30.8	24.6
2088	2750.5	3010.4	949.1	1194.0	740.3	2050.3	23.3	28.1	21.1	19.0	30.5	24.6
2089	3356.9	3258.8	1136.8	1495.4	842.0	1756.0	23.4	28.2	21.1	19.1	30.9	24.6
2090	2643.0	2888.7	1257.6	1342.3	740.9	2182.3	23.5	28.2	21.1	18.9	30.6	24.8
2091	3338.4	2744.5	1089.3	1240.5	693.2	1586.4	23.5	28.2	21.2	18.9	30.7	24.8
2092	3529.2	2564.6	1074.9	1579.5	594.8	1772.8	23.2	28.2	21.0	19.0	30.5	24.5
2093	3914.6	2800.5	1074.1	1383.1	866.8	1805.4	23.8	28.4	21.3	19.1	30.9	24.9
2094	3290.4	3187.8	1018.5	1342.0	702.6	1844.2	23.4	28.1	21.1	18.9	30.6	24.6
2095	3039.6	2826.4	1086.6	1175.0	739.1	2129.6	23.4	28.2	21.1	19.0	30.7	24.7
2096	3230.7	2364.6	1276.1	1247.3	596.7	1683.5	23.5	28.1	21.2	18.8	30.7	24.7
2097	3097.9	2702.6	1049.0	1533.9	838.1	2203.5	23.6	28.2	21.2	19.0	30.8	24.9
2098	3347.1	3086.0	1248.3	1377.3	745.0	2962.7	23.6	28.3	21.3	19.1	30.8	24.8
2099	3800.1	3211.5	1082.0	1166.5	785.8	2232.1	23.3	28.2	21.1	19.0	30.7	24.5
2100	4033.5	3141.8	1327.7	1205.8	853.7	2338.0	23.4	28.3	21.2	19.1	31.0	24.6

References

Alemayehu, T. (2006). Groundwater occurrence in Ethiopia. Addis Ababa University, Ethiopia, 107

A. Davidson (et al), (1983) "Reconnaissance Geology and Geochemistry of Parts of Ilubabor, Kefa, Gemu Gofa and Sidamo, Ethiopia" Page: 63-79

Abbaspour, K. C., Yang, J., Maximov, I., Siber, R., Bogner, K., Mieleitner, J., & Zobrist, J. (2004). Modelling hydrology and water quality in the pre-alpine/alpine Thur watershed using SWAT. Journal of Hydrology, 291(1-2), 1-23.

Abbaspour, K.C., Rouholahnejad, E., Vaghefi, S., Srinivasan, R., Yang, H., Klove, B., and Decrem, Y., 2015. A continental-scale hydrology and water quality model for Europe: Calibration and uncertainty of a high-resolution large-scale SWAT model. Journal of Hydrology, 524, pp.733-752.

Aguilera H, Murillo J (2009) The effect of possible climate change on natural groundwater recharge based on a simple model: a study of four karstic aquifers in SE Spain. Environ Geol 57(5): 963–974

Allen DM, Cannon AJ, Toews MW, Scibek J (2010) Variabiltiy in simulated recharge using different GCMs. Water Resour Res 46:W00F03. doi:10.1029/2009WR008932

Allen DM, Mackie DC, Wei M (2004) Groundwater and climate change: a sensitivity analysis forthe Grand Forks aquifer, southern British Columbia, Canada. Hydrogeol J 12(3):270–290

Allen, R. G., Pereira, L. S., Raes, D., & Smith, M. (1998). Crop Evapotranspiration: Guidelines for Computing Crop Water Requirements. Food and Agriculture Organization of the United Nations.

Allen, R. G., Pereira, L. S., Raes, D., & Smith, M. (2020). Crop Evapotranspiration: Guidelines for Computing Crop Water Requirements. Food and Agriculture Organization of the United Nations.

Alley WM (1993) Regional ground-water quality. Wiley, New York, 634 pp. ISBN: 978-0-471-28453-6

Alley WM (2001) Ground water and climate. Ground Water 39(2):161

Alley WM (2006) Tracking U.S. groundwater reserves for the future? Environment 48(3):10–25

Alley WM, Healy RW, LaBaugh JW, Reilly TE (2002) Flow and storage in groundwater systems. Science 296:1985–1990

Alley WM, Reilly TE, Franke OL (1999) Sustainability of ground-water resources, U.S. geological survey circular 1186. U.S. Geological Survey, Denver, 79 pp

Anderson M, Kustas W (2008) Thermal remote sensing of drought and evapotranspiration.Eos 89(26):233–234

Arnold, J. G., Srinivasan, R., Muttiah, R. S., & Williams, J. R. (1998). Large area hydrologic modeling and assessment part I: model development 1. JAWRA Journal of the American Water Resources Association, 34(1), 73-89

Arnold, J.G., Moriasi, D.N., Gassman, P.W., Abbaspour, K.C., White, M.J., Srinivasan, R., Santhi, C., Harmel, R.D., van Griensven, A., Van Liew, M.W. and Kannan, N., 2012. SWAT: Model use, calibration, and validation. Transactions of the ASABE, 55(4), pp.1491-1508.

Arrueta, L., Jackson-Smith, D., & Kalcic, M. (2022). Simulating behavioral heterogeneity in watershed models: A systematic review of fertilizer use in SWAT studies. Journal of Soil and Water Conservation, 77(3), 249-260.

Aureli A, Taniguchi M (2006) Groundwater assessment under the pressures of humanity and climate changes – GRAPHIC. United Nations Educational Scientific and Cultural Organization, Paris

Ballentine TM, Stakhiv EZ (eds) (1993) Climate change and water resources management. In:Proceedings of the national conference on climate change and water resources management

C. W. (2001). Applied Hydrogeology (4th ed.). Prentice Hal

Carlson, M. A., Lohse, K. A., McIntosh, J. C., & McLain, J. E. (2011). Impacts of urbanization on groundwater quality and recharge in a semi-arid alluvial basin. Journal of hydrology, 409(1-2), 196-211.

Carr, C. J., & Carr, C. J. (2017). Turkana survival systems at lake turkana: vulnerability to collapse from omo basin development. River Basin Development and Human Rights in Eastern Africa—A Policy Crossroads, 157-189.

Chaemiso, T. D., Melesse, A. M., & Ayele, G. T. (2016). Hydrological modeling of the Borkena watershed in the Eastern Nile Basin, Ethiopia using the Soil and Water Assessment Tool (SWAT) model. *Catena*, 136, 13-23.

Chow, V. T., Maidment, D. R., & Mays, L. W. (2019). Applied Hydrology. McGraw-Hill Education.

Claudia J. Carr (2017) River Basin Development and Human Rights in Eastern Africa — A Policy Crossroads

Environment and Climate Change Canada/Environnement et Changement Climatique Canada. (November, 2021). CMIP6 ensemble of daily predictor variables (Version 1) [Dataset]. Canadian Climate Data and Scenarios. https://climate-scenarios.canada.ca/?page=pred-cmip6

Essenfelder, A. H. (2016). SWAT Weather Database: A Quick Guide. Version: v.0.16.07. doi: 10.13140/RG.2.1.4329.1927

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Freeze, R. A., & Cherry, J. A. (1979). Groundwater. Prentice-Hall.

Gassman, P. W., Reyes, M. R., Green, C. H., & Arnold, J. G. (2007). The Soil and Water Assessment Tool: Historical development, applications, and future research directions. *Transactions of the ASABE*, 50(4), 1211-1250.

IPCC. (2021). Climate Change 2021: The Physical Science Basis. Contribution of Working Group I to the Sixth Assessment Report of the Intergovernmental Panel on Climate Change [Masson-Delmotte, V., P. Zhai, A. Pirani, S. L. Connors, C. Péan, S. Berger, N. Caud, Y. Chen, L. Goldfarb, M. I. Gomis, M. Huang, K. Leitzell, E. Lonnoy, J.B.R. Matthews, T. K. Maycock, T. Waterfield, O. Yelekçi, R. Yu, and B. Zhou (eds.)]. Cambridge University Press. https://www.ipcc.ch/report/ar6/wg1/

Jones, B., Smith, C., & Johnson, D. (2019). Global Climate Models. Cambridge University Press.

Kebede, S., & Taye, M. T. (2021). Groundwater scarcity and management in the arid areas in East Africa. In Global Groundwater (pp. 177-186). Elsevier.

Kløve, B., Ala-Aho, P., Bertrand, G., Gurdak, J. J., Kupfersberger, H., Kværner, J., Muotka, T., Mykrä, H., Preda, E., & Rossi, P. (2014). Climate change impacts on groundwater and dependent ecosystems. Journal of hydrology, 518, 250-266.

Kumar, C. (2012). Climate change and its impact on groundwater resources. International Journal of Engineering and Science, 1(5), 43-60.

KUMAR, C. P. (2014). Impact of Climate Change on Groundwater Resources.

Li, Z., Wu, J., & Hu, Y. (2019). Estimating groundwater recharge in a large-scale watershed using SWAT. Water, 11(7), 1356.

Maraun, D., Widmann, M., Gutierrez, J. M., Kotlarski, S., Chandler, R. E., Hertig, E., ... & Wilcke, R. A. (2010). Precipitation downscaling under climate change: recent developments to bridge the gap between dynamical models and the end user. Reviews of Geophysics, 48(3).

Milly, P. C. D., Betancourt, J., Falkenmark, M., Hirsch, R. M., Kundzewicz, Z. W., Lettenmaier, D. P., & Stouffer, R. J. (2008). Stationarity is Dead: Whither Water Management? Science, 319(5863), 573-574.

Mishra, V., Shah, R. D., & Pandey, A. (2016). Assessment of groundwater recharge using SWAT model in a semi-arid region of India. Journal of Hydrology: Regional Studies, 5, 50-67.

Moss, R. H., Edmonds, J. A., Hibbard, K. A., Manning, M. R., Rose, S. K., van Vuuren, D. P., ... & Wilbanks, T. J. (2010). The next generation of scenarios for climate change research and assessment. Nature, 463(7282), 747-756.

Moriasi, D. N., Arnold, J. G., Van Liew, M. W., Bingner, R. L., Harmel, R. D., & Veith, T. L. (2007). Model evaluation guidelines for systematic quantification of accuracy in watershed simulations. Transactions of the ASABE, 50(3), 885-900.

Munday, P. L., Donelson, J. M., & Domingos, J. A. (2017). Potential for adaptation to climate change in a coral reef fish. Global change biology, 23(1), 307-317.

NASA. (n.d.). What's the Difference Between Weather and Climate? NASA Climate Kids. Retrieved September 2021, from https://climatekids.nasa.gov/weather-climate/

Neitsch, S. L., Arnold, J. G., Kiniry, J. R., & Williams, J. R. (2005). Soil and Water Assessment Tool (SWAT): Theoretical documentation (Vol. 406). Texas Water Resources Institute.

Neitsch, S.L., Arnold, J.G., Kiniry, J.R., Williams, J.R. and King, K.W., 2011. Soil and Water Assessment Tool theoretical documentation version 2009. Texas Water Resources Institute Technical Report No. 406. Texas Water Resources Institute, College Station, Texas, USA.

Oliveira, P. T. S., Leite, M. B., Mattos, T., Nearing, M. A., Scott, R. L., de Oliveira Xavier, R., da Silva Matos, D. M., & Wendland, E. (2017). Groundwater recharge decrease with increased vegetation density in the Brazilian cerrado. Ecohydrology, 10(1), e1759.

Olivera, F., Valenzuela, C. R., Srinivasan, R., Choi, J., Cho, H., Koka, S., & Agrawal, A. (2006). ArcGIS-SWAT: A geodata model and GIS interface for SWAT. *Journal of the American Water Resources Association*, 42(2), 295-309.

Parajuli, P. B., Zhang, Y. K., & Katuwal, H. B. (2010). Sensitivity analysis of SWAT model for estimating groundwater recharge in agricultural watersheds. Agricultural Water Management, 97(10), 1517-1526.

Paré Guy, Trudel Marie-Claude, Jaana Mirou, Kitsiou Spyros. 2015. "Synthesizing Information Systems Knowledge: A Typology of Literature Reviews." Information & Management 52:183–99. Crossref.

Paris Agreement. (2015). United Nations Treaty Collection. Retrieved September 2021, from https://treaties.un.org/pages/ViewDetails.aspx?src=TREATY&mtdsg_no=XXVII-7-d&chapter=27&clang=_en

Regassa, H., Ture, K., Elias, E., & Abiko, F. (2022). The Impact of Rainfall Variability and Crop Production on Vertisols in the Central Highlands of Ethiopia.

Russo, T. A., Lópes, D. M., & Ribeiro, L. (2018). Groundwater Recharge and Wells: A Guide to Aquifer Storage Recovery. CRC Press.

Scanlon, B. R., Keese, K. E., Flint, A. L., Flint, L. E., Gaye, C. B., Edmunds, W. M., & Simmers, I. (2006). Global synthesis of groundwater recharge in semiarid and arid regions. Hydrological Processes: An International Journal, 20(15), 3335-3370.

Scanlon, B. R., Healy, R. W., & Cook, P. G. (2002). Choosing appropriate techniques for quantifying groundwater recharge. Hydrogeology journal, 10(1), 18-39.

Shamir, E., Megdal, S. B., Carrillo, C., Castro, C. L., Chang, H.-I., Chief, K., Corkhill, F. E., Eden, S., Georgakakos, K. P., & Nelson, K. M. (2015). Climate change and water resources management in the Upper Santa Cruz River, Arizona. Journal of hydrology, 521, 18-33.

Shiaeles, S., Kolokotronis, N., & Bellini, E. (2019). IoT vulnerability data crawling and analysis. 2019 IEEE World Congress on Services (SERVICES),

Shiferaw E. et al (2023) Modelling the impact of hydrological parameter effect on streamflow due to futuristic climate change scenarios in the South Omo-Gibe River basin, Ethiopia

Smith, A. B., et al. (2009). Statistical downscaling and climate change information. In Climate Change in the Midwest: Impacts, Risks, Vulnerability, and Adaptation (pp. 131-148). Indiana University Press.

Smith, R. K., Schultz, D. M., & Freidenreich, S. M. (2018). Climate Modeling: Advances in Models, Climate Dynamics, and Predictability. Springer.

Taylor, K. E., et al. (2012). Overview of CMIP5 and the experiment design. Bulletin of the American Meteorological Society, 93(4), 485-498.

Taylor, K. E., Stouffer, R. J., & Meehl, G. A. (2020). An Overview of CMIP5 and the Experiment Design. Bulletin of the American Meteorological Society, 93(4), 485-498.

Todd, D. K. (1980). Groundwater Hydrology (2nd ed.). John Wiley & Sons.

UNFCCC. (2015). Paris Agreement. Retrieved, from https://unfccc.int/sites/default/files/english_paris_agreement.pdf

United Nations Framework Convention on Climate Change (UNFCCC). (2015). The Paris Agreement. Retrieved from https://unfccc.int/process-and-meetings/the-paris-agreement

United Nations. (2019). World Population Prospects 2019: Highlights (ST/ESA/SER.A/423). United Nations Department of Economic and Social Affairs, Population Division.

Wilby, R. L., & Dawson, C. W. (2013). The Statistical Downscaling Model: Insights from One Dimensional Regression. Hydrological Sciences Journal, 49(6), 1049-1059.

Wu, Y., Zhang, T., Wang, L., & Li, L. (2019). Calibrating the SWAT model for groundwater recharge estimation in an agricultural watershed. Water, 11(5), 990.

Zhang, Y., Liu, S., Zhang, Q., & Cheng, G. (2016). Calibration of the SWAT model for streamflow and groundwater level in a large irrigation district on the North China Plain. Hydrology Research, 47(2), 392-408.

Zhang, Y., Liu, S., Zhang, Q., & Cheng, G. (2018). Estimation of groundwater recharge in a large-scale basin using SWAT model coupled with a groundwater model. Water, 10(11), 1640.