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Exploring projected groundwater sustainable yield across African countries with implications for green hydrogen production.

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DEDICATION

I dedicate this humble work to:

- My late father, Djiba KONATE,
- My late mother, Fanta CONDE,

May God have mercy on their souls.

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ABSTRACT:

Africa's abundant renewable energy resources position it to play a crucial role in achieving carbon neutrality and meeting climate targets. Green hydrogen, in particular, holds promise for clean energy generation, transportation, and storage. To make green hydrogen production successful, understanding water resource availability, including future projections, is vital.

Our study focuses on assessing groundwater resources across diverse African countries and their relevance to green hydrogen production. We conduct a spatio-temporal analysis, considering groundwater recharge, human water use, the HWU/GWR ratio, and groundwater sustainable yield. We examine two climate scenarios (RCP 2.6 and 8.5) from 2015 to 2100 to identify trends in groundwater recharge and water use in fifty-one African nations.

Our methodology combines water balance assessments and statistical analysis. We utilize meteorological data from Global Climate Models (GCMs) and Regional Climate Models (RCMs) as input for the Community Land Model (CLM) to calculate groundwater recharge. Additionally, the PCRGLOBWB global hydrological model simulates human water use.

Our findings highlight significant variations in groundwater recharge and the HWU/GWR ratio across regions. Some areas, such as West Africa (coastal regions), Central Africa (near the equator), and Southern Africa, demonstrate substantial potential for long-term green hydrogen production due to promising sustainable groundwater yields. However, regions like the Sahara zone, encompassing Mali and Niger, do not exhibit significant sustainable groundwater recharge yields for green hydrogen.

Climate change impacts are noticeable in the trends, especially in Northern Africa, where groundwater recharge is decreasing. These insights emphasize the dynamic nature of groundwater resources and their critical role in sustainable water management and the advancement of green hydrogen initiatives in Africa.

Keywords: groundwater, human water use, sustainable yield, green hydrogen, climate change, Africa.

RESUME :

Les abondantes ressources en énergie renouvelable de l'Afrique la positionnent pour jouer un rôle crucial dans la réalisation de la neutralité carbone et l'atteinte des objectifs climatiques. L'hydrogène vert, en particulier, offre des promesses en matière de production d'énergie propre, de transport et de stockage. Pour rendre la production d'hydrogène vert réussie, il est essentiel de comprendre la disponibilité des ressources en eau, y compris les projections futures.

Notre étude se concentre sur l'évaluation des ressources en eau souterraine dans divers pays africains et leur pertinence pour la production d'hydrogène vert. Nous menons une analyse spatio-temporelle en tenant compte de la recharge des eaux souterraines, de l'utilisation humaine de l'eau, du rapport UHE/GWE (utilisation humaine de l'eau/recharge des eaux souterraines) et du rendement durable des eaux souterraines. Nous examinons deux scénarios climatiques (RCP 2.6 et 8.5) de 2015 à 2100 pour identifier les tendances de la recharge des eaux souterraines et de l'utilisation de l'eau dans cinquante et un pays africains.

Notre méthodologie combine des évaluations du bilan hydrique et une analyse statistique. Nous utilisons des données météorologiques issues des modèles climatiques mondiaux (MCM) et des modèles climatiques régionaux (MCR) en tant qu'entrées pour le Modèle de Terre Communautaire (CLM) afin de calculer la recharge des eaux souterraines. De plus, le modèle hydrologique global PCRGLOBWB simule l'utilisation humaine de l'eau.

Nos résultats mettent en évidence des variations significatives de la recharge des eaux souterraines et du rapport UHE/GWE selon les régions. Certaines zones, telles que l'Afrique de l'Ouest (régions côtières), l'Afrique centrale (près de l'équateur) et l'Afrique australe, présentent un potentiel substantiel pour la production à long terme d'hydrogène vert en raison de rendements durables prometteurs des eaux souterraines. Cependant, des régions comme la zone du Sahara, englobant le Mali et le Niger, n'affichent pas de rendements significatifs de recharge des eaux souterraines durables pour l'hydrogène vert.

Les impacts du changement climatique sont perceptibles dans les tendances, notamment dans le Nord de l'Afrique, où la recharge des eaux souterraines diminue. Ces constatations soulignent la nature dynamique des ressources en eau souterraine et leur rôle crucial dans la gestion durable de l'eau et la promotion des initiatives d'hydrogène vert en Afrique.

Mots-clés : eau souterraine, utilisation humaine de l'eau, rendement durable, hydrogène vert, changement climatique, Afrique.

ACRONYMS AND ABBREVIATION

BMBF: German Federal Ministry of Education and Research

CLM: Community Land Model

EU: European Union

GCMs: General Circulation Models

GHG: Global Greenhouse Gas

GIS: Geographic Information System

GWR: Groundwater Recharge

HWU: Human Water Use

IBG-3: Institute of Biology and Geosciences

IMP-EGH: International Master Programme in Energy and Green Hydrogen Production

IPCC: Intergovernmental Panel on Climate Change.

MPI: Max Planck Institute

NOR-ESM: Norwegian Earth System Model

OECD: Organisation for Economic Co-operation and Development

PCRGLOBWB: global hydrological model

PEM: Proton Exchange Membrane

PV: Photovoltaic

RCMs: Regional Climate Models

RCP: Representative Concentration Pathways

SOE: Solid Oxide Electrolysers

SWAT+: Soil Water Assessment Tool Plus

SY: sustainable groundwater yield

UFHB: Université Felix Houphouet Boigny

UN: United Nation

UNEP: United Nation Environment Programme

WASCAL: West African Science Service Centre for Climate Change and Adapted Land Use

WCRP: The World Climate Research Programme

LIST OF TABLE

LIST OF FIGURES

TABLE OF CONTENTS

Contents

GENERAL INTRODUCTION:

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In recent years, the global community has become increasingly concerned about the urgent need to mitigate greenhouse gas emissions and combat climate change. The Paris Agreement and more recently COP26 have set ambitious targets to limit global warming below 2°C to avoid catastrophic consequences for our planet (IPCC, 2022). The energy sector is a significant contributor to global greenhouse gas (GHG) emissions, responsible for a substantial portion of the world's total emissions. As stated by climate scientists worldwide, approximately 76% of global greenhouse gas emissions, which are primarily attributed to energy-related CO_2 emissions, pose a significant threat to Earth's sustainability and the well-being of humanity (AbouSeada and Hatem, 2022).

The African continent, however, though currently responsible for only about 3% of global greenhouse gas emissions due to low economic activity, heavily relies on traditional biomass for its energy needs (Yohannes *et al.*, 2022). Africa's future growth trajectory, with a predicted population of 2.5 billion by 2050 and an annual economic growth rate of 2.2% to 3.1%, is likely to increase the continent's energy consumption and emissions substantially (Wijayantha et al., 2020). Estimates suggest that by 2050, Africa's emissions could contribute between 5% and 20% of the global total (Seada and Hatem, 2022).

To support this rapid growth while curbing emissions, there is a pressing need to find sustainable energy solutions. Therefore, as a key solution to reduce emissions, renewable energy resources have garnered significant attention. Hence, Africa aims to become a global powerhouse and recognizes the importance of transitioning to green energy, as outlined in Agenda 2063 of the African Union (Bhandari, 2022). To facilitate this vision, Germany plans to invest two billion Euros in green hydrogen projects outside its borders (FMEAE, 2020). This support makes hydrogen emerge as a promising candidate for decarbonizing Africa's energy sector.

In order to enable a green hydrogen economy, it is essential to produce hydrogen through electrolysis by splitting water into hydrogen-powered by renewable electricity (Yohannes *et al.*, 2022). This "green hydrogen" can serve as a long-term storage medium, fuel for transportation, and an energy vector for various applications. Therefore, the production of green hydrogen requires careful consideration of water consumption and available water resources. Thus, for hydrogen generation, water is the one of main element since we try to convert water to hydrogen. Therefore, water will be consumed directly. For example, the amount of water which is required for green hydrogen production is about 9000 kg water per

1000 kg of hydrogen (Wijayantha et al., 2020).

Africa possesses vast renewable energy resources, including water, solar, and wind power, offering the potential for large-scale green hydrogen production (Kakoulaki et al., 2021). Harnessing this potential can not only help Africa decarbonize its own energy consumption but also position the continent as a major hub for global green hydrogen production, exporting clean energy to both regional and international markets (Delloh et al., 2022). While green hydrogen presents a significant opportunity for Africa's sustainable development, its successful implementation requires addressing certain challenges.

One crucial aspect is the sustainable management of water resources, particularly groundwater, which serves as a vital source of freshwater for various purposes. Groundwater provides a distributed, low-cost, and climate-resilient source of freshwater, making it an essential resource for addressing water stress and supporting development agendas (MacDonald et al., 2021a). Furthermore, Groundwater is the Earth's largest reservoir of fresh water, accounting for nearly 70 times more water than is present as surface water, and it accounts for approximately 20% of total water use worldwide.

Furthermore, significant groundwater resources are known to exist in Africa (MacDonald *et al.*, 2012), only 1% of the cultivated land of Africa is estimated to be irrigated by groundwater (Siebert *et al.* 2010), 80% of this occurs in North Africa. In contrast, water scarcity assessments rely on renewable freshwater resources, such as river discharge and estimated groundwater recharge, which only amount to around 0.004 million km^3 ("Africa water atlas," 2010; Siebert et al., 2013) . This significant difference highlights the immense potential of groundwater as a crucial water supply for various human needs and economic activities in Africa. Hence, especially groundwater is considered as a one of the key elements for green hydrogen production in African.

However, climate change is expected to have considerable impacts on groundwater resources, making it imperative to understand the relationship between climate variability and groundwater level fluctuations in the African context (Taylor et al., 2019). Moreover, groundwater is essential for sustaining human life in many parts of Africa, especially where surface water is scarce or contaminated. As the demand for freshwater increases due to population growth and development, groundwater's role becomes even more critical (Bonsor et al., 2018).

Thus, to ensure the long-term viability of green hydrogen production in Africa, it is essential to assess and understand the potential impacts of climate change and population growth on groundwater resources. Therefore, quantifying groundwater recharge, detecting trends in groundwater recharge, evaluating water availability, and considering the implications for green hydrogen production is critical for making informed decisions on sustainable water management practices and green hydrogen production. Accurately quantifying groundwater recharge poses challenges due to the complex interplay of factors such as rainfall distribution, percolation capacity, underlying geologic structures, drainage density, topography, and land use patterns (MacDonald et al., 2021a; Singh et al., 2019). Thus, previous studies have focused on estimating groundwater recharge in African countries, such as MacDonald et al. (2009), investigating the impact of climate change on rural groundwater supply in Africa by combining groundwater modelling and spatial distribution. Chuin (2012) conducted a study on climate change projections by considering factors such as land use changes, population growth, and socio-economic developments, which can influence water demand and usage patterns. Furthermore, Ayano et al. (2021) investigated the spatial and temporal distribution of groundwater recharge using a physically distributed hydrological model, highlighting the significant variation of recharge and its sensitivity to factors such as average rainfall intensity. The H2ATLAS project (https://www.h2atlas.de/de/ueber-uns), for example, focuses on assessing groundwater availability and accessibility at the continental and regional levels in Africa, providing valuable insights into estimating recharge in different regions. But very unfortunately they did not provide the projected groundwater sustainable yield in term of green hydrogen production in African countries. This is what makes the difference and the originality of our study on estimating groundwater recharge in African countries.

This study is part of a larger effort to make available detailed on exploring the projected groundwater sustainable yield for future green hydrogen production in African countries. By studying groundwater sustainability and recharge under various climate scenarios, policymakers, investors, and stakeholders can develop strategies for green hydrogen initiatives that align with sustainable water use. These efforts aim to assess water security, predict future changes, and inform policy decisions (MacDonald et al., 2021a). This study aims to delve into the projected groundwater sustainable yield and its trends across African countries and discuss its implications for green hydrogen production. By analysing groundwater recharge trends from 2015 to 2100 and considering the impact of projected human water use under Representative Concentration Pathways (RCP) 2.6 and 8.5 climate scenarios, the research aims to shed light on the sustainability of groundwater resources for green hydrogen initiatives. Specifically, we aim to: (1) understand the trend of projected groundwater recharge and human water use in Africa considering two climate change scenarios (RCP 2.6 and 8.5); and (2) explore the sustainability of groundwater use in Africa by considering the Ratio between HWU and GWR, in Africa under scenarios RCP 2.6 and 8.5. To achieve this, we performed statistical analysis of GWR which is calculated by the land surface model CLM5. This input comes from the CORDEX project's GCMs and RCMs data, as well as from the global hydrological model PCRaster Global (PCRGLOBWB), for use in CLM. This study contributes to improve our understanding of the relationship between climate dynamics, groundwater resources, and the potential for sustainable green hydrogen production. Through a comprehensive literature review and the use of appropriate methodologies, the research contributes valuable knowledge to support the development of green hydrogen projects in Africa. Understanding the relationship between climate dynamics, groundwater resources, and green hydrogen production potential will play a vital role in achieving sustainable and climate-resilient energy solutions for the continent.

As we strive to combat global warming, promote clean energy, and achieve the United Nations Sustainable Development Goals, this study's findings will offer critical insights and help guide the path toward a greener, more sustainable future for Africa and the world at large.

The structure of this study is as follows: Chapter 1 offers the concept of groundwater and previous work, which covers the various studies carried out. Chapter 2 shows the materials and methods. Chapter 3 describes and discusses the results of the study. Finally, limitations and future work are stated.

CHAPTER 1:

CONCEPT OF GROUNDWATER AND PREVIOUS STUDIES

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Introduction

This chapter presents the concept of groundwater recharge, climate change projections and the previous studies related of this study.

1.1. Climate change projections

In the context of exploring projected groundwater sustainable yield across African countries and its implications for green hydrogen production, it is essential to consider the anticipated climate change projections for the region. Scientific studies and climate models provide valuable insights into the potential climate scenarios that Africa may experience in the coming decades (Hagemann et al., 2013; Taylor et al., 2013; Kusangaya et al., 2014; Bonsor et al., 2018). Climate projections are based on a range of greenhouse gas emission scenarios, such as the RCPs, which outline plausible future trajectories of greenhouse gas concentrations in the atmosphere. According to these projections, Africa is expected to face changes in precipitation patterns, temperature regimes, and overall hydrological dynamics (Cook et al., 2022). The temperature increases in the region are projected to be higher than the global mean temperature increase; regions in Africa within 15 degrees of the equator are projected to experience an increase in hot nights as well as longer and more frequent heat waves (Doblas-Reyes et al., 2021). West and Central Africa will see particularly large increases in the number of hot days at both 1.5° C and 2° C. Over Southern Africa, temperatures are expected to rise faster at 2° C, and areas of the southwestern region, especially in South Africa and parts of Namibia and Botswana, are expected to experience the greatest increases in temperature (UN, 2022). It is anticipated that rainfall distribution may shift, resulting in altered seasonal patterns, changes in the intensity and frequency of extreme weather events, and potential shifts in regional climate zones (Chang, 2017). A warming world will have implications for precipitation. At 1.5° C, less rain would fall over the Limpopo basin and areas of the Zambezi basin in Zambia, as well as parts of Western Cape in South Africa. But at 2° C, Southern Africa is projected to face a decrease in precipitation of about 20% and increases in the number of consecutive dry days in Namibia, Botswana, northern Zimbabwe and southern Zambia. This will cause reductions in the volume of the Zambezi basin projected at 5% to 10% (IPCC, 2022). These climate projections can significantly impact groundwater recharge rates, water availability, and water demand across African countries (Macdonald et al., 2009). Increased temperatures associated with climate change may increase evapotranspiration rates, potentially leading to higher water loss from vegetation and soils (Arnell and Gosling, 2013). This, in turn, could influence the overall water balance and groundwater recharge processes. Additionally, changes in precipitation patterns may affect the timing and amount of water inputs, further impacting groundwater replenishment and recharge rates (Cook et al., 2022). Moreover, climate change projections also consider factors such as land use changes, population growth, and socio-economic developments, which can influence water demand and usage patterns (Chuin, 2012). These factors, combined with the expected changes in climate, can present both challenges and opportunities for sustainable groundwater management and green hydrogen production.

Understanding the specific climate change projections for African countries is crucial for effective water resources planning, adaptation strategies, and the development of sustainable water management practices. By considering these projections, policymakers, water resource managers, and stakeholders can better anticipate future water availability, plan for potential water scarcity or excess, and make informed decisions regarding the feasibility and sustainability of green hydrogen production using groundwater resources. Simulation models incorporating future projections of hydrological variables, such as GCMs, RCMs, and hydrological models, aid in future planning and management strategies to address growing water demand and scarcity.

1.1.1. GCMs and RCMs

Hydrological models simulate climate change effects on water cycles and future hydrological patterns using input from global climate models (GCMs), which capture broad climate processes at a coarse scale (~110-280 km grid resolution) (Teutschbein, 2013). This study employed GCM and RCM to quantify future climate projections, facilitating the investigation of climate impacts through hydrological models reliant on climate forcing (Hagemann et al., 2013). General circulation models (GCM) and Regional Climate Models (RCM) are climate models that are frequently used for future climate projections (Demory et al., 2020). GCMs are physically based models that account for interactions at the global scale between numerous elements of the Earth system (atmosphere, ocean, sea ice, vegetation). GCMs usually simulate the earth at spatial resolutions of about 50km to 100km resolution. RCMs dynamically reduce the output of GCMs to produce higher spatial resolution climate data for a specific area. They are also known for their ability to describe small-scale physical activities in the convection permitting zone (Taylor et al., 2013)**.**

1.1.2. Climate scenarios

Climate scenarios are hypothetical representations of future climatic conditions based on greenhouse gas (GHG) emissions, used to assess vulnerability to climate change (Tramberend et al., 2021)**.** These hypothetical representations are captured in different setups designed to represent a range of possible emissions trajectories and corresponding radiative forcing levels called RCP. Four main RCPs exist specifying particular radiative forcing levels by the year 2100 (Akinsanola et al., 2015). Noteworthy are the implications of the RCPs on temperature. The projected global mean surface temperature change ranges from 0.3°C to 0.7°C for the period 2016-2035, and by the end of the 21st century, it is likely to hit 1.7°C for RCP2.6, 2.6ºC for RCP 4.5, 3.1ºC for RCP 6.0, and 4.8ºC for RCP 8.5 compared to the historical industrial period(Table1). This study utilizes RCP 2.6 and RCP 8.5, representing optimistic and pessimistic emission scenarios, respectively.

Table 1:Representative Concentration Pathways

RCP	**Temperature Change (°C) 2016-2035**	**Temperature Change (°C) by end of 21st century**
RCP2.6	0.3°C to 0.7°C	1.7°C
RCP4.5	-	1.5°C to 2.6°C
RCP6.0	-	3.1°C
RCP8.5	-	4.8°C

1.2. Projected human water use

Projected human water use refers to the estimated amount of freshwater that will be used by humans in the future. The projections of water demand, specifically groundwater, are based on various factors such as population growth, climate change, development, and agricultural practices (UN, 2017). The projections suggest that global water use is likely to increase by 20 to 50 percent above current levels by 2050, with industrial and domestic sectors growing at the fastest pace (NIC, 2021). Currently, the population of Africa is estimated to be growing at 2.6%, the fastest in the world (UN, 2017). By 2050, the population is projected to more than double from its current 1.25 billion to 2.53 billion (UN, 2017), with 28 African countries projected to more than double their populations (UN, 2016). Moreover, by 2100, ten countries are expected to at least quintuple their populations (UNFPA, 2009). These increases are expected to be exacerbated by rapid urbanization. Population growth is causing a widening gap between water availability and water demand (Güneralp et al., 2017)**.** It is anticipated that there will be a substantial increase in demand for groundwater to boost agricultural output (Macdonald et al., 2009). The Green Revolution is seen as a central tenet of the poverty alleviation strategies in many African countries (MacDonald et al., 2013). At present, 1% of cultivated land in Africa is irrigated by groundwater (Siebert et al., 2013), leaving significant scope for expansion. The increasing demand for groundwater will have significant implications for water security, socio-economic development, and environmental sustainability. The projections highlight the need for effective water management strategies, including water conservation, water reuse, and sustainable water use practices, to ensure the availability of groundwater resources for future generations and green hydrogen production.

1.2.1. Human water use scenarios

In the context of this study, human water use scenarios encompass a comprehensive array of human activities with direct implications for groundwater resources. These scenarios encompass essential factors, including irrigation, domestic, livestock, and industrial water utilization, collectively shaping the intricate relationship between human actions and groundwater dynamics. Approximately 75% of Africa's groundwater is utilized for irrigation, while around 20% is dedicated to domestic water use, as reported by Altchenko *et al.* (2011). Notably, about 75% of the continent's population, particularly in arid and semi-arid regions, relies on groundwater as their drinking water source according to UNECA (2000). Additionally, adequate access to groundwater for livestock watering and small-scale and commercial irrigation represents an important measure of poverty and livelihood potential (Altchenko *et al.*, 2011). Anticipated factors such as rapid population growth and projected climate change are expected to escalate water demand across sectors in Africa. Additionally, groundwater is being incorporated into traditional water usage sectors like agriculture, municipalities, and industries to facilitate green energy production.

1.3. Groundwater recharge Estimation

Estimating available groundwater recharge is a crucial part of managing groundwater resources. There are various techniques for calculating groundwater recharge, with different degrees of complexity. The following is one of the techniques for calculating groundwater recharge:

1.3.1. Water Balance analysis

The water balance approach is vital for calculating groundwater recharge as it systematically tracks water inputs and outputs in a specific area over time, considering factors like precipitation, evaporation, and runoff (Weatherl et al., 2021). By quantifying infiltrated water, it helps comprehend groundwater replenishment, considering complex factors such as climate, geology, and hydrology (Lee et al., 2006). This approach is crucial for sustainable water management and understanding the impact of changes like land use and climate variations (Larbi et al., 2020). Since the water balance serves as the foundation for understanding the processes that affect recharge, comprehending it is necessary to perform any type of estimate of the recharge. See Eq. 1 below, the simplified water balance, where GWR is groundwater recharge [mm year^{-1}], P is precipitation [mm year^{-1}], Q is surface runoff [mm year^{-1}], and ET is evapotranspiration [mm year^{-1}] (Gibrilla et al., 2017; Siabi et al., 2022).

$$\mathbf{GWR = P - Q - ET} \qquad (\mathbf{1})$$

In conclusion, determining how much water recharges underground is a complicated procedure that necessitates the use of many methodologies based on the data that is available and the subsurface unique properties. The approach should be chosen based on the data's correctness and dependability as well as the requirements unique to the water resource management plan (van Rooyen et al., 2020; Addisie, 2022).

1.3.2. Concept of groundwater sustainable yield

Groundwater sustainable yield is the amount of water that may be drawn from an aquifer over an extended period without having negative environmental, economic, or social effects (Maimone, 2004). Numerical modelling techniques can be used to estimate the sustainable yield (Lin and Lin, 2019) of an aquifer, and it is crucial to make sure that the rate of usage does not exceed the rate of natural renewal to maintain the sustainability of groundwater supplies.

1.4. Previous studies

The literature review focuses on sustainable groundwater recharge estimation in African countries. Groundwater recharge assessment is pivotal for effective resource management, especially for public water supply. Factors like changing precipitation patterns, temperature shifts, coastal flooding, urbanization, and land use alterations impact future groundwater and recharge dynamics. Numerous scientists have conducted studies using different methods to estimate groundwater recharge globally, in Africa, and in specific regions and countries.

During this work we made use of certain articles, dissertations, thesis in relation to our research.

Beekman and Yongxin (2003) conducted a review of methods for estimating groundwater recharge in arid and semi-arid areas in southern Africa. Doll et al. (2008) used the WaterGAP WGHM global hydrological model to estimate large-scale average groundwater recharge. The study's findings revealed that the global groundwater recharge estimation was 12,666 km^3 per year for the climate normal period of 1961–1990, equivalent to 32% of the total renewable water resources. MacDonald et al. (2012) mapped groundwater recharge in Africa using ground-based observations, mixed linear modelling, and kriging methods. The study found a relationship between long-term average rainfall and recharge at the continental scale, with spatial dependence up to 900 km. The research highlighted the importance of factors beyond rainfall at local scales and incorporated geological characteristics to estimate groundwater recharge distribution. Ayano et al. (2021) investigated the spatial and temporal distribution of groundwater recharge using a physically distributed hydrological model, highlighting the significant variation of recharge and its sensitivity to factors such as average rainfall intensity. Pavelic *et al.* (2013) used a water balance approach to estimate groundwater recharge potential and demand for irrigation Sub-Saharan Africa. The authors suggested that, the potential may improve the livelihoods of approximately 40% of the current rural population. Kouassi et al. (2019) assessed groundwater resources in the Ivorian portion of the Niger basin to address water accessibility challenges. They used a multidisciplinary approach involving Remote Sensing, Multicriteria Analysis, and a Spatial Reference Hydrogeological Information System. Their findings reveal that the Niger basin has substantial groundwater potential, with around 59% of the total area showing good to excellent availability of groundwater. Hesham et al. (2019) estimated runoff rates, groundwater recharge volumes, catchment delineation, and streamlines in the Ras Gharib area in Egypt using the Service curve number soil conservation method is a soil conservation technique used to estimate direct runoff and potential soil erosion in a particular area, water balance methods, and Geographic Information System (GIS) functions. Their results suggested the depth of runoff and estimated the volume of groundwater recharge. Akinsanola *et al.*, (2015); Tirogo *et al.*, (2016a); Siabi *et al.*, (2022b) have observed that six countries in West Africa, namely Benin, Burkina Faso, Ghana, Mauritania, Niger, and Nigeria, are likely to face a water crisis by 2025. Bridget et al. (2020) highlighted the importance of modelling tools in assessing groundwater recharge estimates and their application for risk assessment and management. MacDonald et al. (2009) investigated the impact of climate change on rural groundwater supply in Africa by combining groundwater modelling and spatial distribution. Their optimization approach suggested that changes in irrigation practices and reduction of leaks in irrigation and municipal distribution networks were effective mitigation measures. Nasir et al. (2021) conducted a study in the Kakia and Esamburbur sub-catchment of Narok, Kenya, to identify groundwater recharge areas and estimate groundwater recharge. They utilized geophysical surveys and the Soil Water Assessment Tool Plus (SWAT+) to estimate groundwater recharge, with a long-term average recharge rate ranging from 0 to 175 mm $year^{-1}$. Ayano et al. (2021) investigated the spatial and temporal distribution of groundwater recharge using a physically distributed hydrological model, highlighting the significant variation of recharge and its sensitivity to factors such as average rainfall intensity.

Kukuric et al. (2008) utilized terrestrial monitoring, remote sensing observations, and global hydrological modelling to estimate groundwater recharge and assess the impact of climate change and socio-economic developments on groundwater resources in Africa. Sibanda et al. (2009) compared different methods for estimating groundwater recharge in the semi-arid region of Nyamandhlovu, Zimbabwe. The authors concluded that the flow net computational and modeling methods provided better estimates for aerial recharge than the other methods. Predicting future emissions and the multitude of human factors influencing climate change is a challenging task.

Therefore, scientists employ a range of scenarios that consider various assumptions about future economic, social, technological, and environmental conditions (Chuin, 2012). Taylor et al. (2013) project that climate change will result in elevated water temperatures in shallow aquifers worldwide. Additionally, regions experiencing increased precipitation may encounter groundwater pollution, as pollutants from soils can be leached into recharge zones connected to surface water bodies. Gebremedhin et al. (2015) focused on estimating groundwater recharge and future potentials under climate change in the Werii catchment of the Tekeze river basin in Ethiopia. The authors employed statistical downscaling, a hydrological model, and a distributed spatial water balance model to compare simulation results with water resources, exploitation, and estimated annual groundwater recharge.

Olarinoye *et al.* (2020) employed satellite imagery, urban growth modelling, groundwater modelling, and hydrogeological field expeditions to estimate potential recharge and the impact of rapid urbanization and climate change on groundwater recharge in Arusha, Tanzania. Their results predicted a reduction in groundwater recharge of 30-44%, leading to lower groundwater levels up to 75 m over 2015-2050, primarily due to increased evapotranspiration and expansion of paved surfaces.

Ayodele and Munda (2019) conducted a study to produce green hydrogen from renewable energy sources in South Africa. They suggest that South Africa is an optimal land for the development and investment in green hydrogen production. Abou Seada and Hatem (2022), conducted a study on Climate action: Prospects of green hydrogen in Africa to understand the demand for electricity to promote economic growth and meet global targets for CO_2 reduction. The authors show theoretical detailed, environmental, technological, and economic assessment putting the local energy demands into consideration. Bhandari (2022) conducted a study on the potential for green hydrogen production in West Africa, specifically focusing on Niger. The aim was to assess the projected hydrogen demand in both the electricity and transportation sectors up to the year 2040. The author concludes that only a small fraction of 5% of the land area in Niger would be sufficient to generate the required electricity from solar PV to produce hydrogen.

While previous studies have explored groundwater recharge estimation in various parts of Africa, a national estimate specifically for green hydrogen production is lacking. The work in this thesis presents an opportunity to apply and assess established methods for estimating sustainable groundwater recharge in African countries for green hydrogen production. The study aims to delve into the projected groundwater sustainable yield and its trends across African countries and discuss its implications for green hydrogen production. While numerous geoscientists have conducted studies on groundwater recharge estimation in various African regions, the absence of national estimates for green hydrogen production underscores the originality of our work. This study, exploring projected groundwater sustainable yield across African countries with implications for green hydrogen production, serves as a crucial foundation for future investigations in the region. Groundwater modelling techniques offer valuable decision-making tools to project sustainable groundwater recharge for green hydrogen production in African countries.

PARTIAL CONCLUSION

Chapter 1 has laid the essential groundwork for our study. It highlighted the critical aspects of climate change projections, the use of climate models, and the importance of climate scenarios. Additionally, we emphasized the projected growth in human water demand, the methodological approach for groundwater recharge estimation, and the concept of groundwater sustainable yield. Furthermore, we acknowledged the existing body of research in this field, emphasizing the unique contribution our study aims to make. These foundational concepts provide the necessary context for our subsequent analysis of groundwater resources in Africa and their relevance to green hydrogen production.

CHAPTER 2:

MATERIALS AND METHODS

CHAPTER 2: MATERIALS AND METHODS

Introduction

This chapter presents the hydrological data collection equipment and data analysis methods aimed at exploring the potential of projected groundwater resources in various African countries and their implications for green hydrogen production.

2.1 Materials

2.1.1. Overview of Projected Atmospheric Forcing from CORDEX

The World Climate Research Programme (WCRP) is funding a project called the Coordinated Regional Climate Downscaling Experiment (CORDEX) that aims to create regional climate projections (Tangang et al., 2020). In this work, some regional climate models (RCM) namely CCLM5, REGCM4, REMO2015 (Fotso-Nguemo *et al.*, 2017) were set up at a horizontal grid resolution of 0.22° (approx. 22 km) and used to dynamically downscale GCM outputs. These RCMs were driven by two global climate models (GCMs): the Max Planck Institute Earth System Model (MPI-ESM) and the Norwegian Earth System Model (NorESM) (Dosio et al., 2015) under two different scenarios: RCP2.6 and RCP8.5, to predict natural groundwater recharge from 2006 to 2100. Three climate periods 2015-2044, 2045-2074, and 2075-2100 were the subjects of the analysis. To assess the sustainability of Africa's groundwater recharge in the context of green hydrogen, we evaluate the trend of natural groundwater recharge, the fraction of water usage, and the sustainable yield over an 86-year span.

2.1.2. Overview of Projected Human water use

The projected human water use is from the PCRaster Global Water Balance (PCRGLOBWB). PCRGLOBWB is a global hydrological model that simulates various water-related processes on a global scale (Altchenko and Villholth, 2015). The projected human water use was forced with outputs of 5 GCMs which were used in CMIP6 simulations. The five GCMs include: ISPL-ESM, MIP-ESM, MRI-ESM2, UKESM-ESM and GFDL-ESM4. See (Table 2) below for models' description, spanning the period from 2015 to 2100.

Table 2:Models used to define climate projections for sectorial water use

Acronym	**Model name**
ISPL-ESM	Institute Pierre-Simon Laplace Coupled Model version 6A, Low Resolution
MIP-ESM	Max Planck Institute for Meteorology
MRI-ESM2	Meteorological Research Institute
UKESM-ESM	United Kingdom Earth System Model
GFDL-ESM4	Geophysical Fluid Dynamics Laboratory

2.1.3. Projected Groundwater Recharge by CLM

In this work, energy, water, and carbon exchanges between the land surface and the atmosphere were simulated using the Community Land Model (CLM) version 5, a land surface model (Lawrence et al., 2019). The CLM was used over the CORDEX African domain with a resolution of 0.44° x 0.44° (approx. 50 km x 50 km). CLM has been used as a tool to simulate projected evapotranspiration (ET) and projected surface runoff. Then we calculated the projected recharge based on such CLM outputs.

2.1.4. Projected Groundwater Sustainable Yields

- **Environmental Flow Rate**

The minimal amount of water required to maintain ecosystems and their benefits is known as environmental flow, also referred to as the minimum ecological water need (Lin and Lin, 2019; Maimone, 2004; Rudestam and Langridge, 2014; Scanlon et al., 2012). Regarding how much of the overall recharge should be allocated to environmental flow, various suggestions have been offered. The conservative, optimum, and suitable scenarios recommend setting aside 90, 60, and 30% of the total recharge for environmental flow, respectively. For the purposes of this study, the optimum scenario was specifically chosen and examined.

- **Sustainability Analysis**

To evaluate the sustainability of groundwater use in Africa, the long-term average sustainable groundwater output (2015–2100) was calculated as a function of groundwater recharge, environmental flow, and total human water use. The Sustainability Performance was used to determine the groundwater sustainable yield (SY):

$$\boldsymbol{SY = R - EF - HWU} \qquad (\mathbf{2})$$

where SY is the groundwater sustainable yield [mm $year^{-1}$], R is groundwater recharge [mm $year^{-1}$], EF is environmental flow [mm $year^{-1}$], and HWU is human or sectoral water use [mm $year^{-1}$].

The maps were generated with a spatial resolution of 10 km for all variables in Eq. 2. Because the sectoral water consumption dataset was only available for 86 years (2015–2100), the calculation of the long-term average sustainable yield was also limited to that period (2006-2100).

2.2. Methods

Water balance and statistical analysis are just two of the data processing techniques covered in this section.

2.2.1. Water Balance Approach

- **Groundwater Recharge**

The CLM model has been forced by CORDEX data to estimate groundwater recharge using the water balance technique. The analysis covered the years 2006 to 2100 and incorporated key components such as precipitation, evapotranspiration, and surface runoff. By considering this time frame, the average natural groundwater recharge over the long term was determined. The water balance equation was applied to estimate groundwater recharge according Eq 1.

- **Sustainability Yield**

By calculating the long-term average groundwater recharge and human water usage, the sustainability of groundwater supplies was determined. The sustainability performance, see Eq 2 above, was used to compute groundwater sustainable yield.

2.2.2. Statistical analysis

We computed the ensemble mean of GWR and HWU using climate models sourced from CORDEX and PCRGLOBWB, respectively, for each climate scenario. This process involved assessing the average, maximum, and minimum values of GWR and HWU across three distinct climate periods: 2015-2044, 2045-2074, and 2075-2100. Additionally, we determined the ratio between HWU and GWR, offering insights into their relative proportions. Furthermore, we conducted calculations to establish the standard deviation of the ensemble mean of GWR and HWU for each climate scenario. This enabled us to evaluate the level of agreement among the various scenarios under scrutiny.

- **Average**

The average for GWR and HWU across three distinct climate periods: 2015-2044, 2045-2074, and 2075-2100 respectively is given by Eq 3:

$$\bar{\mathbf{X}} = \sum_{\mathbf{i=1}}^{\mathbf{n}} \frac{\boldsymbol{X_i}}{\mathbf{n}} \quad (3)$$

Where: X_i is the value of X and n is the number of samples

- **Standard deviation**

In sub-section , we explain the calculation and application of standard deviation (SD), a statistical measure quantifying value dispersion around the mean, denoted as σ(x). It's derived as the square root of variance (σ^2) in relation 4. In our study, we use the standard deviation as a measure of uncertainty related to inputs driving CLM5, a regional climate model. We assess uncertainty concerning aspects like Global Warming Response GWR and Heatwave Intensity HWU.

$$\boldsymbol{\sigma}(\mathbf{X}) = \sqrt{\mathbf{VAR}(\mathbf{X})} = \sqrt{\sum_{\mathbf{i=1}}^{\mathbf{n}} \frac{(\boldsymbol{X_i} - \boldsymbol{\bar{X}})^{\mathbf{2}}}{\mathbf{n}}} \quad (4)$$

2.2.3. Evaluation Parameters

Ensemble mean were calculated for both natural groundwater recharge and human water use models. This approach was undertaken to provide a more comprehensive evaluation of the outcomes derived from the global climate models and regional climate models employed in this study. To determine the expected trends in natural groundwater and human water use, these averages were then separated into three climate periods, with the average for each period being determined.

- **Determination of the HWU/GWR Ratio**

Over an 86-year period, each climate scenario was used to calculate the groundwater exploitation fraction, which is calculated see (Eq 5) as human water use divided by groundwater recharge from (2015-2100). In order to achieve a more stable estimate of groundwater recharge, averages over a longer time frame (10 years central smoothed) were calculated. This method identified countries where groundwater abstraction is greater than renewable groundwater resources and where the recharge of exploited aquifers is very poor.

$$\boldsymbol{SI} = \frac{\boldsymbol{HWU}}{\boldsymbol{GWR}} \quad (5)$$

Where SI is the sustainability index or ratio, HWU is human or sectoral water use [mm $year^{-1}$] and GWR is groundwater recharge [mm $year^{-1}$]

- **Determination of the trend line**

In order to indicate the general direction and pattern of data over time, trend lines were employed to show the slope of the GWR trend, whether it was positive or negative. For 51 African nations, this analysis was done by using the linear regression equation. The linear regression equation is represented by the formula in Eq 6. Where Y is the dependent variable, X is the independent variable, a is the slope of the regression equation, and b is the constant or intercept term.

$$\mathbf{Y = aX + b} \qquad (6)$$

- **Moving Average smoothing**

Moving Average Smoothing is a method used in time series analysis to reduce the noise and highlight underlying trends at the same time. It involves calculating the average of a fixed number of consecutive data points and placing the average in the middle time period. The order of the moving average determines how smooth the trend estimate will be. Centered moving averages are commonly used to estimate trend-cycle from seasonal data. In this study, we applied a 10-year moving average to smooth the data from 2015 to 2100. It means that each data point is the average of 10 consecutive years, and the first and last terms have equal weight in the calculation see equation 7 below.

$$\boldsymbol{X_{t,n}} = \frac{(\boldsymbol{X_t} + \boldsymbol{X_{(t-1)}} + \cdots + \boldsymbol{X_{\left(t-\left(\frac{n}{2}\right)\right)}} + \boldsymbol{X_{\left(t+\left(\frac{n}{2}\right)\right)}} + \cdots \boldsymbol{X_{(t+1)}})}{\boldsymbol{n}} \qquad (\mathbf{7})$$

Where Xt is the value of the time series at time t and n is the number of periods or years.

PARTIEL CONCLUSION

Chapter 2 establishes the methodological framework for our study on projected groundwater resources in Africa and their relevance to green hydrogen production. We employed a comprehensive approach that includes:

RCMs and GCMs: Regional climate models (RCMs) driven by global climate models (GCMs) from CORDEX were used to project groundwater recharge under diverse climate scenarios and across three critical climate periods.

Projected Human Water Use: Data from the PCRaster Global Water Balance (PCRGLOBWB) model, based on outputs from five GCMs spanning 2015 to 2100, provided insights into future human water demand's impact on groundwater resources.

Groundwater Recharge Estimation: The Community Land Model (CLM) version 5 simulated land-atmosphere interactions to calculate projected groundwater recharge.

Sustainability Assessment: We evaluated groundwater sustainability, considering environmental flow and human water use, with a focus on the optimum scenario.

Statistical Analysis: Statistical analyses, including ensemble means, standard deviations, and ratios, were conducted to assess trends and uncertainties in the data. This methodological foundation sets the stage for our subsequent analysis of African groundwater resources and their implications for green hydrogen production.

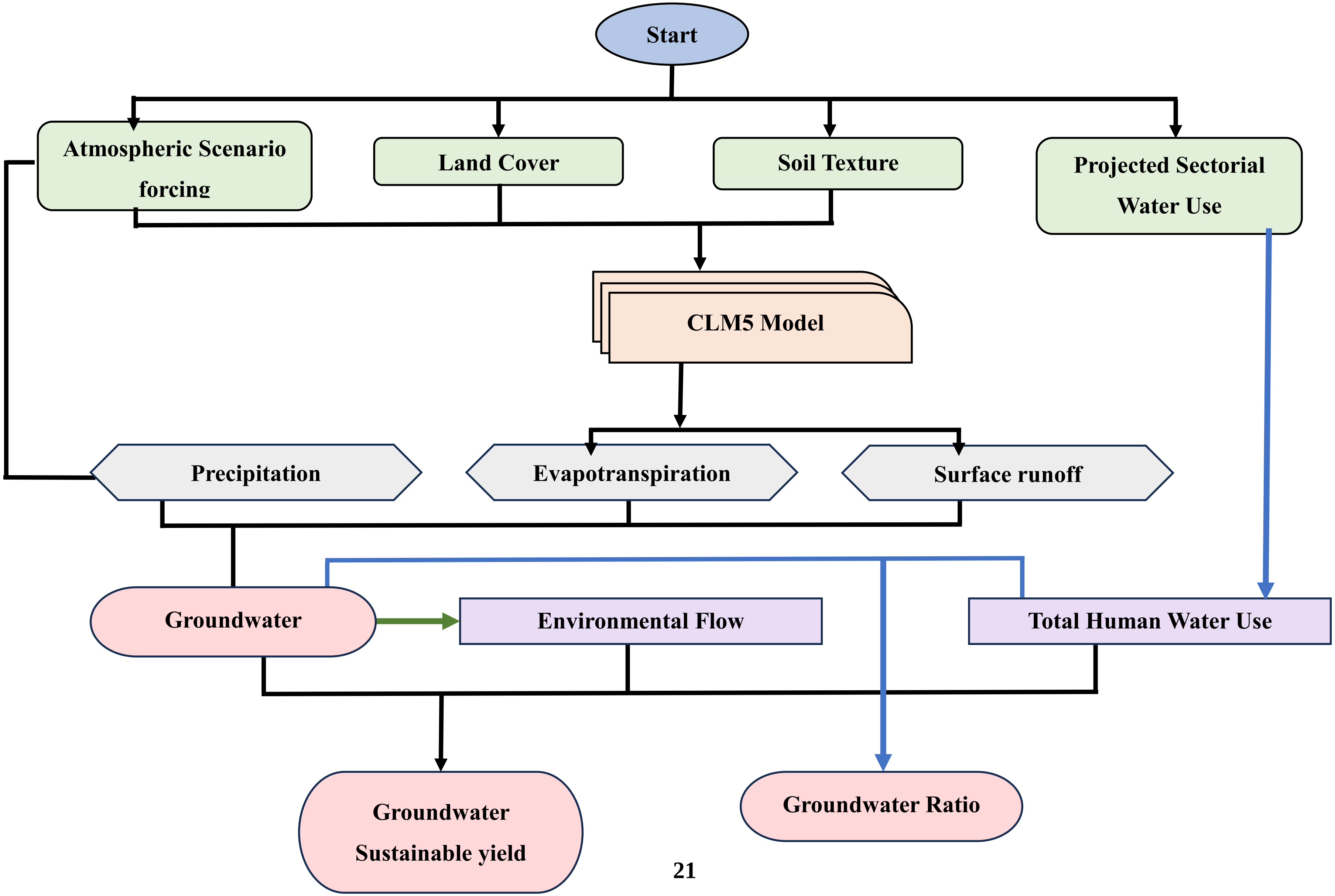

Figure 1:Flow chart of the methodology applied

CHAPTER 3:

RESULTS AND ANALYSIS

CHAPTER 3: RESULTS AND ANALYSIS

Introduction

This section outlines the spatio-temporal patterns of groundwater recharge, human water use, HWU/GWR ratio, and sustainable groundwater yield in Africa. It examines how these variables vary across regions and time periods on the continent, including trends under climate scenarios RCP 2.6 and 8.5 for fifty-one African countries from 2015 to 2100. Results for countries are also grouped for the regions Northern Africa, Central Africa, Southern Africa, West Africa, and Eastern Africa. Results are provided on evolving groundwater dynamics and their impacts on sustainable water management and green hydrogen production.

3.1. Projected Spatial and Temporal Distribution of Groundwater Recharge in Africa under scenarios RCP 2.6 and 8.5.

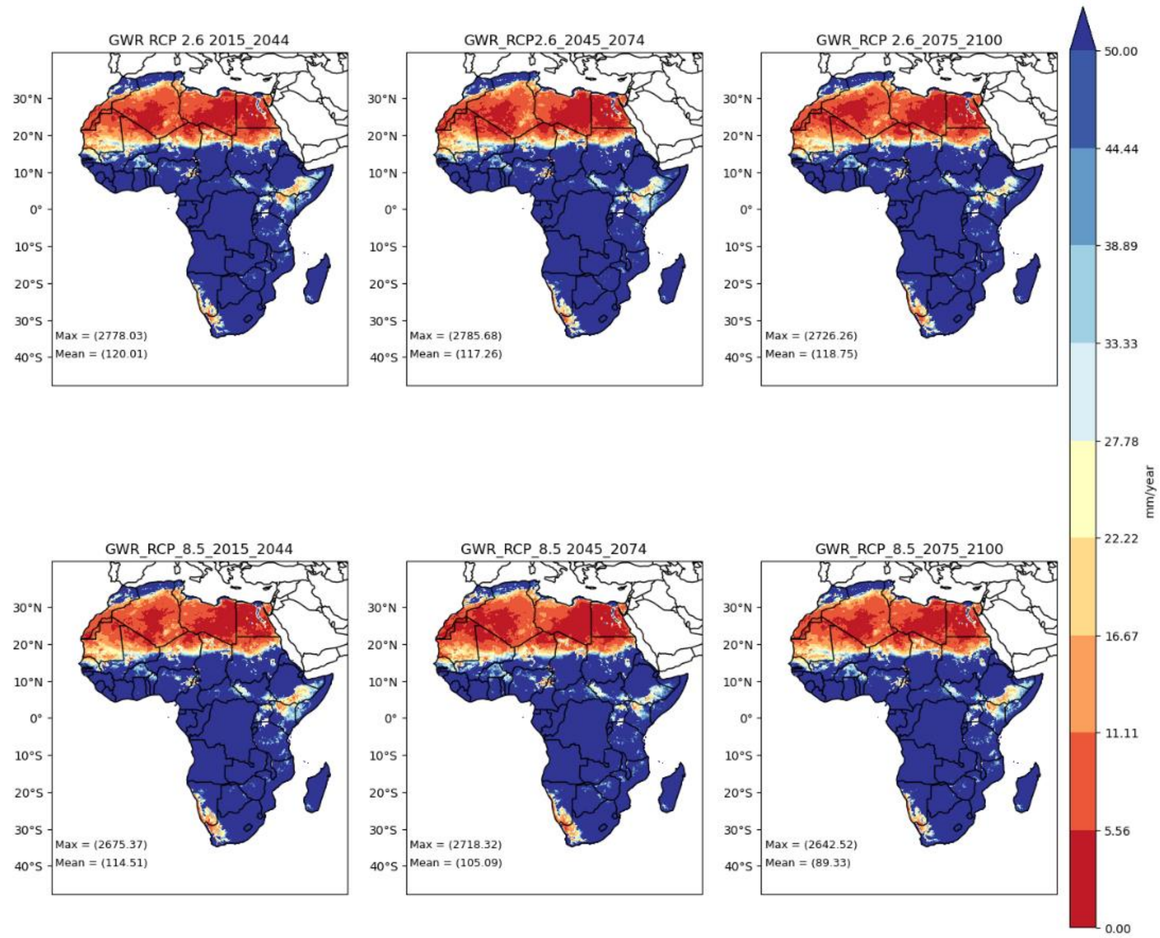

Figure 2:Groundwater Recharge over Africa for climate scenarios 2.6 and 8.5, for the time periods of 2015-2044, 2045-2074, 2075-2100. The mean values are also indicated in the lower left corner of the plots.

Fig. 2 shows a map displaying the spatial distribution of groundwater recharge over Africa for different climatic periods (2015–2044, 2045–2074, and 2075-2100). Comparing the three climate periods, a decrease in groundwater recharge across the continent can be observed. Nevertheless, the observed changes in recharge are relatively minor, showing no significant decline. The average projected recharge for Africa ranges from 118.75 to 120.01 [mm year^{-1}] for the RCP 2.6 scenario and from 89.33 to 114.51 [mm year^{-1}] for the RCP 8.5 scenario. Notably, the average recharge for RCP 2.6 is higher than that for RCP 8.5.

The regions with the highest estimates of groundwater recharge are located in tropical areas near the Equator range. On the other hand, lower estimates are observed in the Sahara region, including parts of Mali, Niger, Mauritania, Chad, and other countries in Northern Africa such as Egypt, Sudan, Libya, and Tunisia, as well as in Ethiopia and Somalia in Eastern Africa. Conversely, higher estimates are found in West Africa, particularly in coastal regions like Nigeria, Sierra Leone, and Liberia, Guinea, as well as in central and southern Africa, compared to other parts of the region.

In this discusion section, we explore the factors influencing groundwater recharge, climate change impacts, and variations in water use. Additionally, we discuss the implications of these findings for green hydrogen production and water resources management and planning in each region.

In West Africa, higher groundwater recharge estimates (Figure 1) are influenced by various factors. Abundant rainfall, emphasized by Scanlon *et al.*, (2012); MacDonald *et al.*, (2021a), enhances recharge through increased soil infiltration and aquifer replenishment. Tirogo *et al.*, (2016b) suggested that, dense vegetation is associated with high transpiration thus reducing recharge. Additionally, favorable soil permeability in regions with higher rainfall expedites water penetration into aquifers (Amos *et al.*, 2014; MacDonald *et al.*, 2021b). On the other hand, Taylor *et al.* (2019) and Cook *et al.* (2022) indicated that geological formations and surface water bodies like rivers and lakes significantly contribute to recharge, facilitated by processes such as riverbank infiltration and groundwater-surface water interactions. The maps in Figure 21 highlight potential sustainable groundwater yield, particularly in the Southwest of West Africa, coastal regions, and near the Equator. These areas exhibit conditions conducive to groundwater recharge, supporting sustainable water supply. The evaluation determines the extractable amount without ecological harm. Elevated yield estimates in coastal zones, in the southeast of Southern Africa, and Central Africa result from factors including high rainfall, ocean proximity, and favorable hydrogeological conditions, such as permeable soils and geology, promoting robust recharge (Kusangaya *et al.*, 2014; MacDonald *et al.*, 2021b; Cook *et al.*, 2022). The influence of climate change on recharge trends and sustainable yield is notable. Changes in precipitation patterns and temperature can impact water resources, potentially altering groundwater recharge across regions. The differential potential yield between RCP 2.6 and RCP 8.5 scenarios can be attributed to factors like precipitation variations and emissions-induced climate change effects. On the other hand, it is very likely that potential ET increases for further temperature increase, negatively affecting groundwater recharge (Riahi *et al.*, 2011; Didovets *et al.*, 2020). Additional land use changes affect vegetation and therefore evapotranspiration and infiltration (Scanlon *et al.*, 2012; Mena *et al.*, 2021; Cook *et al.*, 2022; Popeangă and Lungu, 2021).

3.2. Projected Spatial and Temporal Distribution of Human Water Use in Africa under scenarios RCP 2.6 and 8.5.

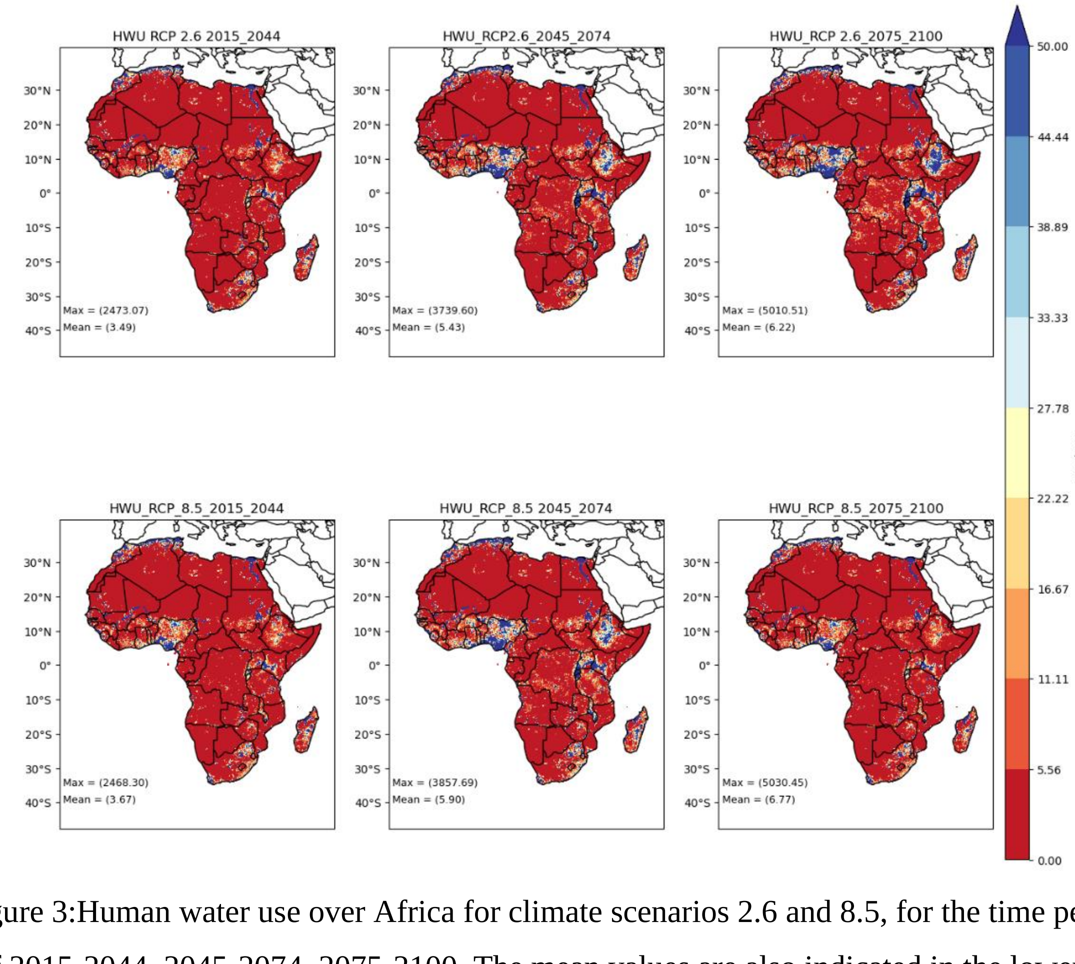

Figure 3:Human water use over Africa for climate scenarios 2.6 and 8.5, for the time periods of 2015-2044, 2045-2074, 2075-2100. The mean values are also indicated in the lower left corner of the plots.

Fig. 3 illustrates the temporal and spatial patterns of human water use across Africa during distinct climate periods (2015–2044, 2045–2074, and 2075-2100). Over these periods, there is an observed rise in human water consumption continent-wide. A comparison between scenarios RCP 2.6 and RCP 8.5, reveals slightly lower human water use estimates under RCP 2.6 (3.49 to 6.22 [mm year^{-1}]) compared to RCP 8.5 (3.67 to 6.77 [mm year^{-1}]). Notable regional variations are evident, with higher water use observed in West Africa (e.g., Nigeria, Benin), Northern Africa (e.g., Egypt, Tunisia), Eastern Africa (e.g., Ethiopia, Burundi, Kenya), Central Africa (e.g., Cameroon), and Southern Africa (e.g., South Africa, Eswatini, Lesotho).

The analysis of Figure 3, which presents maps depicting the spatial and temporal distribution of human water use in Africa over different climatic periods, reveals variations in water use across different regions. The study identifies increases in water use in several areas, including West Africa (e.g., Nigeria, Benin), Northern Africa (e.g., Egypt, Tunisia), Eastern Africa (e.g., Ethiopia, Burundi, and Kenya), Central Africa (e.g., Cameroon), and Southern Africa (e.g., South Africa, Eswatini, and Lesotho). The observed increases in water use across various regions highlight the growing demand for water resources in response to population growth, economic development, and changing climatic conditions. As suggested by Wijayantha et al. (2020) Africa's future growth trajectory, with a predicted population of 2.5 billion by 2050 and an annual economic growth rate of 2.2% to 3.1%, is likely to increase the continent's water demand. On the other hand, the variations in water use could be explained by the influence of a range of factors, including population dynamics, industrial activities, and agricultural practices especially in Northern Africa where 80% of groundwater is used for irrigation (MacDonald *et al.*, 2021b; Sherif *et al.*, 2023). Authors such as Cohen (2006), Arnell and Gosling (2013) and Güneralp *et al.* (2017) came out with the same conclusion. The findings from the study conducted by Huang *et al.* (2018) highlight an important aspect of irrigation water usage in the southern parts of South America and southern Africa. According to their research, irrigation water withdrawal in these regions' accounts for approximately 70% of the total annual irrigation. Furthermore, Potts (2012), Siabi *et al.* (2022b) and Potter (2012) indicated that rapid growth of urbanization may increase water demand. The differences in estimated water use between RCP 2.6 and RCP 8.5 can have several possible explanations, such as climate change, economic growth, water management and availability.

3.3. Trends in Groundwater Recharge under RCP 2.6 and 8.5 in African Regions

This subsection outlines groundwater recharge trends for 51 African countries under climate scenarios RCP 2.6 and 8.5 from 2015 to 2100, categorized by regions: Northern Africa (8 countries), Central Africa (8 countries), Southern Africa (5 countries), West Africa (15 countries), and Eastern Africa (15 countries).Southern Africa, comprising Botswana, Namibia, South Africa, Lesotho, and Eswatini.

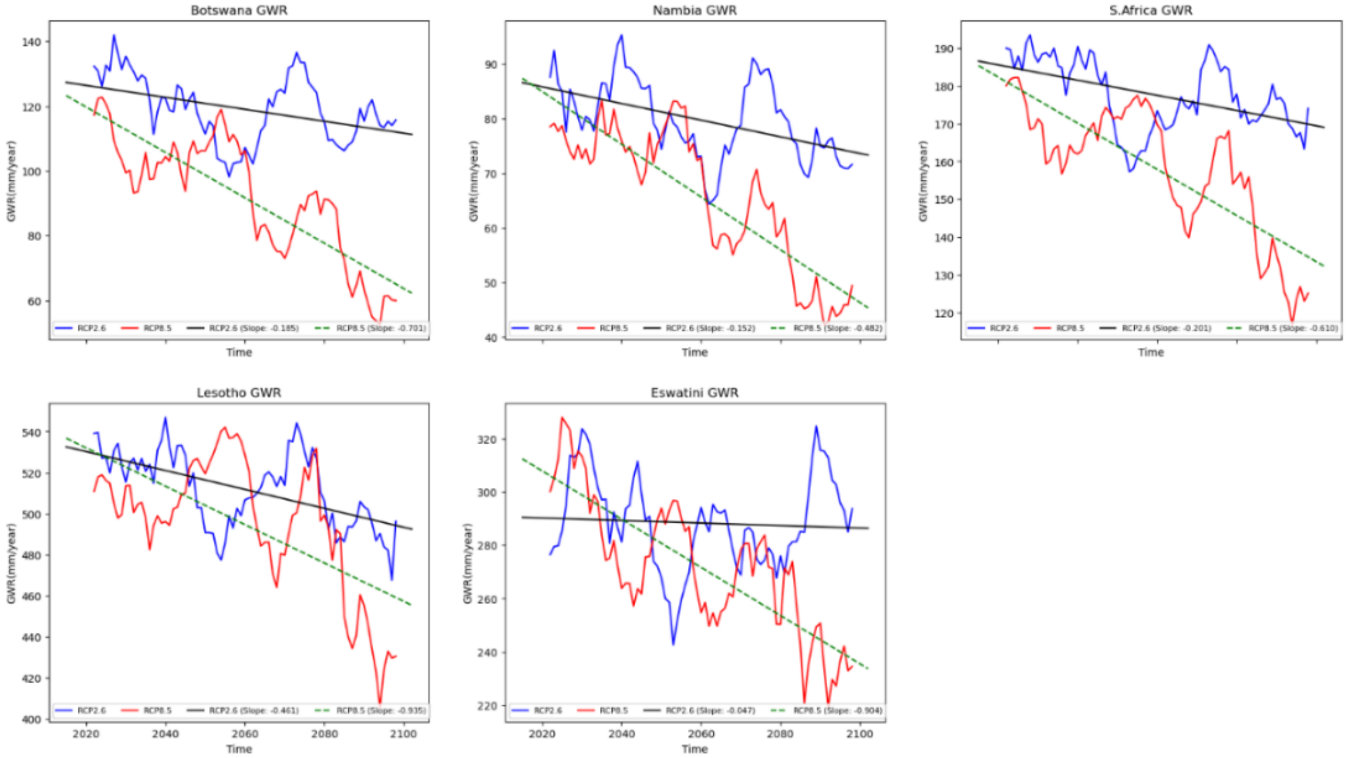

Figure 4:Projected groundwater recharge in countries of Southern Africa under climate scenarios RCP 2.6 and 8.5. The trends are expressed in mm/year.

Fig. 4 presents the projected groundwater recharge (GWR) trends over time in Southern Africa. Table 3 in the appendix, presents an analysis of the slope values of of GWR under the both scenarios, demonstrate negative recharge trends in all Southern African countries. Indicating a potential decrease in groundwater recharge for both climate scenarios. With negative recharge trends, there may be challenges in meeting future water demands and maintaining ecosystem health.

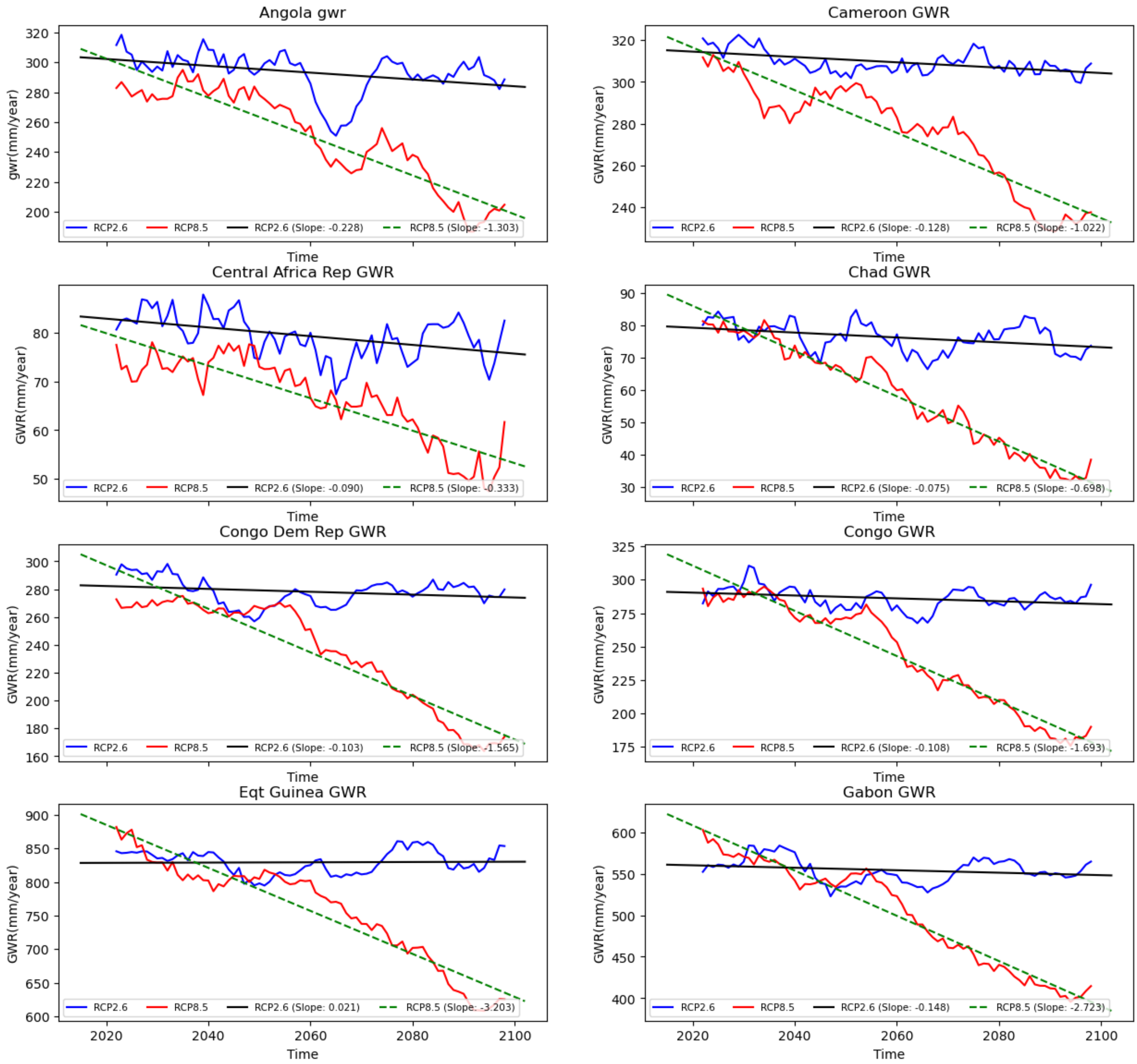

Figure 5:Projected groundwater recharge in countries of Central Africa under climate scenarios RCP 2.6 and 8.5. The trends are expressed in mm/year.

For Central Africa (Fig. 5), under the two climate scenarios RCP 2.6 and RCP 8.5, seven countries are analysed: Angola, Cameroon, Central African Republic, Chad, Republic of the Congo, Democratic Republic of the Congo, and Gabon. It appears from the analysis of Table 4 in the appendix for the slope values of GWR seven countries of Central Africa, including Angola, Cameroon, Central African Republic, Chad, Republic of the Congo, Democratic Republic of the Congo, and Gabon, both RCP scenarios indicate negative trends in GWR, with significant declines in groundwater recharge over time. An exception to these negative trends is observed in Equatorial Guinea. Under scenario 2.6, Equatorial Guinea exhibits a positive trend, indicating a potential increase in groundwater recharge. However, under scenario 8.5, it shows a (strongly) negative trend. In general, we see that for RCP8.5 the negative trend in GWR is much more pronounced than for RCP2.6 for the countries in Cental Africa.

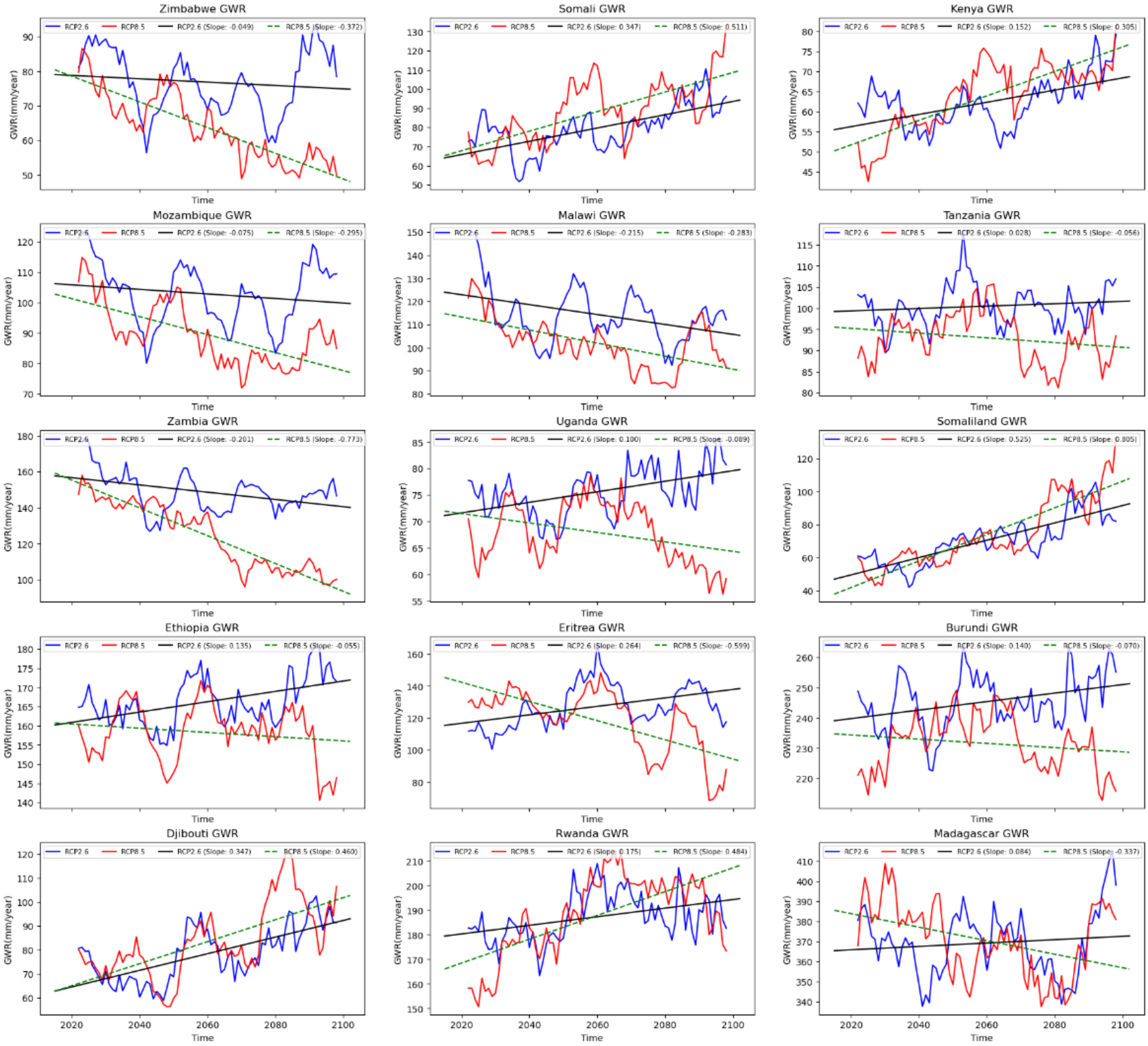

Figure 6:Projected groundwater recharge in countries of Eastern Africa under climate scenarios RCP 2.6 and 8.5. The trends are expressed in mm/year.

Fig. 6 presents the projected groundwater recharge (GWR) trends over time in Eastern Africa under scenarios 2.6 and 8.5. The results show varying trends across different countries in the region. The analysis in Table 5 in the appendix illustrates the slope values of GWR under the both scenarios. In countries like Mozambique, Zimbabwe, Malawi, and Zambia, both RCP scenarios indicate steeper negative gradients, suggesting a potential decrease in groundwater recharge over time. This could have implications for water availability and ecosystem health in these areas. On the other hand, some countries, including Somalia, Kenya, Somaliland, Djibouti, and Rwanda, exhibit positive trends in both RCP scenarios, indicating a potential increase in groundwater recharge. Additionally, Ethiopia, Burundi, Madagascar, Eritrea, Uganda, and Tanzania show positive GWR trends under RCP 2.6, while RCP 8.5 shows negative recharge trends in these countries. We see that over Eastern Africa GWR trends are in general more negative under the RCP8.5 scenario, but for some countries GWR increases more under the RCP8.5 scenario than under the RCP2.6 scenario (Kenya, Somalia, Somaliland, Djibouti).

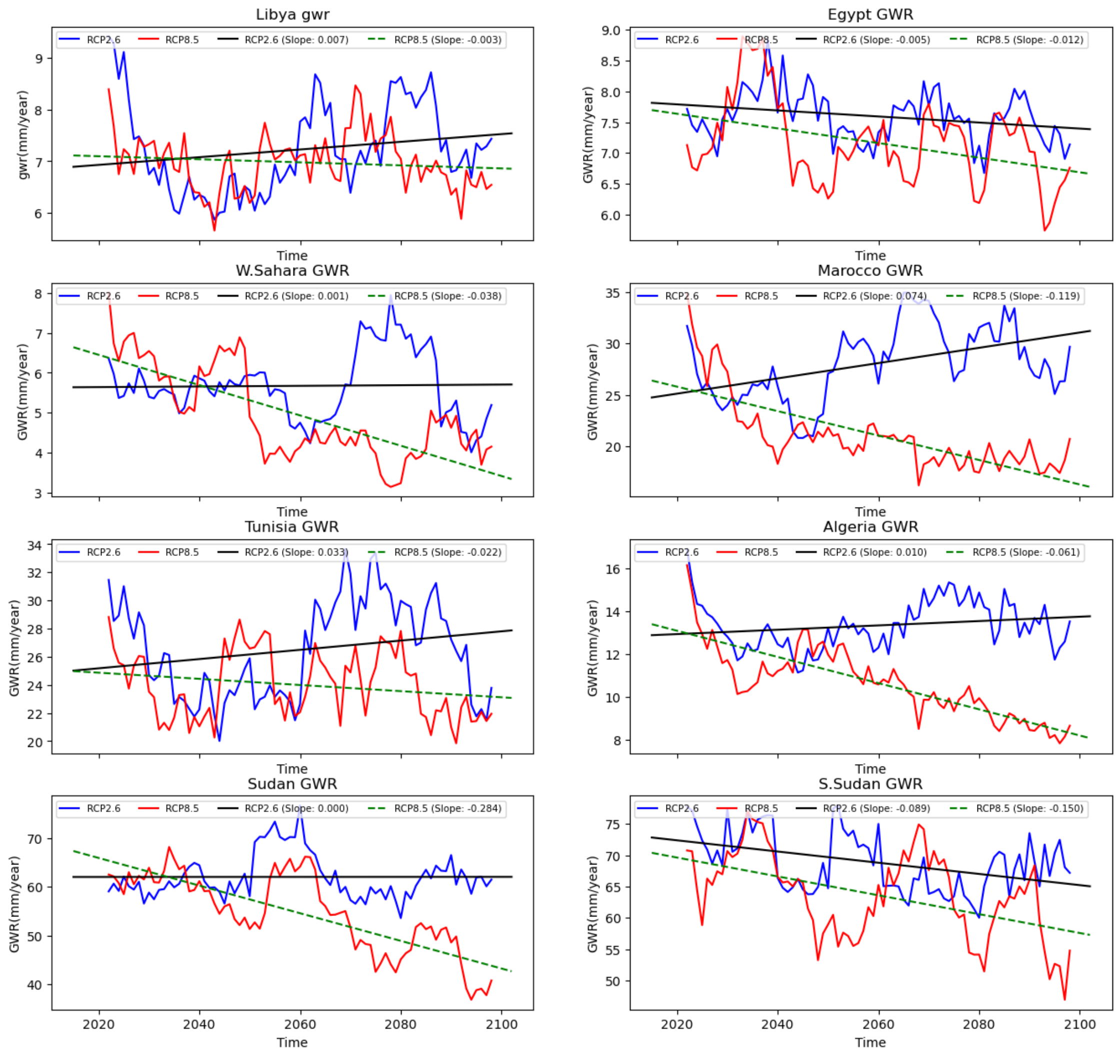

Figure 7:Projected groundwater recharge in countries of Northern Africa under climate scenarios RCP 2.6 and 8.5. The trends are expressed in mm/year.

Fig. 7 illustrates the projected trends of groundwater recharge (GWR) in Northern Africa under two climate scenarios, RCP 2.6 and RCP 8.5. The analysis reveals different patterns in GWR across the region over time. Examination of Table 6 in the appendix for the slope values of GWR under the both scenarios. It becomes evident that both RCP scenarios 2.6 and 8.5 show negative trends in GWR for Egypt and South Sudan. Conversely, the other six countries exhibit positive trends including Libya, Western Sahara, Morocco, Tunisia, Algeria, and Sudan, under RCP 2.6. while under RCP 8.5 shows a negative trend. The negative trends in Egypt and South Sudan for both climate scenarios indicate a potential decline in groundwater recharge, which could have implications for water availability and sustainability in these countries. On the other hand, the positive trends in the other six countries under RCP 2.6 indicate a potential increase in groundwater recharge, which may present opportunities for improved water security and management should carbon emissions indeed reduce fast in the future.

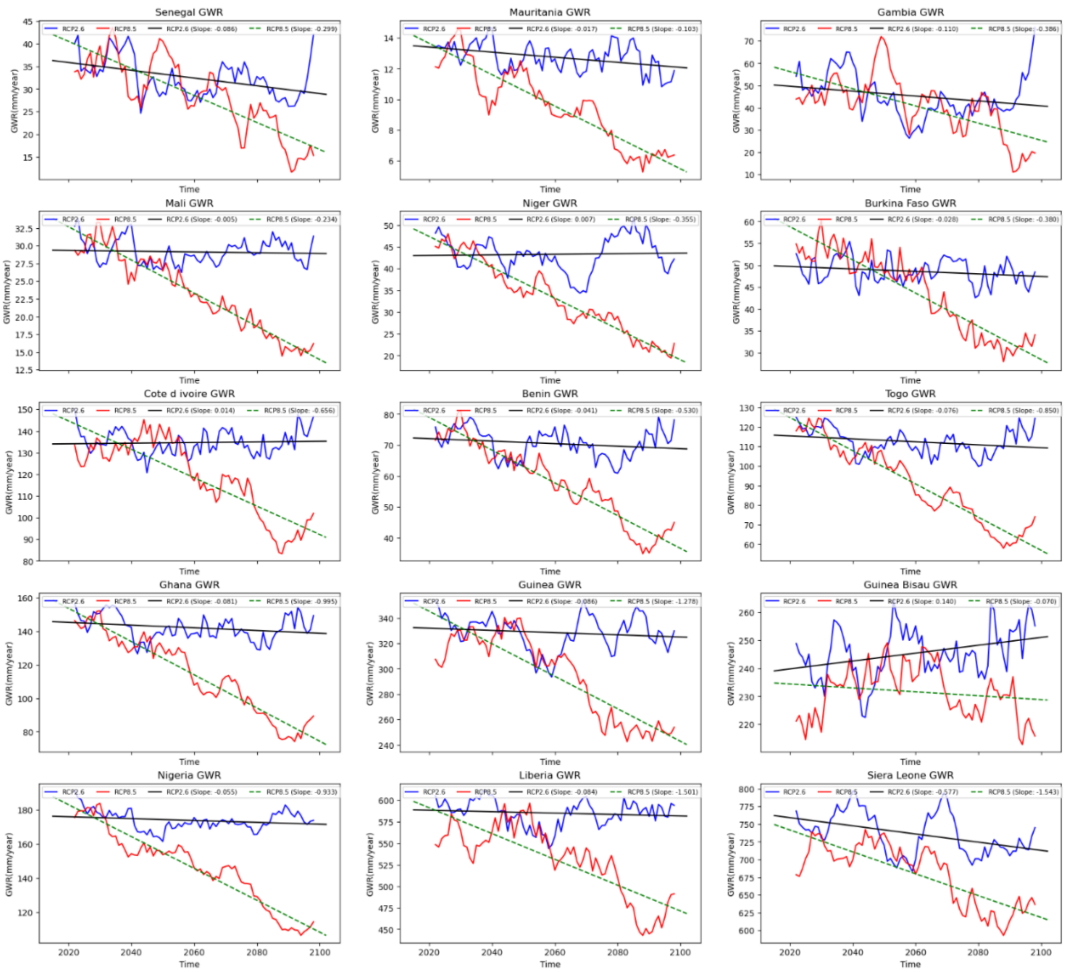

Figure 8:Projected groundwater recharge in countries of Western Africa under climate scenarios RCP 2.6 and 8.5. The trends are expressed in mm/year.

Figure 8 presents the projected groundwater recharge (GWR) trends over time in West Africa under climate scenarios RCP 2.6 and 8.5. The results in Table 7 in the appendix demonstrate consistent trends in the slope values under the two climate scenarios across the majority of West African countries. In 12 West African countries, including Senegal, Mauritania, Gambia, Mali, Burkina Faso, Benin, Togo, Ghana, Guinea, Nigeria, Sierra Leone, and Liberia, both RCP scenarios indicate negative GWR trends. This suggests a potential decrease in groundwater recharge over time in these countries. Such a trend could have significant implications for water availability and sustainability in the region. However, there are some variations in the trends among the West African countries. Specifically, three countries, namely Cote d'Ivoire, Guinea Bissau, and Nigeria, show positive GWR trends under RCP 2.6, indicating a potential increase in groundwater recharge. However, these countries exhibit negative trends in groundwater recharge under RCP 8.5. These findings highlight the complex and region-specific nature of groundwater recharge trends in West Africa. While many countries face the challenge of decreasing recharge, some countries may have opportunities for improved water availability in the future under certain climate scenarios.

This subsection examines groundwater recharge trends in various African subregions and countries, as shown in Figures 4 to 8. Negative trends in Northern Africa, particularly in Egypt and South Sudan (Figure 7), as well as across all countries in Southern Africa (Figure 4), and in 12 countries of West Africa (Figure 8), indicate decreasing recharge and water sustainability concerns. Conversely, positive trends in six Northern African countries (Figure 7) under RCP 2.6 suggest heightened recharge potential and improved water security. This depends also on human water use. If the HWU/GWR ratio increases, more stress on water resources. This is basically everywhere the case for the climate scenarios. Similar patterns are observed in Central Africa (Figure 5), while positive recharge trends in Eastern Africa (Figure 6) hold significance for water availability and ecosystem health.

The negative trends in groundwater recharge observed in Egypt and South Sudan appears to be linked to shifts in precipitation patterns, potentially resulting in decreased rainfall and modified distribution. These changes directly impact groundwater recharge rates. These trends align with projections of decreased precipitation in these regions, which can worsen groundwater recharge and sustainability challenges (Lee, Chen and Lee, 2006; Mohamed, 2019; Raza, Lee and Kwon, 2019; Li *et al.*, 2020; Sherif *et al.*, 2023). Furthermore, higher temperatures and changing land use practices may elevate evapotranspiration rates, decreasing water infiltration and exacerbating negative recharge trends (Amos *et al.*, 2014; Cook *et al.*, 2022). Excessive groundwater pumping for irrigation could also contribute, as suggested by Sherif et al. (2023). Changes in land use, such as urbanization and agriculture, could further impact recharge, as observed in studies by Mohamed (2019), Picard *et al.* (2023) and Sherif *et al.* (2023). Similarly, the negative recharge trends in Southern Africa (under both scenarios) could be attributed to elevated temperatures and changing land use practices, which elevate evapotranspiration rates, reducing groundwater infiltration (Cook *et al.*, 2022). Changes in land use, including deforestation and urbanization, can disrupt natural hydrological cycles, reducing recharge (Bianchi *et al.*, 2020; MacDonald *et al.*, 2021a). Climate change impact on precipitation patterns, temperature, and evapotranspiration rates, as highlighted by Arnell and Gosling, (2013), can further affect recharge trends. In West Africa, the complex and region-specific nature of groundwater recharge trends becomes apparent, with some countries facing decreasing recharge, while others potentially experiencing improved availability. Climate change, influencing precipitation patterns, temperature, and evapotranspiration rates, plays a pivotal role (Amos *et al.*, 2014; Dosio *et al.*, 2015; Tirogo *et al.*, 2016a; Fotso-Nguemo *et al.*, 2019). Particularly vulnerable to climate change, West Africa's projected temperature increases and precipitation shifts can disrupt the hydrological cycle, potentially leading to negative recharge trends (Akinsanola *et al.*, 2015; Tirogo *et al.*, 2016a; Siabi *et al.*, 2022). The distribution of rainfall along the coast and localized highlands, as explored by Akinsanola et al., (2015), could affect groundwater recharge trends in the coastal zone. However, there are several potential reasons for Equatorial Guinea's positive trend in groundwater recharge under scenario RCP 2.6. This could contribute to the observed positive trend in groundwater recharge in Equatorial Guinea. Tangang *et al.* (2020) and MacDonald *et al.*, (2021a), came out with the same assertion. Positive groundwater recharge trends can increase the availability of water for drinking, irrigation, and industrial purposes, leading to improved water security and economic development in the region. Mileham *et al.* (2009), Kahsay *et al.* (2019) and Tangang *et al.* (2020) indicated that an increased water availability resulting from positive groundwater recharge trends can improve the health of ecosystems, including wetlands, rivers, and other habitats, leading to increased biodiversity and improved ecosystem services. Additionally, in their study Arnell and Gosling, (2013) came out with the same conclusion.

3.4. Projected Trend of Groundwater Recharge and Water Use in Africa regions under Scenarios 2.6 and 8.5.

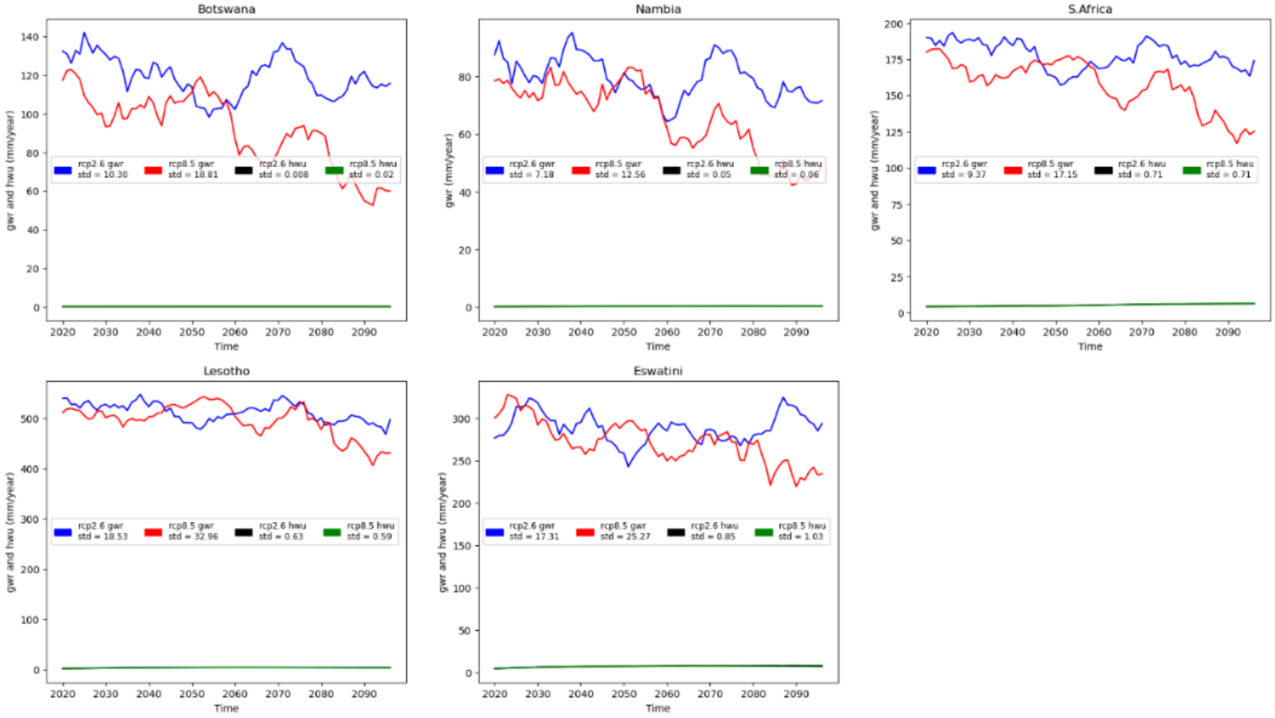

Figure 9:Projected trends of recharge and human water use over time for Southern African countries under scenarios 2.6 and 8.5. Standard deviations for recharge and human water use are also indicated.

Fig. 9 presents the projected trend of groundwater recharge and human water use over time with standard deviation in Southern Africa under scenarios 2.6 and 8.5. The results show variations in different countries within the region. In Southern Africa, Lesotho exhibits the highest standard deviation for groundwater recharge, with values ranging from 18.53 to 32.96 mm/year for both RCP 2.6 and 8.5 scenarios, respectively. This indicates significant fluctuations in groundwater recharge rates over time in Lesotho. On the other hand, Botswana demonstrates a low standard deviation for human water use, with a small variation ranging from 0.008 to 0.02 mm/year for both scenarios RCP 2.6 and 8.5, respectively. Similarly, Namibia shows a low standard deviation ranging from 7.18 to 12.56 mm/year for groundwater recharge, implying relatively stable groundwater recharge trends in these countries.

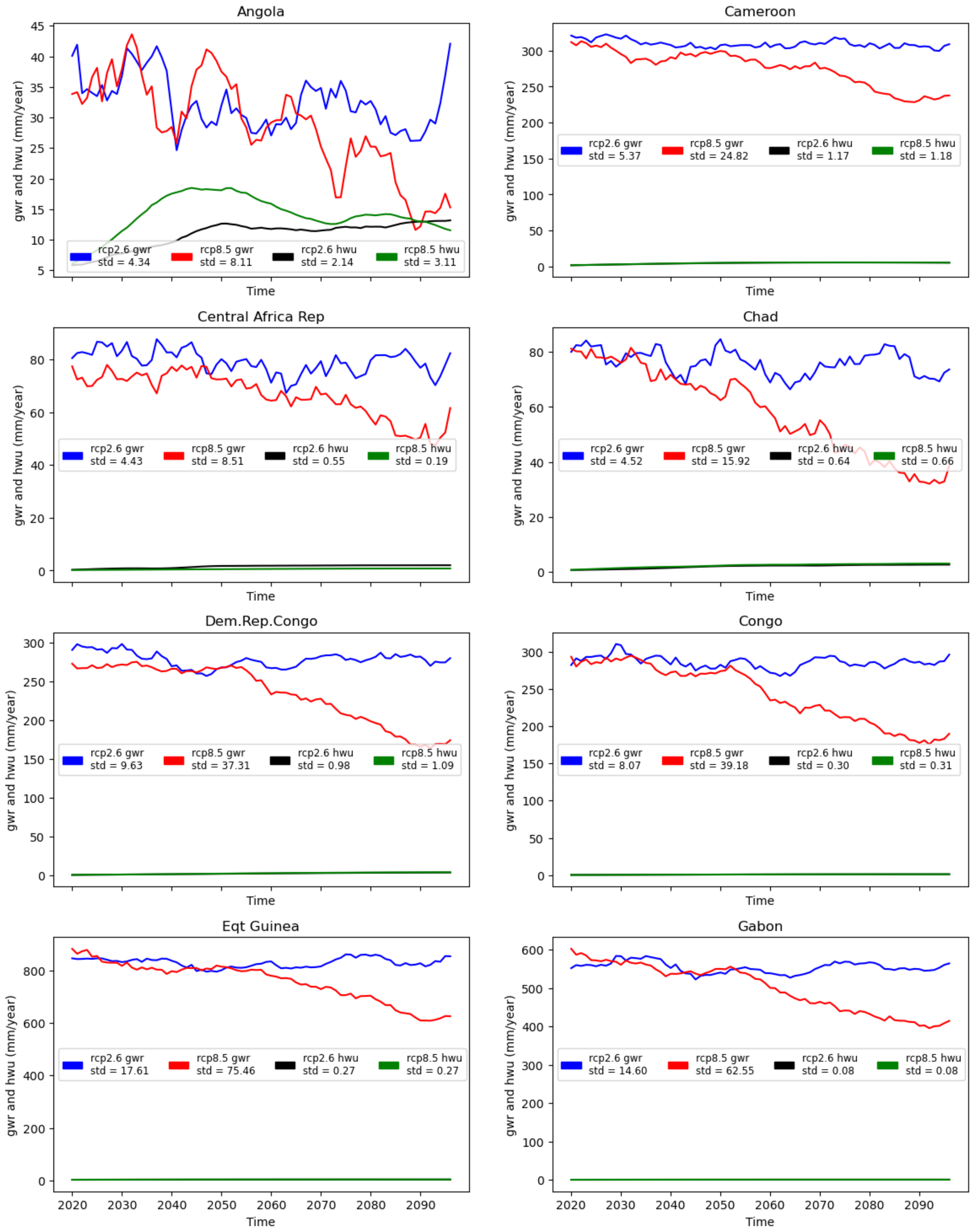

Figure 10:Projected trends of recharge and human water use over time for Central African countries under scenarios 2.6 and 8.5. Standard deviations for recharge and human water use are also indicated.

Fig. 10 shows the projected trend of groundwater recharge and human water use over time including standard deviation over Central African countries under RCP 2.6 and 8.5. Angola has low standard deviation values for both RCP 2.6 and 8.5 scenarios in groundwater recharge, with a range of 4.34 to 8.11 mm/year. On the other hand, Gabon exhibits a low standard deviation for human water use, with a variation of 0.08 mm/year. However, Equatorial Guinea records the highest standard deviation for groundwater recharge, ranging from 17.61 to 75.46 mm/year. Similarly, Angola exhibits the highest standard deviation for human water use, with a variation of 2.14 to 3.11 mm/year. These findings highlight the variability in groundwater recharge and human water use trends across different countries in Central Africa under different climate scenarios. The low standard deviation in groundwater recharge for Angola and Gabon suggests relatively stable and consistent trends in these countries. Conversely, the high standard deviation for Equatorial Guinea in groundwater recharge indicates significant fluctuations in recharge rates over time. Similarly, the high standard deviation for human water use in Angola suggests considerable variations in water consumption patterns.

Figure 11:Projected trends of recharge and human water use over time for Eastern African countries under scenarios 2.6 and 8.5. Standard deviations for recharge and human water use are also indicated.

Fig. 11 presents the projected trend of groundwater recharge and human water use over time with standard deviation in Eastern Africa under scenarios 2.6 and 8.5. The results show variations in different countries within the region. In Eastern Africa, Rwanda registers the highest standard deviation (std) for groundwater recharge, with values ranging from 9.80 to 18.28 mm/year for both RCP 2.6 and 8.5 scenarios. This indicates significant fluctuations in groundwater recharge rates over time in Rwanda. On the other hand, Zimbabwe displays a low standard deviation for human water use in both scenarios, with a relatively stable trend over time. Understanding these variations in groundwater recharge and human water use trends is crucial for effective water resource management in Eastern Africa. Countries with higher standard deviation values, such as Rwanda, may face greater challenges in managing their water resources due to the variability in groundwater recharge. On the other hand, countries with lower standard deviation values, like Zimbabwe, may have more predictable human water use patterns, which can be advantageous for water planning and management.

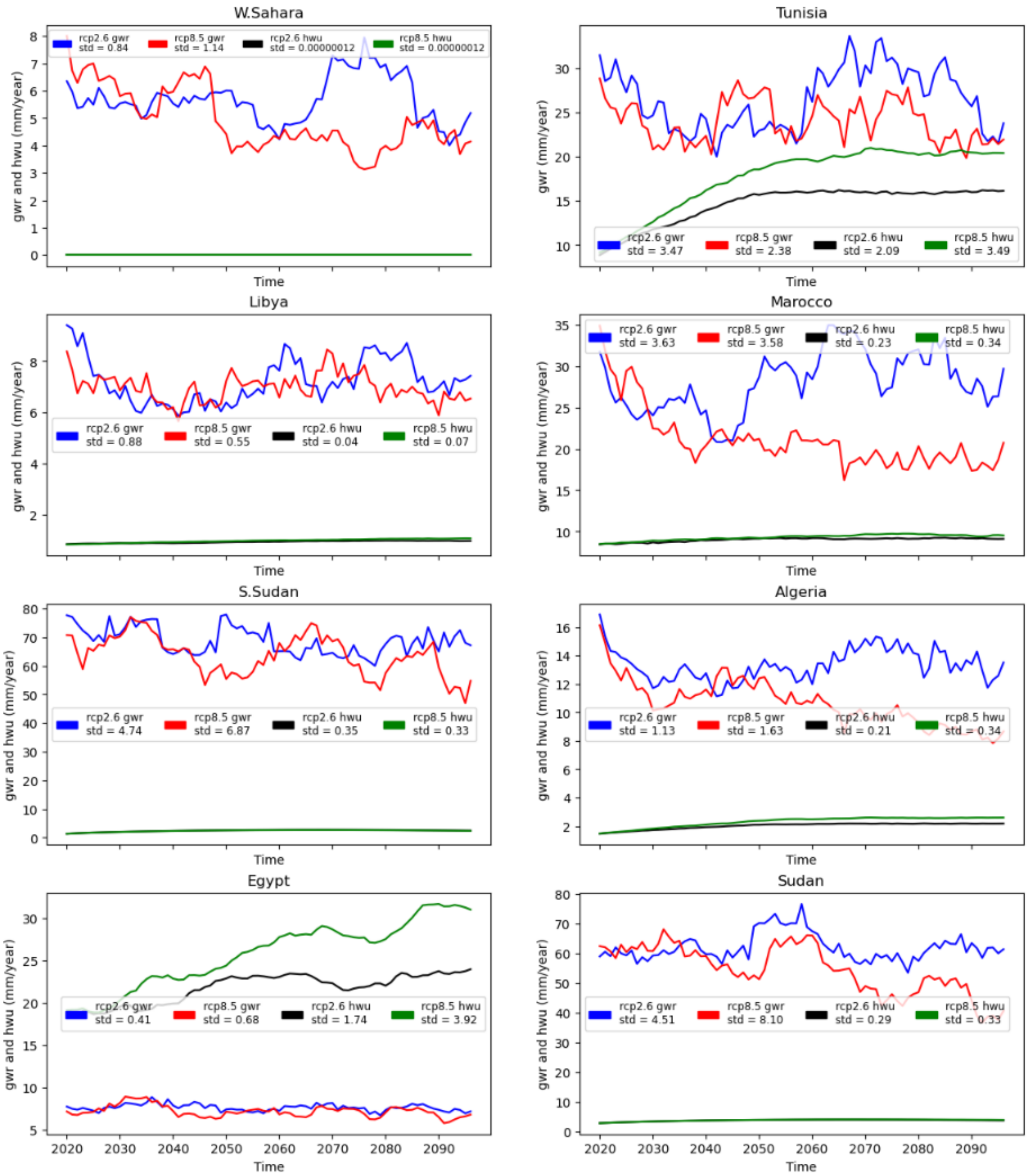

Figure 12:Projected trends of recharge and human water use over time for Northern African countries under scenarios 2.6 and 8.5. Standard deviations for recharge and human water use are also indicated.

Fig. 12 presents the projected trend of groundwater recharge and human water use over time with standard deviation in Northern Africa under scenarios 2.6 and 8.5. The results highlight variations in different countries within the region. In Northern Africa, Egypt exhibits a low standard deviation for both RCP 2.6 and 8.5 scenarios in terms of groundwater recharge, with values ranging from 0.41 to 0.68 mm/year. This indicates relatively stable and consistent trends in groundwater recharge for Egypt. On the other hand, West Sahara shows a low standard deviation for human water use, with a very small variation for both scenarios. This suggests consistent and steady human water use patterns in the region. However, Sudan records the highest standard deviation for groundwater recharge in both scenarios RCP 2.6 and 8.5, ranging from 4.51 to 8.10 mm/year, respectively.

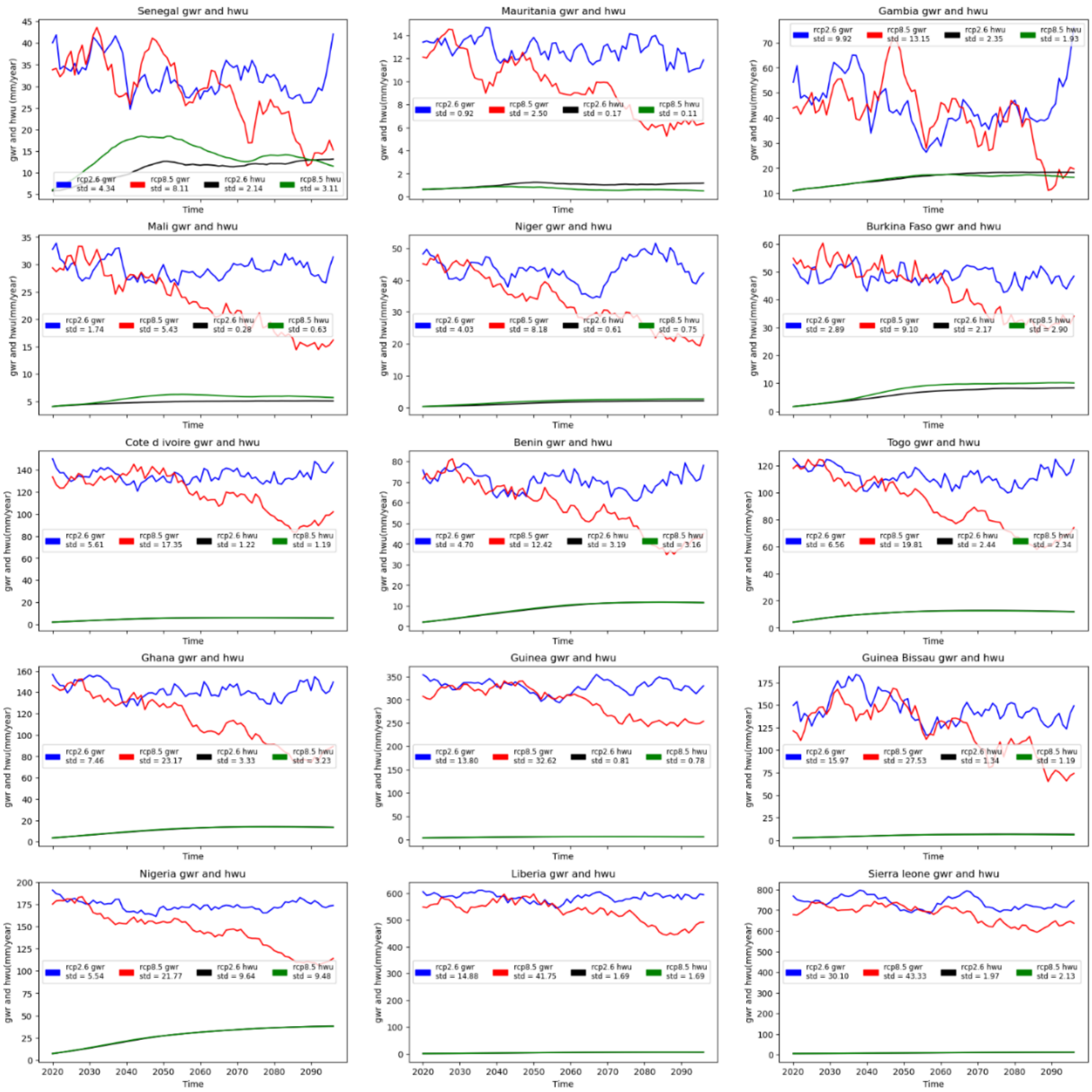

Figure 13:Projected trends of recharge and human water use over time for Western African countries under scenarios 2.6 and 8.5. Standard deviations for recharge and human water use are also indicated.

Fig. 13 presents the projected trend of groundwater recharge and human water use over time with standard deviation in West Africa under scenarios 2.6 and 8.5. The results reveal variations in different countries within the region. In West Africa, Sierra Leone exhibits the highest standard deviation (std) for groundwater recharge, with values ranging from 30.10 to 43.33 mm/year for both RCP 2.6 and 8.5 scenarios. This indicates significant fluctuations in groundwater recharge rates over time in Sierra Leone. On the other hand, Mauritania shows a low standard deviation for human water use in both scenarios, with relatively stable trends over time. Understanding these variations in groundwater recharge and human water use trends is crucial for effective water resource management in West Africa. Countries with higher standard deviation values, such as Sierra Leone, may face greater challenges in managing their water resources due to the variability in groundwater recharge. On the other hand, countries with lower standard deviation values, like Mauritania, may have more predictable human water use patterns, which can be advantageous for water planning and management. By considering the different standard deviation values for each country, policymakers and water resource managers can develop tailored strategies to address specific challenges and opportunities in each region. This approach can contribute to enhanced water security and sustainable water use practices in West Africa, even in the face of changing climatic conditions. These findings provide valuable insights for decision-makers and stakeholders in West Africa to better manage their water resources and promote long-term water sustainability in the region. By leveraging this information, countries can work towards more effective and efficient water use, ensuring a more resilient water future for their communities and ecosystems.

The low standard deviation in groundwater recharge observed in Angola and Gabon indicates consistent and stable trends in these countries. This information is valuable for decision-makers in pinpointing regions with higher recharge potential and implementing effective water management strategies (Mohamed and Gonçalvès, 2021). Similarly, countries with lower standard deviation values in human water use, such as Zimbabwe and Mauritania, may exhibit more predictable patterns, offering an advantage for water planning and management (Mahmoodi *et al.*, 2021). By considering varying standard deviation values for each country, policymakers and water resource managers can devise tailored strategies to address specific challenges and opportunities in different regions. This approach contributes to improved water security and sustainable water utilization practices across sub-regions and countries, even amidst changing climate conditions. However, the high standard deviation in groundwater recharge for countries like Equatorial Guinea, Rwanda and Sierra Leone indicates significant fluctuations in recharge rates over time. Hughes and Farinosi, (2020); Mohan et al., (2018) came out with the conclusion. This variability can pose challenges for water resource management in these countries as it may be difficult to predict future recharge rates accurately (Portmann *et al.*, 2013). Similarly, the high standard deviation for human water use in Angola suggests considerable variations in water consumption patterns (Hughes and Farinosi, 2020; Ofoezie et al., 2022). This variability can make it challenging to develop effective water management strategies that account for changing water demand patterns.

3.5. Projected Continental Groundwater Recharge Ratio and Sustainable Yield in Africa under RCP 2.6 and 8.5

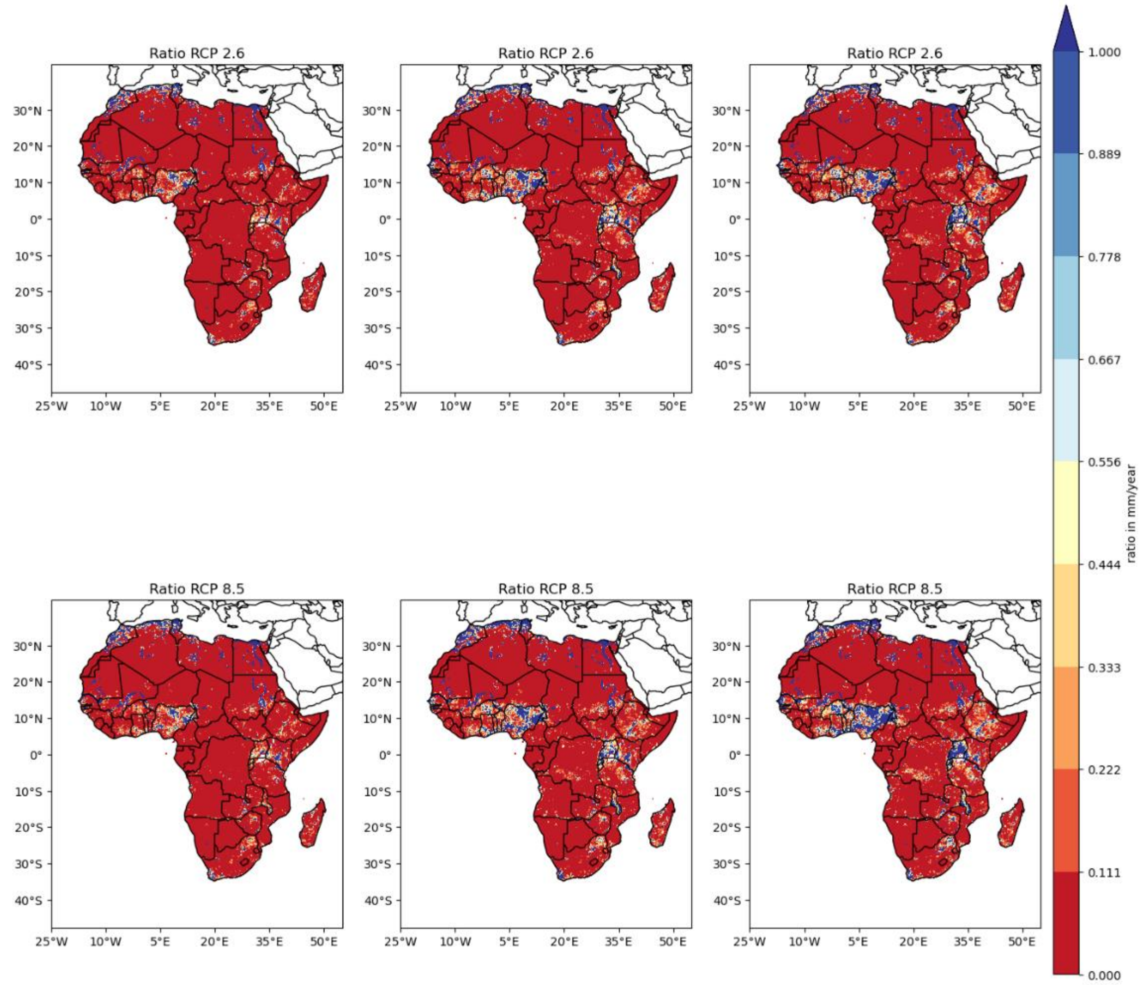

Figure 14:The ratio of human water use and groundwater recharge over Africa for climate scenarios 2.6 and 8.5, for the time periods of 2015-2044, 2045-2074, 2075-2100. The mean values are also indicated in the lower left corner of the plots.

Fig. 14 displays a map depicting the ratio between projected human water use and groundwater recharge across Africa during different climate periods under two scenarios, RCP 2.6 and 8.5. The map indicates a substantial increase in the ratio continent-wide. Notably, this increase is observed in multiple regions and countries, including:

1. Northern Africa: Egypt, Morocco, Algeria, Libya, Sudan
2. West Africa: Gambia, Benin, Ghana, Nigeria
3. East Africa: Uganda, Ethiopia, Rwanda, Burundi
4. Southern Africa: South Africa, Eswatini
5. Central Africa: Central African Republic.

3.6. Projected Recharge Ratio Trend under RCP 2.6 and 8.5 in Africa regions

This subsection presents projected ratio HWU/GWR trends for 51 African countries under climate scenarios RCP 2.6 and 8.5 from 2015 to 2100, grouped by regions: Northern Africa (8 countries), Central Africa (8 countries), Southern Africa (5 countries), West Africa (15 countries), and Eastern Africa (15 countries).

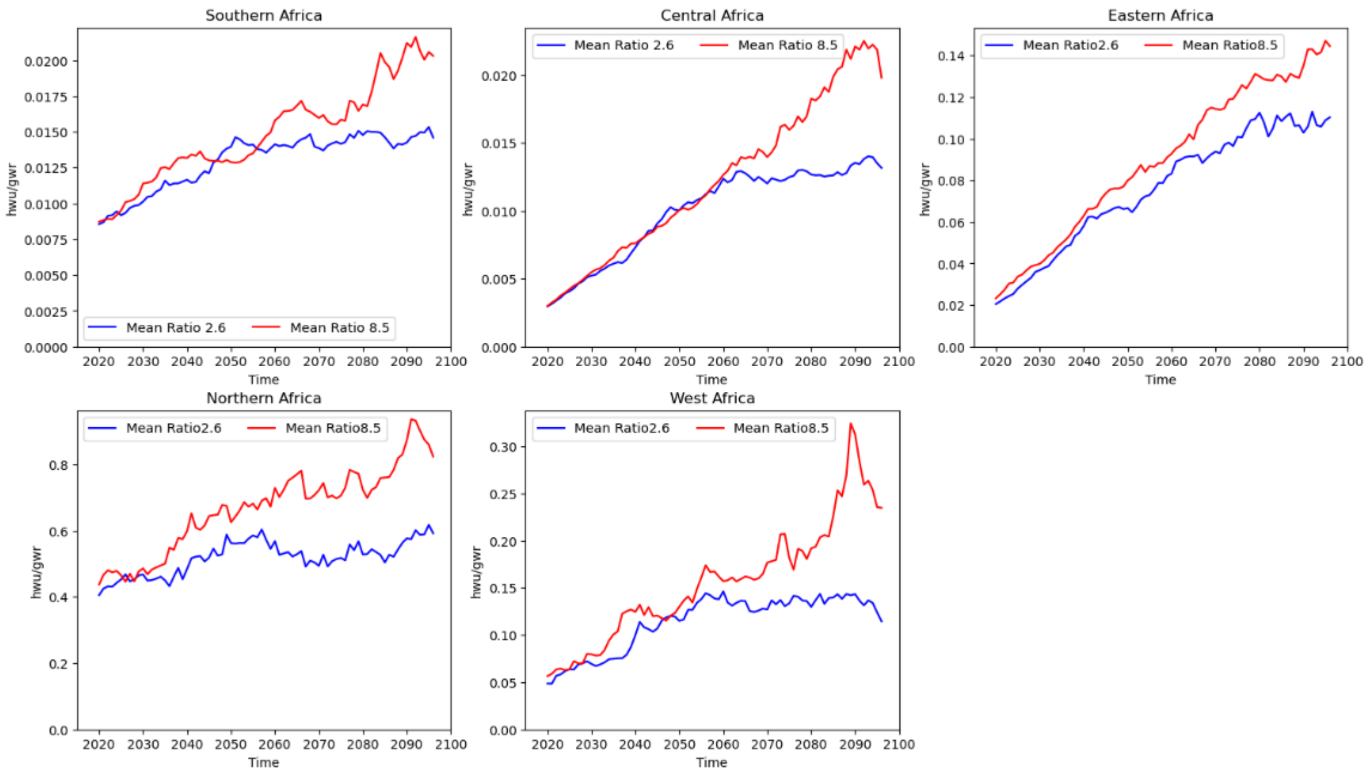

Figure 15:Projected HWU/GWR ratio trends in different African regions under climate scenarios RCP 2.6 and 8.5.

Fig. 15 presents the projected mean ratio HWU/GWR trend of recharge over time for the five regions under scenarios 2.6 and 8.5. The results show different patterns for different subregions. In Southern Africa, the ratio HWU/GWR increases until 2050 in both RCP 2.6 and 8.5 scenarios. Interestingly, for RCP 2.6 the ratio HWU/GWR remains above RCP 8.5 and continues to increase throughout the period. After 2050, the ratio HWU/GWR stabilizes in RCP 2.6, while in RCP 8.5, it also flattens out. In Central Africa, both RCP scenarios show a linear increasing trend until 2060. After 2060, the HWU/GWR ratio stabilizes in RCP 2.6, while in RCP 8.5, it continues to increase. In Eastern Africa, both RCP scenarios exhibit a similar increasing trend in the recharge ratio. In Northern Africa, the HWU/GWR ratio increases in RCP 2.6 until 2050, and oscillates afterwards with decreases and increases. In West Africa, the ratio HWU/GWR will increase until 2050 in RCP 2.6. From 2050 on, the HWU/GWR ratio stabilizes, with some decrease observed from 2090 until 2100. In contrast, in RCP 8.5, the ratio HWU/GWR increases until 2090 and is much higher than in RCP2.6. The observed differences in the recharge ratio trends across regions and scenarios emphasize the need for region-specific approaches in water management.

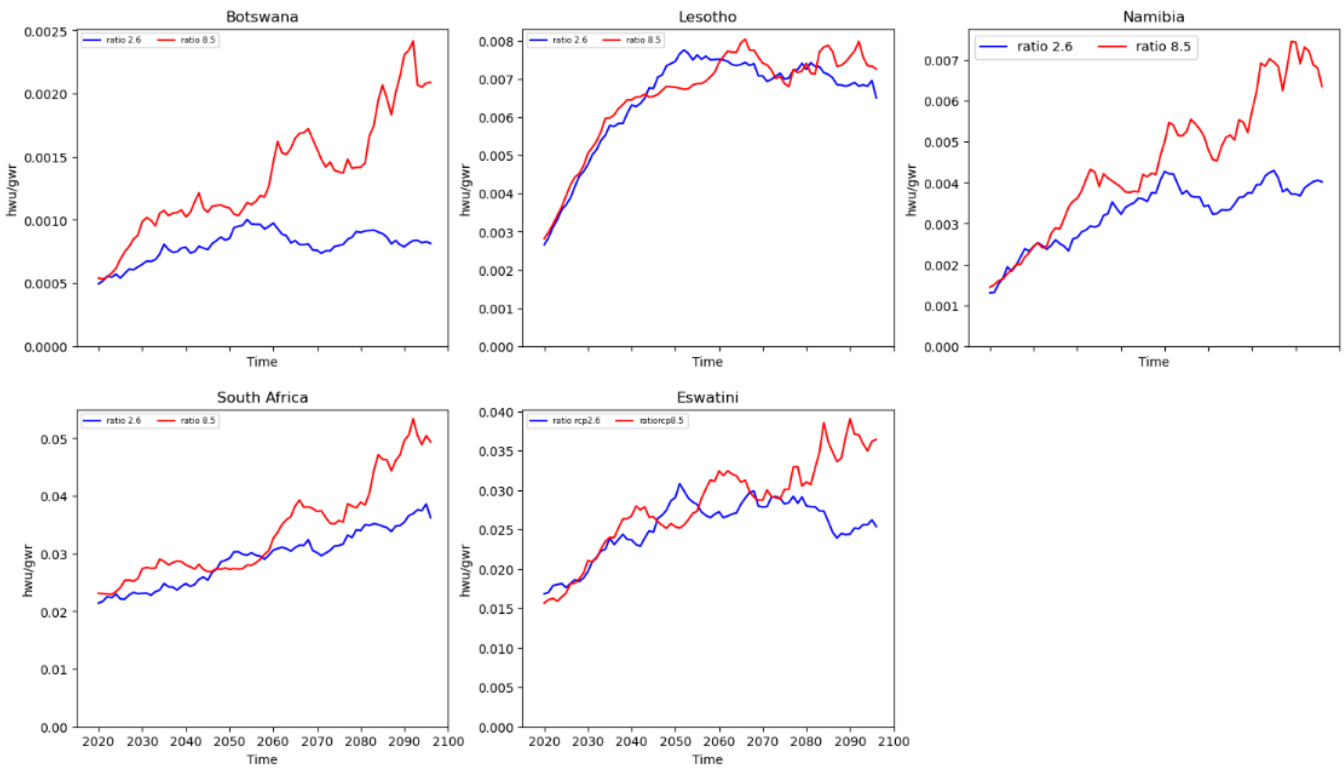

Figure 16:Projected HWU/GWR ratio trends in different Southern African countries under climate scenarios RCP 2.6 and 8.5.

Figure 16 illustrates the projected HWU/GWR ratio trend over time in the Southern African countries under scenarios 2.6 and 8.5. In Southern Africa, South Africa shows the highest recharge ratio up to 0.05 compared to other countries, although still (much) lower than for other African countries. Botswana exhibits the lowest HWU/GWR ratio. Lesotho and Eswatini display increasing HWU/GWR ratios for both scenarios, which stabilize in the second half of the century and with limited differences between RCP2.6 and RCP8.5. Namibia and South Africa show increasing HWU/GWR ratios for both scenarios, especially for RCP 8.5 while for RCP2.6 the ratio stabilizes after 2050.

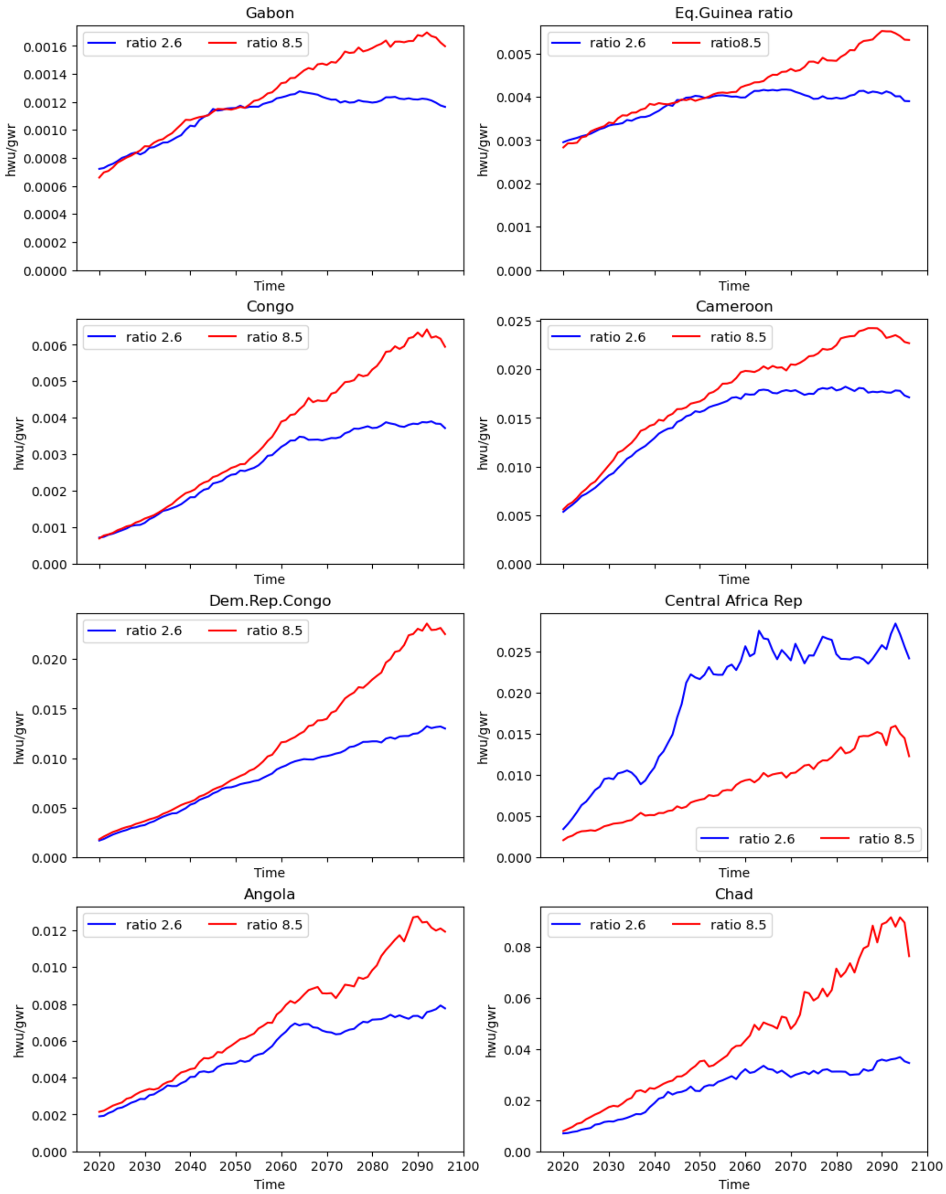

Figure 17:Projected HWU/GWR ratio trends in different Central African countries under climate scenarios RCP 2.6 and 8.5.

Figure 17 shows the projected HWU/GWR ratio trend over time for Central African countries under RCP scenarios 2.6 and 8.5. The HWU/GWR ratio varies between the two scenarios in the region. In Central Africa Rep, RCP 8.5 has a lower ratio compared to RCP 2.6. Both scenarios exhibit a low HWU/GWR ratio in Congo, remaining stable until 2060. After 2060, RCP 8.5 increases stronger than RCP 2.6 up to 0.006. Similarly, Cameroon's ratios are comparable in both scenarios, but later in the century the ratio is higher for RCP8.5 than RCP2.6. Gabon shows an increasing trend in both RCP 2.6 and 8.5, stabilizing after 2050 in RCP 2.6. Equatorial Guinea has flat trends until 2060 in both scenarios, followed by stabilization under the RCP 2.6 scenario and continued increase under the RCP 8.5 scenario. Dem. Rep. Congo also exhibits stable increasing trends until 2050, with increasing differences between RCP2.6 and RCP8.5 thereafter. Angola and Chad have an increasing HWU/GWR ratio in both scenarios, with similar trends, but from 2050-2060, RCP 2.6 has a clearly lower ratio than RCP 8.5. In general, Gabon has the lowest HWU/GWR ratio in the region, while Chad shows the highest ratio (around 0.08 at the end of the century). Overall, RCP 2.6 has a lower ratio than RCP 8.5 in most countries, except for Central Africa Rep, where RCP 2.6 has a higher projected ratio than RCP 8.5.

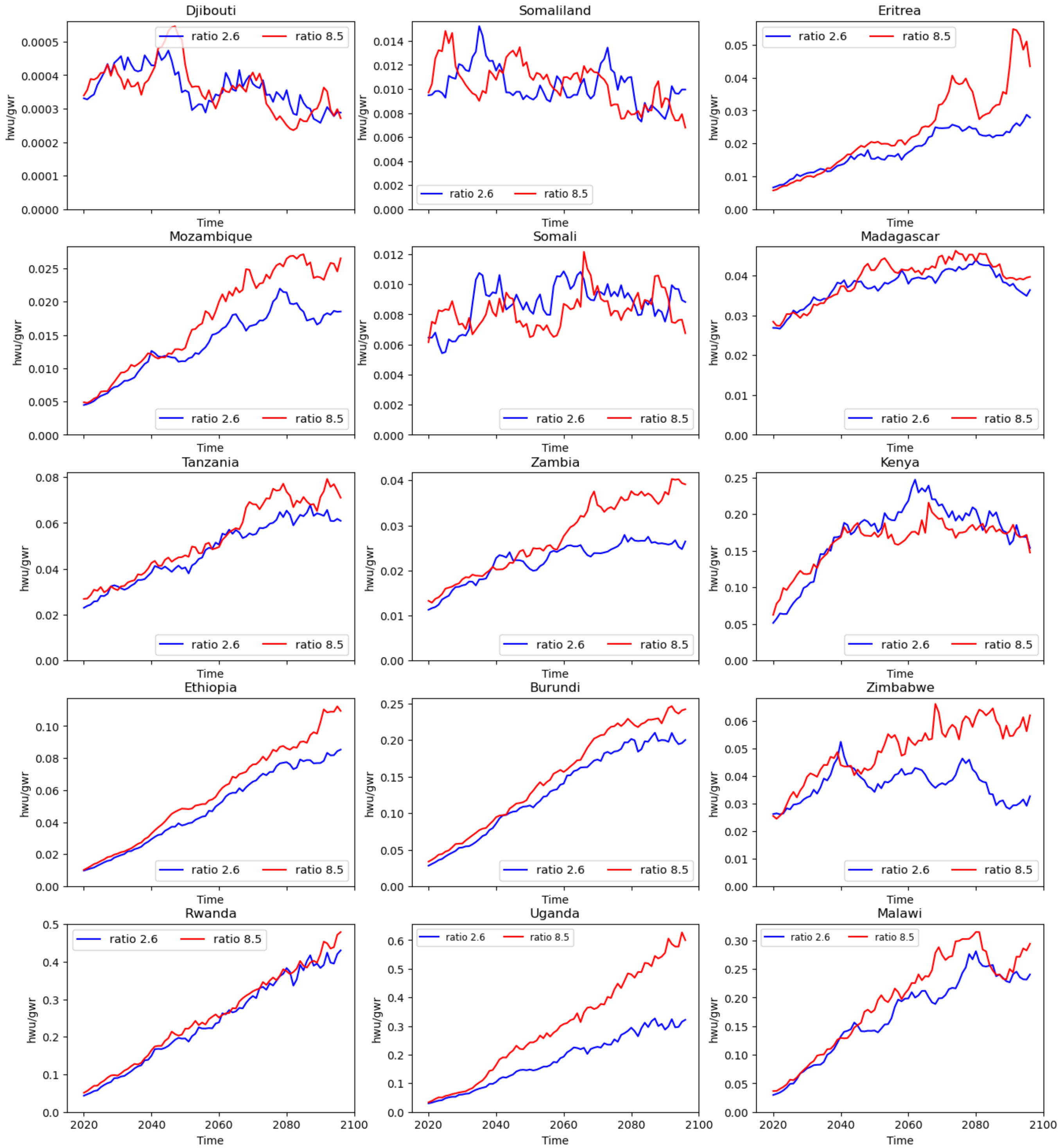

Figure 18:Projected HWU/GWR ratio trends in different Eastern African countries under climate scenarios RCP 2.6 and 8.5.

Fig.18 illustrates the projected HWU/GWR ratio trends over time in the Eastern Africa countries under scenarios 2.6 and 8.5. Uganda has the highest recharge ratio among the Eastern African countries (up to 0.6 at the end of century for RCP8.5). Djibouti has the lowest HWU/GWR ratio in the region. Djibouti, Somali and Somaliland do not show a clear increasing trend in the HWU/GWR ratio. Rwanda shows increasing HWU/GWR ratio in both scenarios, with only minor differences between RCP 2.6 and RCP 8.5 and maximum ratio values reaching 0.4. Madagascar, Tanzania, Ethiopia, Burundi, Malawi and Eritrea exhibit increasing HWU/GWR ratios for both scenarios, with in general slightly higher ratio´s for RCP8.5 than for RCP2.6. Comparing the two RCP scenarios, RCP 2.6 generally has a lower ratio than RCP 8.5 in all countries.

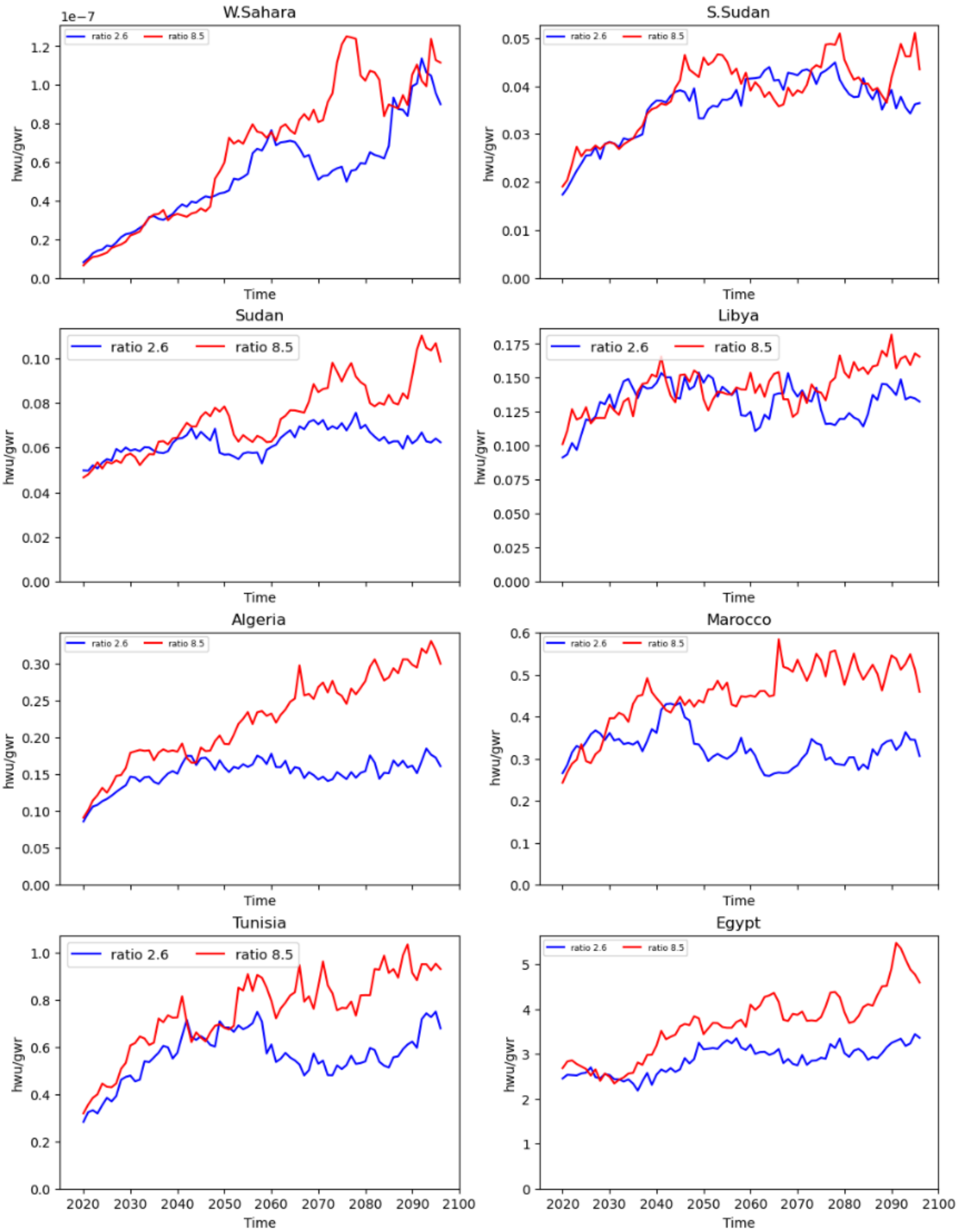

Figure 19:Projected HWU/GWR ratio trends in different Northern African countries under climate scenarios RCP 2.6 and 8.5.

Fig. 19 illustrates the projected HWU/GWR ratio trend over time for the Northern Africa countries under scenarios 2.6 and 8.5. In Northern Africa, Egypt presents a very high HWU/GWR ratio for both scenarios and the highest for whole Africa, while Libya shows the lowest ratio in the region. All the countries show increasing HWU/GWR ratios under the RCP 8.5 scenario, for various countries reaching very high values, while for RCP2.6 the increases are smaller.

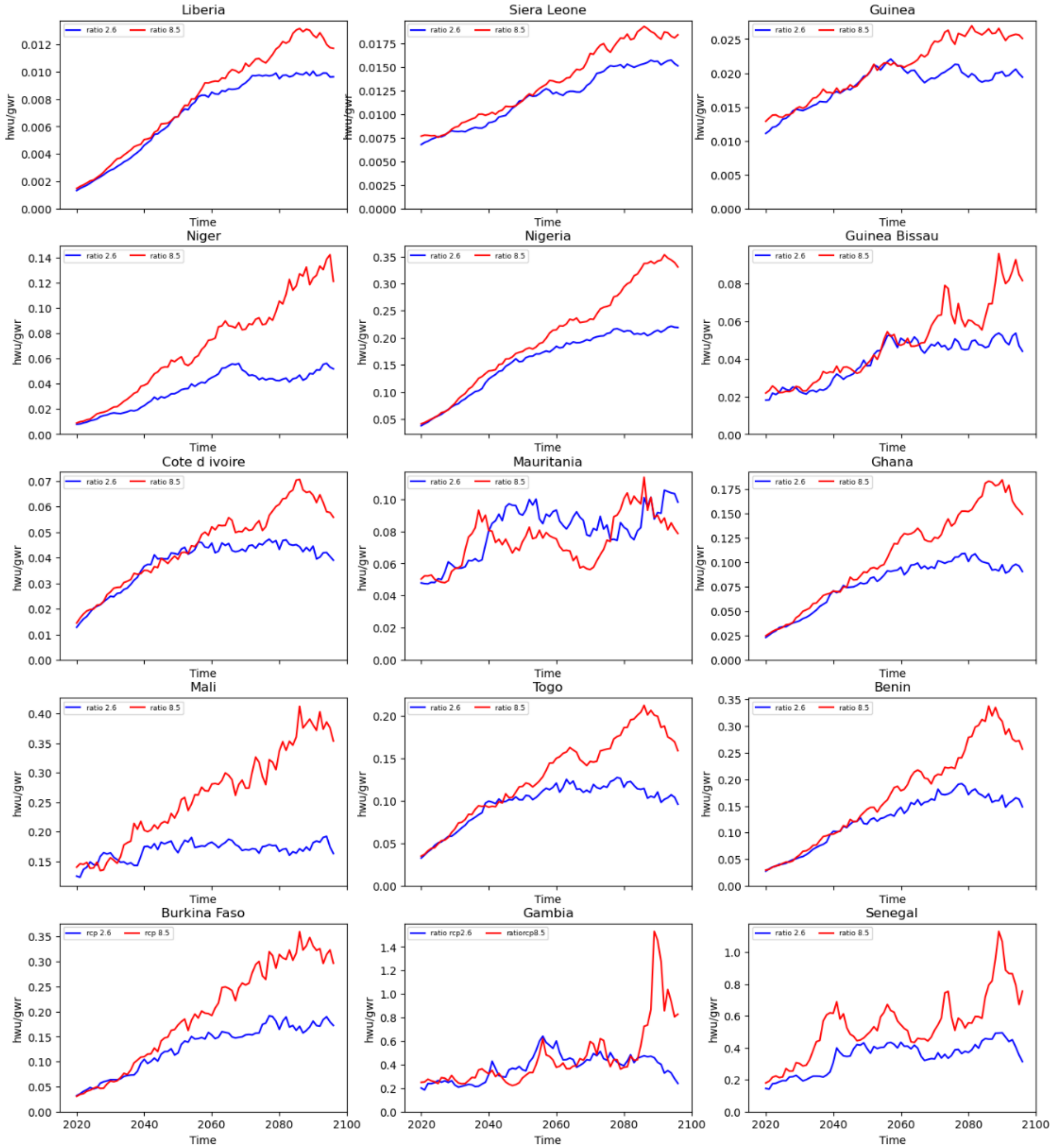

Figure 20:Projected HWU/GWR ratio trends in different Western African countries under climate scenarios RCP 2.6 and 8.5.

Fig. 20 illustrates the projected HWU/GWR ratio trend for West African countries under scenarios 2.6 and 8.5. In West Africa, Gambia and Senegal have the highest HWU/GWR ratios among the countries in the region. Mauritania exhibits similar patterns for both scenarios with limited changes over time. Mali and Niger, on the other hand, show much higher HWU/GWR ratios for the RCP 8.5 scenario than for the RCP 2.6 scenario. Liberia, Sierra Leone, Guinea and Nigeria show increasing trends for both scenarios with higher values for RCP8.5 than RCP2.6 later in the century. Guinea Bissau, Cote d'Ivoire, Togo, Benin, Gambia, and Burkina Faso also show increasing trends for both scenarios, with trends changing after 2060 for RCP 2.6 but in general still increasing for RCP 8.5.

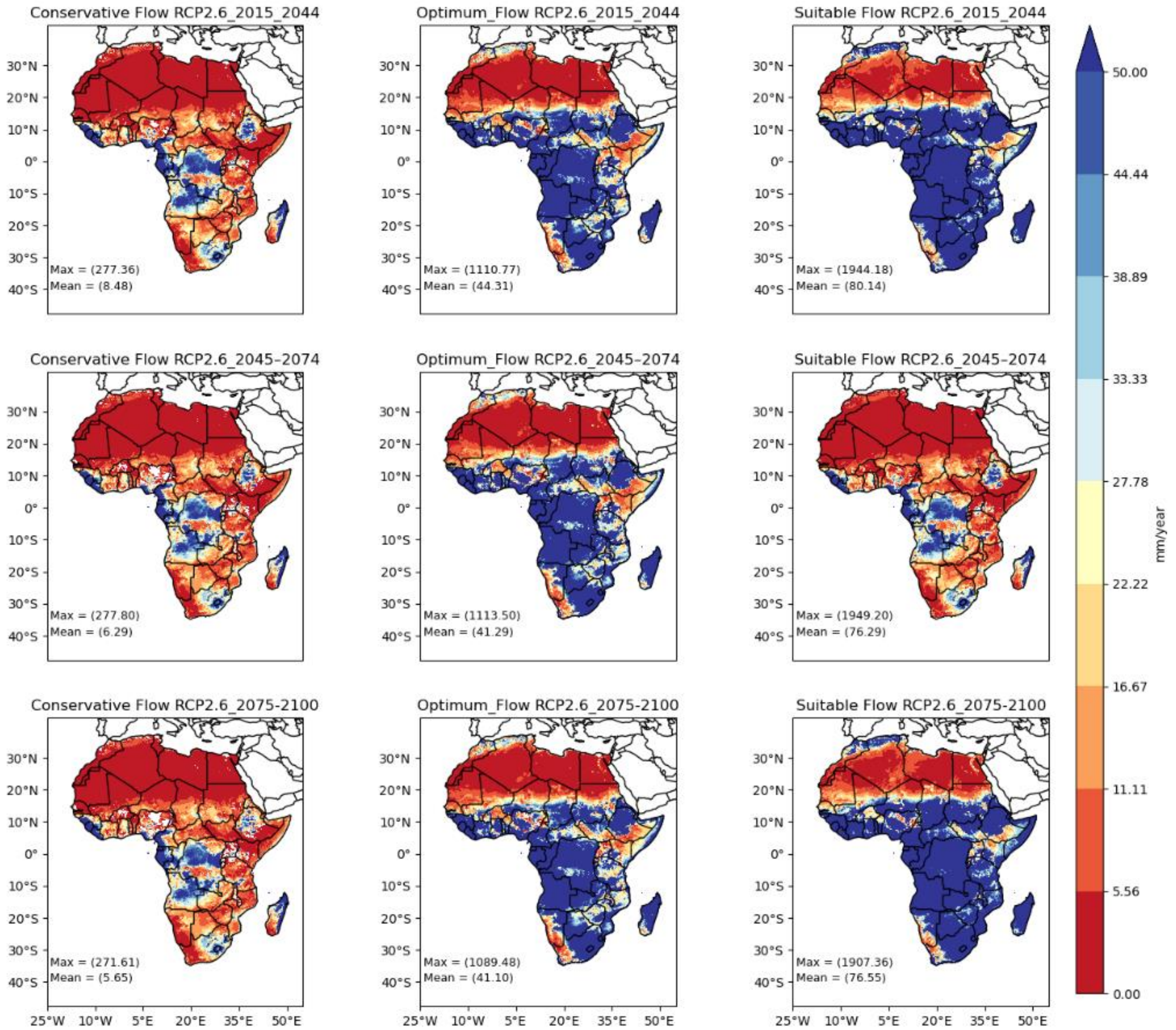

Figure 21:Projected average groundwater sustainable yield, for different sustainability scenarios (conservative, optimum and suitable) over Africa for RCP2.6.

Fig. 21 illustrates the distribution of groundwater sustainable yield in Africa across different time periods (2015–2044, 2045–2074, and 2075-2100). These maps reveal variations in the sustainable yield over the continent, with a focus on the optimum scenario. The projected groundwater sustainable yield ranges from 44.10 to 44.31 [mm year^{-1}] for RCP 2.6. Notably, certain areas, particularly in Southwest and West Africa (coastal and tropical equatorial regions), exhibit a high potential for sustainable yield. However, the potential yield varies across regions, with lower estimates in Sahara zone countries and higher estimates in coastal zones, southeastern Southern Africa, and Central Africa.

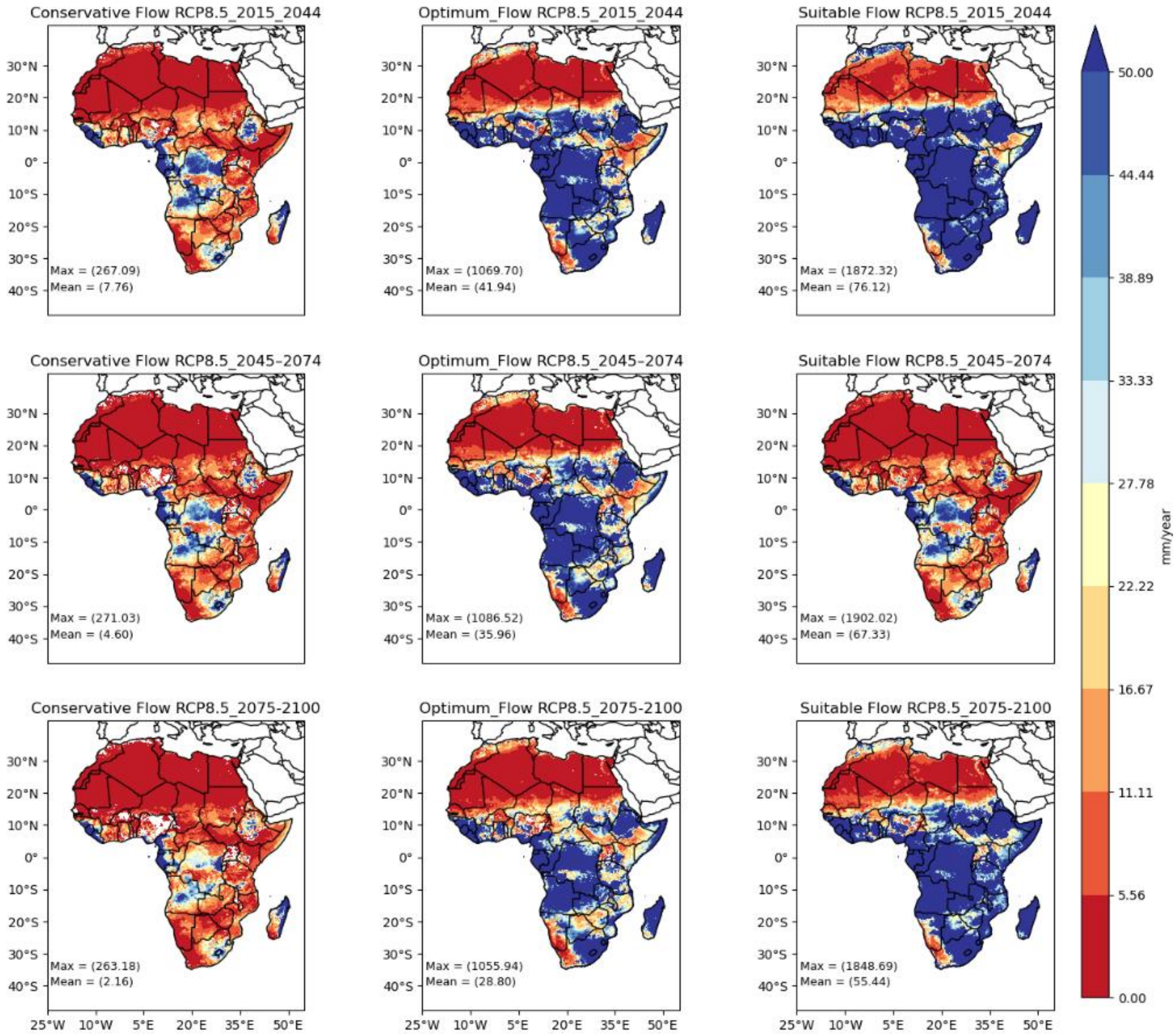

Figure 22:Projected average groundwater sustainable yield, for different sustainability scenarios (conservative, optimum and suitable) over Africa for RCP8.5.

Fig. 22 displays maps depicting the distribution of groundwater sustainable yield in Africa across various time periods (2015–2044, 2045–2074, and 2075-2100). These maps highlight potential yield variations across the continent and its regions. In the optimal scenario, the projected sustainable groundwater yield over the African continent for RCP 8.5 ranged from 41.9 mm/year (2015-2044) to 28.8 mm/year (2075-2100). Comparing the projected sustainable groundwater yield between scenarios (RCP 2.6 and 8.5) under the optimum scenario, RCP 2.6 exhibits a higher sustainable groundwater yield (decreasing only from 44.3 to 41.1 mm/year).

The findings presented in Figures 14 to 20 offer valuable information about HWU/GWR ratio trends across diverse African regions and countries under varying climate scenarios. Differences between RCP2.6 and RCP8.5 are mainly related to differences in precipitation and potential ET. Potential ET is mainly controlled by changes in global radiation and temperature, also wind speed and air humidity. Certain sub-regions of Africa, such as West, Central, and Eastern Africa, exhibit low HWU/GWR ratios and substantial rainfall and consistent recharge. In contrast, Northern Africa, characterized by high up to 0.8 HWU/GWR ratios, owes this to scarce rainfall, traditionally associated with water insecurity. Notably, countries with high HWU/GWR ratios, particularly in North Africa, have the potential to bolster present water security via pumping. However, this approach could jeopardize future water availability. Conversely, countries with low HWU/GWR ratios, common in Africa due to geology, benefit from regular replenishment and reliable water sources. However, excessive pumping, especially for large-scale irrigation, can cause groundwater depletion during droughts, particularly in areas where water resources are limited or under stress. The observed differences in HWU/GWR ratio trends between RCP 2.6 and RCP 8.5 in the Central Africa Republic (Fig. 17) could be related to various factors. Here are some potential reasons: RCP 2.6 and RCP 8.5 represent different climate change scenarios with varying levels of greenhouse gas emissions and global temperature increases. The differences in HWU/GWR ratio trends could be attributed to the contrasting climate conditions projected under these scenarios. RCP 2.6 assumes more stringent mitigation efforts, resulting in lower emissions and potentially more favorable conditions for groundwater recharge compared to RCP 8.5, which represents a high-emission scenario. Additionally, climate change can lead to changes in precipitation patterns, including alterations in rainfall intensity, duration, and spatial distribution (Riahi *et al.*, 2011; Dosio *et al.*, 2015; MacDonald *et al.*, 2021b). These changes may impact the amount and timing of recharge, influencing the HWU/GWR ratio trends. Differences in recharge ratio trends between RCP 2.6 and RCP 8.5 could be related to variations in projected precipitation patterns under these scenarios (Riahi *et al.*, 2011; Cook *et al.*, 2022). For the RCP 2.6. scenario, HWU/GWR ratio is increasing up to 0.025 high than RCP 8.5 in Central Africa Republic. The similar trends of the HWU/GWR ratio in the scenarios RCP2.6 and RCP8.5 in Lesotho, South Africa, and Eswatini (see Figure 16) could be explained by several potential factors, such as: the changes in precipitation for both scenarios and changes in evapotranspiration. On the other hand Scanlon *et al.* (2012), Taylor *et al.* (2019) and MacDonald *et al.* (2021b) mentioned that five countries, including Eswatini and Lesotho, have storage and recharge rates below the African average. These countries are often water insecure and vulnerable to short-term climate hazards and long-term depletion. This suggests that the HWU/GWR ratio in Lesotho and Eswatini may be relatively low compared to other countries in the region. The HWU/GWR ratio in Lesotho, South Africa, and Eswatini, as well as other countries in the region, may be influenced by the aridity or semi-aridity of the area. The differences in HWU/GWR ratio trends between RCP 2.6 and RCP 8.5 in Mali and Niger (see Figure 20) can have several implications. The differences in HWU/GWR ratio trends between the two scenarios can reflect the impact of climate change on groundwater recharge. RCP 2.6 represents a lower greenhouse gas emissions scenario, while RCP 8.5 represents a higher emissions scenario. If Niger shows a higher HWU/GWR ratio under RCP 8.5 compared to RCP 2.6, it suggests that the projected impacts of climate change, such as changes in precipitation patterns, may have a more negative effect on groundwater recharge in Niger under the higher emissions scenario. Gambia and Senegal have shown a high projected HWU/GWR ratio in the region which indicates that the demand for the projected water is high compared to the recharge replacement. The observed differences in the HWU/GWR ratio trends (Figure 19) among the countries in Northern Africa highlight the complex and region-specific nature of groundwater recharge. One study mentioned that the recharge rates in Africa largely vary according to mean annual precipitation, with higher rainfall areas having higher recharge rates (Mileham *et al.*, 2009; Fotso-Nguemo *et al.*, 2019; Tangang *et al.*, 2020). This suggests that differences in precipitation patterns between Egypt and Libya could contribute to the observed differences in recharge ratios. Another study mentioned that hydrogeological conditions, such as soil properties and aquifer types, can impact the recharge amount (Op de Hipt *et al.*, 2018). The main reason for the difference in hydrological condition between Egypt and Libya will be that water consumption in Egypt is much higher than in Libya. HWU is much higher. GWR is very low in both countries. The high HWU/GWR ratio in Egypt is due to the limitation of groundwater recharge and the high demand of human water use. In their studies, Sherif *et al.*, (2023) demonstrate that excessive groundwater abstraction in the Nile Delta area has caused a significant decline in groundwater levels, leading to seawater intrusion that extends over 100 km from the shoreline.

3.7. Implications and Future Considerations

- **Water Security**

This subsection discusses the relationship between HWU/GWR ratio and water security in African countries. It highlights that many countries with low rainfall are typically considered water insecure. Traditional assessments of water stress and security often overlook groundwater storage and focus on annual ratios of renewable water to water use. However, the concept of sustainability has evolved, considering context-specific priorities, including the Sustainable Development Goals. Several countries, particularly in North Africa, exhibit considerable water security when groundwater storage is considered. MacDonald et al. (2016) demonstrate that such abstraction can be continued in large aquifers but not without degradation. Similar degradation occurs in smaller, heavily exploited aquifers in North Africa, such as the Souss in Morocco (Mohamed and Gonçalvès, 2021). As groundwater levels fall and groundwater discharge reduces in response to abstraction, ecological consequences can occur and include the destruction of wetlands, reduction of base flow in rivers, land subsidence and increases in salinity. According to Sherif *et al.* (2023) the percentage of total groundwater use ranges from 0.06 in Libya, and northwestern African countries (Tunisia, Algeria, and Morocco), groundwater use far exceeds the renewal rate. Most aquifers in these regions used for irrigation are at least partially depleted. Sherif *et al.* (2023) demonstrated that groundwater is the second source of water in Egypt after the Nile River. However, in the Nile Delta area, excessive abstraction has led to the depletion of groundwater levels, resulting in seawater intrusion extending more than 100 km from the shoreline. In the Egyptian Western Desert, groundwater resources are estimated to be around 28,000 billion Cubic Meters (BCM), with a natural recharge rate of about 120 million Cubic Meters per year (MCM), which is much lower than the present extraction rate of 4000 (MCM/year) (Sherif *et al.*, 2023). This assertion can explain the found HWU/GWR ratio (see Figure 16 and 18 in the result section) as human water use is exploiting non-renewable groundwater resources (from storage) and surface water flow which enters the country from outside (Nile river). These findings highlight the challenges and implications of groundwater management and sustainability in Egypt.

3.7.1. Impact of climate change on groundwater recharge

Climate change alters total runoff and the partitioning of runoff, leading to changes in groundwater recharge. Increased temperatures result in higher potential evapotranspiration and decreased total runoff. However, the primary driver of changes in total runoff and groundwater recharge is the change in precipitation (Larbi *et al.*, 2021). Climate change-induced temporal variability in precipitation can lead to soil crusting and hydrophobic soils, reducing groundwater recharge. This decrease in recharge can lead to a drop in the groundwater table, affecting vegetation negatively (Doll and Fiedler, 2008). On the other hand, increased groundwater recharge may also present challenges, especially in areas with vegetation accustomed to lower water tables or in built-up urban areas.

Different studies and models have projected changes in groundwater recharge under climate change scenarios. Some regions may experience very strong decreases in groundwater recharge. Such as Northern Africa including countries like Egypt, South Sudan and in all the five countries in Southern Africa presented in this work. Others show variations based on local hydrodynamic parameters (Al-Gamal, 2021), like for Niger, Mali and most countries in Eastern Africa where under RCP 2.6 positive trends in GWR are expected. The vulnerability of groundwater resources to climate change is evident in various regions such as Northern Afrcia, Southern Africa and West Africa, emphasizing the need for sustainable groundwater management practices to address the impacts of climate change.

3.8. Implications for green hydrogen production

One of the fundamental determinants for successful green hydrogen production is water availability. The study's comprehensive evaluation demonstrates that, on the whole, African countries possess sufficient or sustainable water resources to support green hydrogen production over extended periods. This discovery brings forth promising prospects for the development of green hydrogen initiatives throughout the continent. Nevertheless, to ensure accuracy and reliability, further investigations at the country level are necessary to account for the variances in water availability among different regions. The study effectively identifies specific areas with high projected recharge trends and sustainable groundwater yields, most notably in West Africa's coastal zone, Central Africa near the equator, and Southern Africa after removing the need of environment and human. It is remains 44.44 to50 mm/year for green hydrogen production. These regions emerge as potential ideal locations for hosting green hydrogen projects due to their favorable water resource conditions. Notably, the Sahara zone, including countries like Mali, Niger, and Mauritania, exhibits good potential, which varies between 22.22 to 27.78 mm/year in optimum scenario for the both climate scenarios. Although implementing green hydrogen projects in this region might entail higher energy demands compared to the coastal and equatorial zones. The high energy demand could be explained by the depth of the groundwater. For more explanation about groundwater recharge depth in Africa see Fan et al. (2013). To overcome the energy challenges associated with green hydrogen production in the Sahara zone, solar energy is available but water resources are limited. Harnessing renewable energy, particularly solar and wind power, holds significant promise in offsetting the higher energy demand for electrolysis. Integrating renewable energy into the production process can contribute to both environmental sustainability and the economic viability of green hydrogen projects in the region. Climate change represents a critical aspect that can significantly influence groundwater recharge trends in various countries. The study delves into the impact of climate change by analyzing different climate scenarios (RCP 2.6 and 8.5) from 2015 to 2100. The findings highlight the vulnerability of Northern Africa, encompassing countries like Egypt, Morocco, and South Africa, which may face a decline in groundwater recharge trends and HWU/GWR ratio is approximately up to 0.6 in RCP 2.6 and 0.8 in the Northern Africa. This situation is particularly concerning as Northern Africa heavily relies on groundwater for irrigation, and climate change could exacerbate the already existing challenges. However, to gain a comprehensive understanding of the implications of climate change on groundwater recharge, further on-ground investigations are warranted. Green hydrogen production also holds significant promise in driving economic development in African countries. The study's insights into the potential of sustainable groundwater yield enable the evaluation of the feasibility and viability of green hydrogen projects in specific regions. Regions with higher projected groundwater yields are poised to attract more investment opportunities, potentially leading to economic growth and prosperity. Environmental impact considerations play a crucial role in decision-making for green hydrogen investments. Countries with sustainable groundwater yields and lower environmental impacts become more attractive for green hydrogen projects. It is essential to prioritize the responsible and sustainable use of groundwater resources to ensure the long-term viability of green hydrogen production while safeguarding the environment. However, effective water resource management is a pivotal factor for the success of green hydrogen projects in African countries. The study's analysis of projected groundwater sustainable yield provides valuable insights that can inform the development of policies and practices promoting sustainable groundwater use. By implementing robust water management strategies, African countries can ensure

responsible water use for green hydrogen production and other essential purposes.
Strategic measures are imperative to address water availability challenges in regions or countries where groundwater resources are insufficient to sustain green hydrogen production. Additionally, diverse renewable energy (RE) technologies, including Concentrated Solar Power (CSP) and photovoltaic systems, have their own distinct water requisites. Therefore, it is crucial that water utilization across the hydrogen production cycle avoids adverse impacts on local water supply and alleviates conflicts of usage, particularly in regions lacking sufficient groundwater for large-scale green hydrogen production. However, it is important to acknowledge that this approach entails higher energy consumption and costs when compared to regions or countries benefiting from abundant groundwater resources. Furthermore, the H2ATHLAS project highlights a significant challenge pertaining to the assurance of adequate water resources within the northern regions of the ECOWAS states, catering to both the burgeoning population demands and the imperative of green hydrogen production. In response, the establishment of sustainable energy sources within these northern areas necessitates the efficient transmission of generated energy to the coastal regions through a robust and optimized power grid infrastructure. This approach is particularly suited for countries exhibiting a high HWU/GWR ratio. In effect, this strategic framework effectively addresses the intricate interplay between the availability of water resources and the advancement of green hydrogen technologies across African nations. It encapsulates a multidimensional solution that leverages geographical disparities to achieve a cohesive and sustainable synergy between energy production and hydrogen generation.

PARTIEL CONCLUSION

In the context of the RCP2.6 scenario, we observe minor decreases in groundwater recharge (GWR) with varying trends across regions and countries. However, under the RCP8.5 scenario, all African regions and countries experience a negative trend in GWR. The most significant impact is seen in Central Africa, Southern Africa, and Northern Africa, where GWR declines significantly. At the national level, there are variations in the human water use to groundwater recharge (HWU/GWR) ratio, with RCP8.5 generally exhibiting higher ratios compared to RCP2.6. The analysis of sustainable yield highlights the highest potential in the southwest region of West Africa, with variations in potential across other regions. The RCP2.6 scenario shows more favorable outcomes for groundwater recharge, while the RCP8.5 scenario presents challenges with declining recharge rates. These results underscore the importance of climate action to mitigate the negative impacts on groundwater resources, especially in regions highly vulnerable to climate change.

GENERAL CONCLUSION AND PERSPECTIVES

GENERAL CONCLUSION AND PERSPECTIVES

This study has provided valuable insights into the projected groundwater sustainable yield in African countries and its implications for green hydrogen production. The analysis revealed that Africa possesses a significant groundwater recharge surpassing other freshwater sources on the continent. The integration of data from climate models, including General Circulation Models (GCMs), Regional Climate Models (RCMs), the CLM model was the main tool in the assessment. Climate models and PCRGLOBWB provided input data for the assessment. Water balance assessments and statistical analysis, contributed to a comprehensive understanding of groundwater recharge dynamics.

Through the examination of two climate scenarios (RCP 2.6 and 8.5) from 2015 to 2100, this research evaluated trends in groundwater recharge and the human water use/groundwater recharge ratio (HWU/GWR ratio) in 51 African countries. The results obtained in this work showed that, the projected recharge for Africa ranges from 118.75 to 120.01 [mm $year^{-1}$] under RCP 2.6 and from 89.33 to 114.51 [mm $year^{-1}$] under RCP 8.5. Notably, RCP 2.6 shows higher average recharge than RCP 8.5. Human water consumption rises continent-wide. Comparing RCP 2.6 and RCP 8.5, RCP 2.6 predicts lower human water use (3.49 to 6.22 [mm $year^{-1}$] vs. 3.67 to 6.77 [mm $year^{-1}$]). West Africa's HWU/GWR ratio increases until 2050 up to 0.10 in RCP 2.6, stabilizing afterwards. In RCP 8.5, it rises until 2090 above 0.3 and then decreases. The findings unveiled considerable variations in groundwater recharge and HWU/GWR ratio across regions, with specific areas demonstrating high potential for green hydrogen production. Notably, regions such as West Africa (coastal zone), Central Africa (tropical zone near the equator), and Southern Africa exhibit promising sustainable groundwater yields for long-term green hydrogen production. However, the Sahara zone, encompassing countries like Mali and Niger, showed potential for green hydrogen projects, albeit necessitating additional energy resources compared to the coastal and equatorial zones. Climate change impacts were evident, particularly in Northern Africa, where decreasing groundwater recharge trends raised concerns about exacerbating existing water scarcity issues. Particularly GWR trends in Egypt and South Sudan are negative in both RCP 2.6 and 8.5 (-0.004 and -0.011 %; -0.074 and -0.144 % respectively), whereas under RCP 2.6, Libya, Western Sahara, Morocco, Tunisia, Algeria, and Sudan exhibit positive trends (0.005, 0.0008, 0.062, 0.027, 0.013, and 0.00 %respectively), indicating an increase in recharge. Conversely, these regions experience a decreasing trend under RCP 8.5. In addressing these challenges and ensuring the long-term viability of green hydrogen production, sustainable groundwater management, and responsible water resource practices are essential. The investigation of climate change impacts on groundwater recharge underscored the importance of understanding recharge trends and the HWU/GWR ratio over time. These insights are invaluable in formulating region-specific water management strategies to optimize groundwater resources under changing climatic conditions. By leveraging the potential of sustainable groundwater yield, African countries can drive economic development, mitigate environmental impacts, and promote the growth of green hydrogen projects, paving the way for a sustainable and greener future.

These findings emphasize the significance of sustainable water management and the integration of renewable energy sources to achieve a resilient and environmentally conscious future for Africa's water and energy sectors. Ultimately, this study contributes to advancing knowledge in the field of green hydrogen production and water resource management, offering valuable guidance for policymakers, stakeholders, and investors in shaping a sustainable future for the African continent.

PERSPECTIVES

Like any research endeavor, this study acknowledges that it is impossible to cover all aspects initially planned. Hydrological modeling of groundwater relies on abundant data availability, influenced by complex factors like geology, land use, and weather. This study focuses on the spatial and temporal distribution patterns of groundwater recharge, human water use, the HWU/GWR ratio, and groundwater sustainable yield. A main limitation is the lack of comprehensive data, notably geological, hydrogeological and the various sources of nourishment of aquifers. Therefore, more extensive research is needed to confirm or refute hypotheses linked to groundwater storage in aquifers, permeability of aquifers and also aquifer pollution.

Nonetheless, the study's knowledge, data, and methods will guide future research. This study results mostly relay on the CLM5 model which is a 1-D model neglecting lateral water flow. Coupling CLM with a sub-surface model could improve the interaction of land surface and sub-surface and can potentially result in more realistic results. Detailed water quality analysis for green hydrogen in Africa requires extended, consistent monitoring over time, potentially including the placement of observation wells in unpopulated areas to refine data. Sampling campaigns should be conducted across countries with high yield potential to pinpoint limiting factors influencing project development.

Given the uncertainties surrounding climate change's groundwater impacts, adaptive and informed groundwater management is vital. This requires expanding groundwater and meteorological monitoring systems on the ground at various scales to assess how groundwater responds to human and climate influences. This expansion requires not only increased scientific understanding of aquifer systems but also improved institutional arrangements, fostering cooperation among nations sharing groundwater resources.

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ANNEXES: Groundwater Recharge Trends in Africa Sub-regions (Tables 3-7) under RCP 2.6 and 8.5.

Table 3:Groundwater Recharge Trends in Southern Africa under RCP 2.6 and RCP 8.5:

Country	**Slope % RCP 2.6**	**Slope % RCP 8.5**
Botswana	-0.155	-0.676
Namibia	-0.128	-0.468
South Africa	-0.169	-0.588
Lesotho	-0.388	-0.902
Eswatini	-0.039	-0.872

Table 4:Groundwater Recharge Trends in Central Africa under RCP 2.6 and RCP 8.5:

Country	**Slope % RCP 2.6**	**Slope % RCP 8.5**
Angola	-0.192	-1.257
Cameroon	-0.107	-0.986
Central African Republic	-0.075	-0.321
Chad	-0.632	-0.673
Republic of the Congo	-0.086	-1.510
Democratic Republic of the Congo	-0.091	-1.634

Gabon	-0.124	-2.628
Equatorial Guinea	0.0176	-3.091

Table 5:Groundwater Recharge Trends in Eastern Africa under RCP 2.6 and RCP 8.5:

Country	Slope % RCP 2.6	Slope % RCP 8.5
Mozambique	-0.063	-0.305
Zimbabwe	-0.041	-0.385
Malawi	-0.181	-0.293
Zambia	-0.169	-0.802
Somalia	0.292	0.529
Kenya	0.128	0.316
Somaliland	0.442	0.834
Djibouti	0.292	0.476
Rwanda	0.147	-0.501
Ethiopia	0.113	-0.056
Burundi	0.117	-0.072
Madagascar	0.070	-0.349

Country	Slope % RCP 2.6	Slope % RCP 8.5
Eritrea	0.222	-0.620
Uganda	0.084	-0.922
Tanzania	0.023	-0.058

Table 6:Groundwater Recharge Trends in Northern Africa under RCP 2.6 and RCP 8.5:

Country	Slope % RCP 2.6	Slope % RCP 8.5
Egypt	-0.004	-0.011
South Sudan	-0.074	-0.144
Libya	0.005	-0.002
Western Sahara	0.0008	-0.036
Morocco	0.062	-0.114
Tunisia	0.027	-0.021
Algeria	0.013	-0.058
Sudan	0	-0.274

Table 7: Groundwater Recharge Trends in West Africa under RCP 2.6 and RCP 8.5:

Country	Slope % RCP 2.6	Slope % RCP 8.5
Senegal	-0.083	-0.288
Mauritania	-0.016	-0.099
Gambia	-0.106	-0.372
Mali	-0.004	-0.225
Burkina Faso	0.0067	-0.342
Benin	-0.039	-0.511
Togo	-0.073	-0.820
Ghana	-0.078	-0.820
Guinea	-0.083	-1.233
Nigeria	-0.053	-0.900
Sierra Leone	-0.556	-1.489
Liberia	0.081	-1.448
Cote d'Ivoire	0.013	-0.633
Guinea Bissau	0.135	-0.067