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Projected increase in stress on African potential groundwater resources due to climate change and increased human water use

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Abstract

Africa's groundwater systems lie at the nexus of escalating human water demands and the intensifying impacts of climate change. This necessitates an understanding of projected groundwater recharge, evolving human water use, and their spatio-temporal interactions. This study performs high-resolution simulations to assess the response of potential groundwater recharge (PGWR) to human water use (HWU) across Africa and under two climate scenarios: RCP2.6 (low emissions) and RCP8.5 (high emissions), throughout the 21st century. The findings reveal marked geographical variability in simulated PGWR, with countries such as Sierra Leone, Liberia, Ethiopia, and parts of Central Africa exceeding 400 mm/year recharge, while hyper-arid regions like the Sahara, Kalahari Desert, and Mandera tripoint remain consistently low. Under RCP8.5, a continent-wide decline of 30.9 mm/year (25.1%) in PGWR is projected from the near future (2015–2044) to the far future (2071–2100), alongside a significant increase in interannual variability. In contrast, RCP2.6 presents a milder trajectory, with continental PGWR declining by only 2.9 mm/year (2.3%), yet demand continues to rise under both scenarios. HWU increases steadily, particularly under RCP8.5 where the average continental consumption reaches 6.6 mm/year. Domestic water use remains dominant under RCP2.6, while irrigation water use expands significantly under RCP8.5, especially in North Africa. Substantially, the fraction of recharge consumed by humans reaches 35.6% in North Africa and 12.6% in West Africa by century's end. Most notably, 7 countries including Morocco, Algeria, Libya, Egypt, Kenya, Uganda and Nigeria are projected to exploit more than 80% of simulated local PGWR under RCP8.5, suggesting possible hotspots of unsustainable use and potential groundwater depletion for an estimated projected population of 685 million people (52.9% African population) by 2045 and 1.031 billion people (72.43%) by 2100. These results underscore the critical need for proactive, region-specific water governance strategies, particularly in highly stressed regions. Without adaptive intervention, the sustainability of groundwater, which is a cornerstone for drinking water, food production, and ecosystem stability, will be at increasing risk in a warming world.

1 Introduction

Groundwater depletion is a global concern. Global abstraction of groundwater for human water use has increased over the past century from an estimated 283km^3/year in the 1960s (Wada et al., 2010) to between 650-1000km^3/year in recent decades (Nazari et al., 2025). Over-exploitation of groundwater contributes to sea level rise (Wada et al., 2010) and pose a threat to local (Srinivasan et al., 2023, Devineni et al., 2022) and global water security (Famiglietti,

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2014). North Africa, the Middle East, South and Central Asia, North China, North America and Australia are regions known to be affected by excessive groundwater depletion (Konikow & Kendy, 2005) while countries including Pakistan, USA, India, Mexico, Iran and China experience groundwater depletion problems as they both produce and import food irrigated from fast declining groundwater resources, which are under increased stress in these countries.

Similar to these global hotspots of groundwater stress, Africa now faces mounting pressure on groundwater resources due to both increasing human water use and the impacts of climate change (Altchenko & Villholth, 2015). Major African cities including Nairobi, Addis Ababa, Cape Town, Dakar, Lagos and Lusaka increased their water demand due to their expansion, leading to over-extraction of groundwater resources. The depletion of groundwater in the Nairobi Aquifer System in Kenya, for instance, has worsened 10-fold since the mid-1970s, with groundwater levels decreasing at a median rate of 6 m/decade since 1950 (Oiro et al., 2020). Also, groundwater scarcity contributed to unrest in Somalia (Banks, 2008).

The availability (MacDonald et al., 2012a,·Edmunds, 2012,·R. G. Taylor et al., 2013) and sustainability (Lutz et al., 2011,·Bayat et al., 2023,·Gaye & Tindimugaya, 2019,·R. G. Taylor et al., 2019,·Aizebeokhai et al., 2019) of groundwater resources in Africa have been assessed at continental and sub-continental scales. These studies reviewed existing groundwater resources knowledge, measurements and mechanistic modelling of Africa's groundwater recharge. They show that despite several challenges faced in assessing and quantifying groundwater resources over Africa, there is potential to meet Africa's groundwater needs in a sustainable manner considering current climate conditions and water consumptions. To the best of our knowledge, however, no study has yet conducted high-resolution climate projections of groundwater recharge across continental Africa to understand the future trends of groundwater resources as applicable to specific communities or localized areas. In addition, stress on groundwater resources, particularly on groundwater recharge, is not only influenced by climate change, but also by changing human water use in the future. Given Africa's population growth rate of 2.5% per year (Abramova, 2022,·You et al., 2015), and an estimated 2.123 Billion people (Cleland & Machiyama, 2017) by 2050, it is important to consider projections of human water use for different sectors.

In this study, we explore the future of Africa's potential groundwater recharge dynamics under the climate conscious (RCP2.6) pathway (also known as an optimistic scenario) and the business-as-usual pathway (RCP8.5) (also known as a pessimistic scenario) at 10km spatial resolution. The Community Land Model version 5.0 (CLM5) (Lawrence et al., 2019) is used to simulate potential groundwater recharge based on six General Circulation Model/Regional Climate Model (GCM-RCM) combinations within the COordinated Regional Downscaling EXperiments (CORDEX) framework (Taylor et al., 2012) and human water use projections from the PCRaster GLOBal Water Balance model (PCRGLOBWB2.0) (Sutanudjaja et al., 2018a,·Kuzma et al., 2023) hydrological model are also analysed. Furthermore, we estimate how the ratios of projected human water use and groundwater recharge change to gain insight on the stability and sustainability of future water consumption over Africa, its regions and countries. This study therefore investigates the spatio-temporal dynamics of groundwater recharge and human water use across Africa under different climate change scenarios, to assess where and to what extent groundwater systems may face increasing stress in the 21st century.

2 Data & Methods

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2.1 Climate Forcings and Land Surface Simulations

To assess long-term groundwater recharge dynamics, we employed CORDEX-Africa downscaled climate projections for two carbon dioxide equivalent Representative Concentration Pathways (RCP2.6 and RCP8.5), driven by two global climate models (GCMs): MPI-ESM (Giorgetta et al., 2013) and NorESM (Bentsen et al., 2013). These projections were dynamically downscaled using three regional climate models (RCMs): CCLM5 (Sørland et al., 2021), REGCM4 (Giorgi et al., 2012), and REMO2015 (Pietikäinen et al., 2018), over the CORDEX-Africa domain. These climate forcings were used to drive the Community Land Model version 5 (CLM5), resulting in 12 unique simulations (2 GCMs × 3 RCMs × 2 RCPs), each at 0.1° by 0.1° (approx. 11km by 11km) spatial resolution. Simulations covered the period 2006–2100, with the first 10 years designated as spin-up years. Results were aggregated to annual sums. Land surface parameters, including soil texture, vegetation types, and leaf area index, were maintained consistently across simulations as described in previous studies (Bayat et al., 2023; Oloruntoba et al., 2025).

2.2 Community Land surface Model version 5 (CLM5)

The CLM5 model was configured in land-only mode also known as offline mode, which means there is no coupling of the land surface model with either an atmospheric model or subsurface model. Atmospheric forcings for CLM5 are precipitation, incoming shortwave radiation, air temperature, air pressure, specific humidity, wind speed and incoming longwave radiation. CLM5 uses a revised canopy interception scheme to distinguish between liquid and solid precipitation, improving simulation of interception and canopy interactions. Soil thickness in CLM5 is spatially explicit (0.4m-8.4m) and soil layering in the upper 3m has been refined to capture shallow processes explicitly using a soil thickness data product (Pelletier et al., 2016). Surface runoff in CLM5 is calculated using the simple TOPMODEL-based (Beven & Kirkby, 1979) SIMTOP scheme (Niu et al., 2005) which connects runoff generation to topographic characteristics and soil moisture conditions. A dry surface layer-based soil evaporation resistance parameterization is invoked by CLM. Transpiration is coupled with photosynthesis via stomatal conductance and responds non-linearly to absorbed radiation. Infiltration is calculated as the soil moisture flux that remains after surface runoff has been removed. The amount retained by the soil is constrained by the maximum infiltration capacity which depends on soil saturation and an ice impedance factor. Whenever incoming soil water exceeds the maximum infiltration capacity, infiltration excess also known as Hortonian runoff is generated and routed back to the surface water store (D. Lawrence et al., 2018). Hydraulic properties which influence the Hortonian runoff and the entire infiltration process are computed to simulate soil moisture transport in the unsaturated soil according to Richards´ equation. These properties are porosity, saturated hydraulic conductivity and soil matric potential at the interface of all soil layers dependent on the combination of soil texture and organic matter content.

The land surface model by default performs its calculations on a timestep of 30 minutes representing a balance between computational efficiency and resolving diurnal variability in the land atmosphere exchanges. Land-atmosphere exchange fluxes of energy and water are calculated each 30 minutes together with state variables like soil moisture, soil temperature and snow water equivalent. Processes that have faster dynamics, like water movement, canopy interception and runoff generation are handled using iterative or sub-stepping schemes like adaptive time stepping (Kavetski et al., 2002) for soil moisture calculations to keep numerical stability. These configurations enable CLM5 to provide a physically consistent and computationally efficient representation of the land-atmosphere, water and energy exchanges,

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making it suited for high resolution simulations (Bayat et al., 2023; Oloruntoba et al., 2025) and other interdisciplinary studies (Ishmam et al., 2024; Winkler et al., 2025) over continental Africa.

2.3 Potential Groundwater Recharge Estimation

Potential Groundwater recharge (PGWR, mm/year) was computed using a water balance approach (Bayat et al., 2023) on a yearly basis:

$$PGWR = RAIN + IRR - SR - ET \quad (1)$$

where RAIN is precipitation (mm/year). IRR represents irrigation, which is the internal mechanism within CLM5 where water is automatically added from river storage to only the irrigated soil column to maintain target soil moisture levels, which are dynamically determined based on the grid cell's soil moisture content and only if Leaf Area Index (LAI) is above a certain threshold. This process is part of CLM5's biophysical parameterization active for only irrigated croplands during crop growth (D. Lawrence et al., 2018; Oloruntoba et al., 2025). SR denotes surface runoff (mm/year), and ET is total evapotranspiration (mm/year). The near future (NF; 2015-2044) and far future (FF; 2071-2100) climate windows were subsequently extracted from the full simulation period for further analysis.

2.4 Trend and Rate of Change Analysis

To examine temporal trends and quantify rates of change in potential groundwater recharge, we computed the ensemble mean across the six GCM-RCM simulations for each grid cell and each year associated with each RCP. Linear regression was applied to each grid cell, treating time as the independent variable and groundwater recharge as the dependent variable:

$$PGWR_t = \alpha + \beta t \quad (2)$$

Here, $PGWR_t$ represents annual groundwater recharge, t is time, α is the intercept, and β indicates the slope, which corresponds to the average rate of change over time mm/(year^2).

2.5 Regional Partitioning

For regional assessments, Africa was divided into five geographical regions based on national administrative boundaries: North Africa, West Africa, East Africa, Central Africa, and Southern Africa. This classification followed earlier work (Bayat et al., 2023) and was based on delineations provided by Maps of World (https://www.mapsofworld.com/africa/regions/; last accessed: 11 May 2026).

2.6 Statistical Attribution of Groundwater Recharge Drivers

To investigate the climatic drivers influencing changes in PGWR between the NF and FF, we computed Pearson correlation coefficients among the differences in rainfall (ΔRAIN), potential evapotranspiration (ΔPET), and PGWR (ΔPGWR). The Pearson correlation coefficient was calculated using:

$$r = \frac{\sum_{i=1}^{n}(x_i - \bar{x})(y_i - \bar{y})}{\sqrt{\sum_{i=1}^{n}(x_i - \bar{x})^2}\sqrt{\sum_{i=1}^{n}[\![(y]\!]_i - \bar{y})^2}} \quad (3)$$

where r is the Pearson correlation coefficient, n is the number of paired observations, x_i and y_i represent the individual sample points of variables x and y, and $\bar{x}$ and $\bar{y}$ are their respective sample means. The numerator reflects the covariance between x and y, while the denominator is the product of their standard deviations. This normalization ensures that r is bounded

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between –1 and +1, indicating the strength and direction of the relationship between the two variables.

2.7 Quantifying Interannual Variability

To assess changes in interannual variability of PGWR, we computed the coefficient of variation (CV) for each grid cell defined as the ratio of the temporal standard deviation to the mean potential groundwater recharge expressed as a percentage.

For each gridcell (i), model simulation (m), climate scenario (s) and climate window (w), the temporal mean PGWR was first computed as:

$$\overline{PGWR}_{i,m,s,w} = \frac{1}{N_w}\sum_{t=1}^{N_w} PGWR_{i,m,s,w,t} \quad (4)$$

where $PGWR_{i,m,s,w}$ is the annual potential groundwater recharge at grid cell i, from model simulation m, under scenario s, within climate window w, and year t. N_w is the number of years in the climate window.

The temporal standard deviation of *PGWR* was then calculated for each grid cell and model simulation as:

$$\sigma_{i,m,s,w} = \sqrt{\frac{1}{N_w}\sum_{t=1}^{N_w}\left(PGWR_{i,m,s,w,t} - \overline{PGWR}_{i,m,s,w}\right)^2} \quad (5)$$

The coefficient of variation was calculated as:

$$CV_{i,m,s,w} = \frac{\sigma_{i,m,s,w}}{\overline{PGWR}_{i,m,s,w}} \times 100 \quad (6)$$

Finally, the ensemble-mean coefficient of variation for each grid cell, scenario and climate window was obtained by averaging across the six model simulations:

$$\overline{CV}_{i,s,w} = \frac{1}{M}\sum_{m=1}^{M} CV_{i,m,s,w} \quad (7)$$

where M=6 represents the six GCM-RCM model combinations used for each RCP scenario.

Figures S7-S10 show interannual variability for each model output under each climate window and climate scenario.

2.8 Comparison of simulated Potential Groundwater recharge with other datasets

The consistency of the simulated groundwater recharge was assessed using three reference datasets in a multi-metric analysis. The datasets include two reanalyses: ERA5-Land (Copernicus Climate Change Service, 2019) and GLDAS (Beaudoing et al., 2020) datasets for comparison of 11 overlapping years (2015-2025) and one CMIP-6 climate projection dataset

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WaterGAP-GFDL (Gosling et al., 2026). Due to difference in model structure forcing data and underlying simulation assumptions, direct comparison of absolute recharge values is not meaningful. This verification focused on diagnostics which assess consistency in recharge temporal correlation, long term trends and variability regimes. The three complementary metrics employed include: (i) temporal correlation (r) (limited to only GLDAS and ERA5) which was computed at each grid cell between annual PGWR time series and each of the reference datasets to measure the agreement in interannual variability and temporal co-evolution of the datasets, (ii) trend sign agreements where each matching grid cell for both datasets were classified into "both decreasing", "both increasing" and "mismatch" to show consistency in long term hydroclimatic signals independent of magnitude differences and (iii) coefficient of variation class agreement. This was calculated first for each grid cell in both datasets to classify them into "stable", "moderate" and "high" variability regimes. Agreement in variability between both datasets was then assessed. This measure shows the model's ability to reproduce spatial patterns of recharge variability. All assessments were performed separately for both climate scenarios over both the historical overlapping period and future projections.

2.9 Analysis of Human Water Consumption

Human water consumption across the African continent was assessed using output from the global hydrological model PCR-GLOBWB 2.0 (Sutanudjaja et al., 2018b, Kuzma et al., 2023). This model provides spatially explicit estimates of sectoral water withdrawals and consumptive use for the domestic, industrial, irrigation, and livestock sectors. The model is particularly relevant for this study due to its integration of both physical and anthropogenic water use processes, high spatial resolution (~5 arcmin), and use of globally consistent datasets, making it well-suited for assessing water demand in data-scarce regions such as Africa.

PCR-GLOBWB 2.0 simulates daily water balance components and anthropogenic water use based on gridded climate inputs (e.g., precipitation, temperature, reference evapotranspiration), land use information, population density, and sector-specific water use intensities. The model distinguishes between water withdrawals which were used in this study and actual consumptive use, accounting for return flows.

The model characterises sector-specific demand for domestic, industrial, irrigation and livestock uses and translates these demands to water withdrawal based on surface water and groundwater availability. It thereafter calculates consumptive use and return flows for the individual sectors. Irrigation demand responds to climatic conditions, crop types, irrigated area, soil moisture sufficiency and irrigation efficiency. Non-irrigation water demand are largely influenced by socio-economic drivers which include population and economic development.

For this study, the annual estimates of sectoral water withdrawals associated with the RCP2.6 and RCP8.5 climate scenarios were extracted and temporally aggregated over Africa for each year within the simulation period. An ensemble mean for each climate scenario was obtained from 5 different simulations where atmospheric input from five CMIP5 global models (Famien et al., 2018; Giordano et al., 2023; Zebaze et al., 2019) including GFDL-ESM2M, HadGEM2-ES, IPSL-CM5A-LR, MIROC-ESM-CHEM and NorESM1-M were varied. Sector specific demand formulations were implemented in PCR-GLOBWB 2.0. they include the effects of population, economic development, influence of climate, crop characteristics irrigated area, soil moisture conditions and irrigation efficiency on irrigation demand, The underlying future water use projections however, assume no further expansion of irrigated area

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after 2050 broadly consistent with FAO long-term projections which suggest limited expansion of irrigated land beyond mid century (Food and Agriculture Organization of the United Nations, 2011). The four primary sectors: domestic, industrial, irrigation, and livestock were analyzed individually and cumulatively to quantify total human water withdrawals. Firstly, the dominant sector per grid cell was identified by selecting the sector with the highest water withdrawals at each location. This provided a spatial overview of the prevailing sectoral water withdrawal patterns across the continent.

Subsequently, the total human water use, hereafter HWU per year was computed by summing all sectoral withdrawals at each grid cell and aggregating over the continent. Consistent with the approach used for groundwater recharge, temporal trends, continental and regional averages, as well as standard deviations and linear slopes, were computed for the total human water use dataset. This enabled a comparative analysis of trends in water demand and groundwater recharge under the different climate and water use assumptions considered in this study.

2.10 Estimation of Stress Ratio

PGWR Stress Ratio (SR) in this work was calculated as:

$$\mathrm{SR} = \frac{\mathrm{HWU}}{\mathrm{PGWR}} \times 100$$

where HWU is the sum of domestic, irrigation, livestock and industrial water use per grid cell and GWR is groundwater recharge as calculated using the water balance approach described in (1).

It compares projected HWU with simulated PGWR. While it does not represent measured groundwater abstraction, groundwater storage depletion or aquifer-level water balance, it shows the degree to which annual human water use approaches or exceeds the simulated groundwater recharge. Our SR index is conceptually like the Water Stress Index (WSI) (van Beek et al., 2011), which relates total human water demand to renewable freshwater availability. However, while WSI is based on surface freshwater availability, our index specifically measures human water use against simulated potential groundwater recharge, thus directly quantifying stress on the renewable potential groundwater flux. As groundwater constitutes the primary reliable source for many African regions (MacDonald et al., 2012b) especially where surface water is deficient, this metric provides a more focused indicator of groundwater sustainability.

We classify SR into five stress levels: low (SR<20%), moderate (20%≤SR<40%), high (40%≤SR<80%), severe (80%≤SR<100%), and critical (SR≥100%). These thresholds are conceptually consistent with widely used demand-to-availability stress indices (e.g., categories at 20% and 40%) but tailored to groundwater by relating it solely to the renewable recharge flux. Unless stated otherwise, we report R in stress classes (low, moderate, high, severe, critical), where critical (SR≥100%) indicates that annual demand meets or exceeds annual renewable recharge.

3 Results

3.1 Projected PGWR recharge over Africa

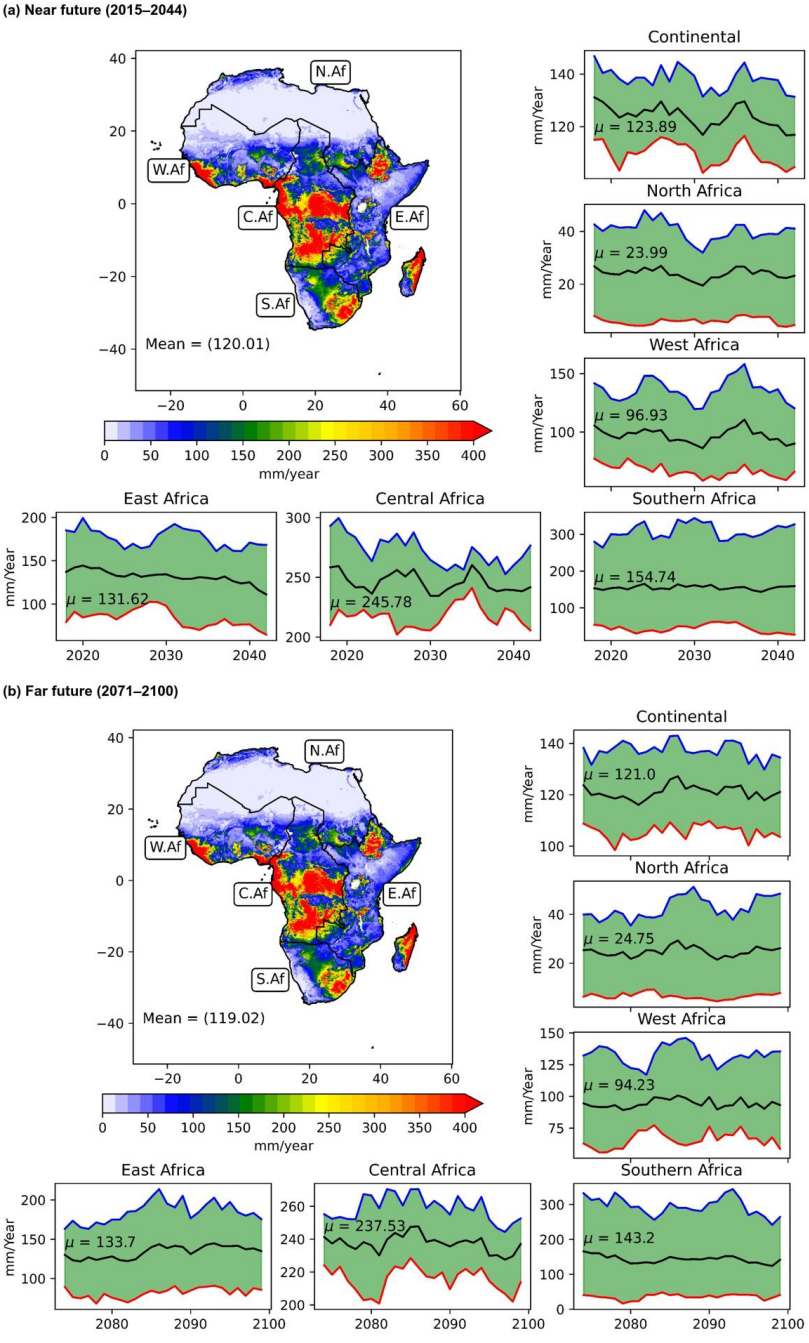
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The simulation of Africa's projected PGWR by CLM5 considering different CORDEX downscaled GCM outputs indicates varied responses to different climate scenarios and changes in climate (Fig. S1). In the 2015-2044 period (NF), the average continental groundwater recharge in Africa ranges from 107.4 mm/year (NOR-REMO2015) to 134.4 mm/year (NOR-REGCM4) under RCP2.6. Projections for the 2071-2100 period (FF) under the RCP2.6 scenario show an average continental potential recharge range of 104.4 mm/year (NOR-REMO2015) to 125 mm/year (MPI-CCLM5). For the RCP8.5 climate scenario (Fig. S2), the projected climate variations are broader, ranging from 100.8 mm/year (NOR-REMO2015) to 144.8 mm/year (MPI-REGCM4) in the NF compared to 68.2 mm/year (MPI-CCLM5) to 130 mm/year (MPI-REGCM4) in the FF. In both scenarios a decline of PGWR over the 21st century is anticipated, larger for RCP8.5 than for RCP2.6. The observed variability, especially for the RCP8.5 scenarios, highlights the uncertainty in future water availability and a critical need for reliable estimates which account for both climate scenario and model-dependent differences.

Under the RCP2.6 (Fig. 1) climate scenario, PGWR across Africa exhibits a heterogeneous pattern of change between the NF and the FF, showing a mixed regional response to long-term climate stabilization. At the continental scale, the time-averaged PGWR is projected to decline from 123.9 mm/year in the NF to 121.0 mm/year in the FF, representing a −2.3% change. This relatively small reduction suggests that mitigation measures associated with RCP2.6 may effectively constrain widespread decreases in PGWR, although not entirely eliminate them.

Regionally, North Africa demonstrates a 3.2% increase in PGWR, around 24.0 mm/year. Given the region's prevailing arid conditions, this marginal increase does not provide relief for water-stressed ecosystems and populations given increasing water consumption. Also East Africa exhibits an increase, of 1.6%, reaching 133.7 mm/year in the FF in agreement with earlier estimates (Reinecke et al., 2021). This stability highlights the region's relative resilience under a low-emissions climate trajectory. In contrast, Southern Africa is projected to experience the most substantial decrease, with PGWR declining by 7.5%, from 154.7 mm/year to 143.2 mm/year. This notable reduction is of concern considering the region's current high interannual rainfall variability which is influenced by oceanic oscillations such as El Niño Southern Oscillation (ENSO), Agulhas Current, Mozambique Channel and southwest Indian Ocean (Rouault et al., 2024) and increasing water demand (du Plessis, 2023). Central Africa, while maintaining the highest PGWR values across all regions, is projected to experience a 3.4% decline (245.8 mm/ to 237.5 mm/year). West Africa shows a 2.8% decrease in PGWR, highlighting the continued vulnerability of densely populated and agriculturally dependent areas (Brouillet & Sultan, 2023; Egbebiyi et al., 2020).

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Figure 1. *Projected PGWR over Africa under the RCP2.6 climate scenario for the near future (2015–2044, top) and far future (2071–2100, bottom). Central maps display the spatial distribution of mean annual PGWR (mm/year), while regional panels show the ensemble spread of spatially averaged PGWR for each of the five African regions and the continental mean. Black lines represent ensemble means, μ indicates continental or regional average, while shaded green areas indicate inter-model spread (bounded by the minimum (red) and maximum (blue) values).*

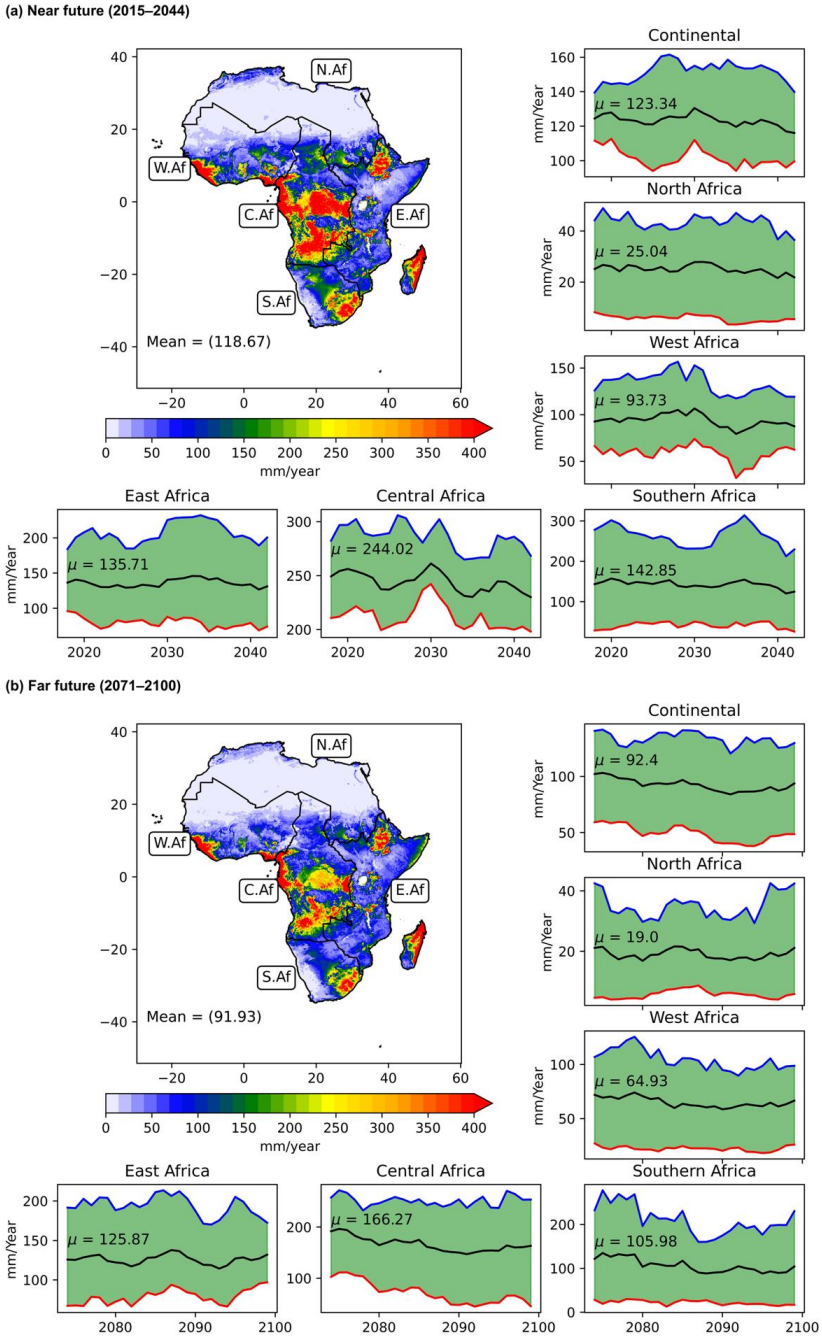
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Under the RCP8.5 climate scenario (Fig. 2), characterized by high greenhouse gas emissions and limited mitigation efforts, Africa is projected to experience substantial reductions in PGWR between the NF (2015–2044) and the FF (2071–2100). The results reveal a consistent downward trend across all spatial domains, reflecting the severe hydrological consequences of unmitigated climate change. At the continental scale, the spatially averaged PGWR computed as the mean across all land grid cells and time steps declines clearly from 123.3 mm/year in the NF to 92.4 mm/year in the FF, representing a 25.1% decrease. The time averaged values from the continental map also exhibit a comparable −22.5% change, declining from 118.7 mm/year to 91.9 mm/year meaning that the simulated changes are spatially widespread and not merely driven by a few extreme locations or years. This significant reduction at the continental level underscores the widespread impact of the RCP8.5 pathway on Africa's water resources.

Regionally, Central Africa, with the highest absolute PGWR values is projected to experience the greatest percentage decline, with PGWR decreasing by 31.9%, from 244.0 mm/year to 166.3 mm/year. West Africa follows closely, with a 30.7% reduction, emphasizing the vulnerability of the region's shallow aquifers and high dependency on seasonal rainfall. Southern Africa also shows a pronounced decline of 25.8%, further intensifying concerns for a region already exposed to recurrent droughts and high evapotranspiration (Lawal et al., 2022). In North Africa, PGWR is projected to decrease from 25.0 mm/year to 19.0 mm/year, amounting to a 24.1% decline. Although absolute values are low, the proportional reduction is critical in a region where groundwater represents a primary source of water supply (Abouelmagd & Ahmed, 2024). East Africa, while exhibiting the smallest reduction among all regions, still faces a 7.3% decline, from 135.7 mm/year to 125.9 mm/year, indicating that even relatively resilient areas will not be exempt from long-term hydrological stress under the business-as-usual climate scenario.

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Figure 2. *Projected groundwater recharge availability over Africa under the RCP8.5 climate scenario for the near future (2015–2044, top) and far future (2071–2100, bottom). Central maps display the spatial distribution of mean annual PGWR (mm/year), while regional panels show the ensemble spread of spatially averaged PGWR for each of the five African regions and the continental mean. Black lines represent ensemble means, μ indicates continental or regional average, while shaded green areas indicate inter-model spread (bounded by the minimum (red) and maximum (blue) values).*

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A comparative assessment of PGWR under RCP2.6 and RCP8.5 reveals large differences for the FF (2071–2100), underscoring the critical implications of global mitigation efforts. In the NF (2015–2044), the difference in continental mean PGWR between the two scenarios is relatively marginal (−0.44 mm/year), related to the fact that initially the climate change trajectories for both RCP´s do not differ much yet. However, by the FF, the differences between RCPs become pronounced and uniformly negative, with the continental mean PGWR under RCP8.5 decreasing by 28.6mm/year (23.6%) relative to RCP2.6. Central Africa, 71.3mm/year (−30.0%), West Africa, 29.3mm/year (−31.1%), and Southern Africa, 37.2mm/year (−26%) emerge as the most affected regions, highlighting the substantial hydrological toll of continued high emissions. These findings reinforce the critical importance of mitigation. In the absence of strong climate action, Africa faces substantial reductions in PGWR across all regions, which could intensify water scarcity, undermine agricultural productivity, and constrain socio-economic development. Conversely, the relatively stable projections under RCP2.6 offer a window of opportunity to preserve groundwater resources through effective emissions control.

3.2 Spatio-temporal analysis of PGWR trends over Africa

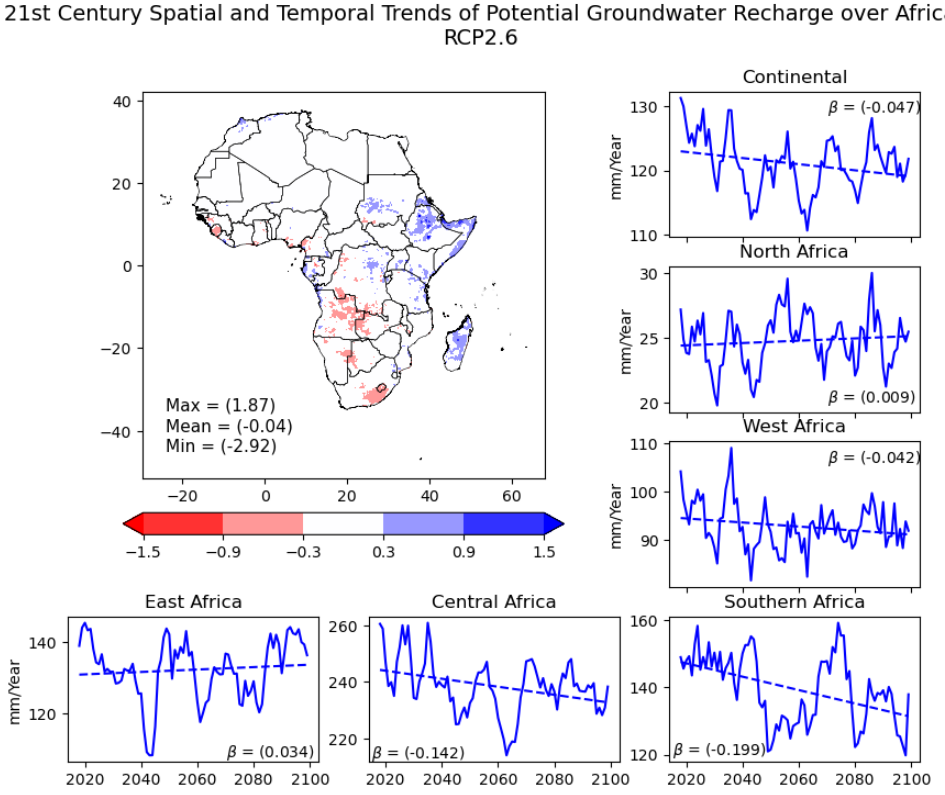


Figure 3 Spatial variation and temporal trends in PGWR across Africa throughout the 21st century under RCP2.6. Central map displays spatial variation trends in annual PGWR (mm/year²), with red shades indicating decreasing trends and blue shades indicating increasing trends. The white areas/without colour represent areas where trend values are within the +/- 0.03mm/year² range or insignificant (p>0.005). The time series panels on the right of and below the map show regionally averaged PGWR trajectories with associated linear trends (dashed lines) and corresponding slopes (β) for six domains: Continental, North Africa, West Africa, East Africa, Central Africa, and Southern Africa.

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The estimated PGWR trends for the 21st century (Fig. 3) highlight the influence of future climate trajectories on Africa's groundwater resources. Under the RCP2.6 scenario, continental average slope is −0.047 mm/year^2, indicating a negligible long-term decline. Regional differences are evident: North Africa (+0.009 mm/year^2) and East Africa (+0.034 mm/year^2) even exhibit marginally increasing trends while West Africa (−0.042 mm/year^2), Central Africa (−0.142 mm/year^2), and Southern Africa (−0.199 mm/year^2) show mild declines. consistent with earlier findings of moderate PGWR reductions in the FF under RCP2.6. The spatial distribution, under RCP2.6 reflects these patterns with limited decreases primarily over Southern and Central parts of Africa.

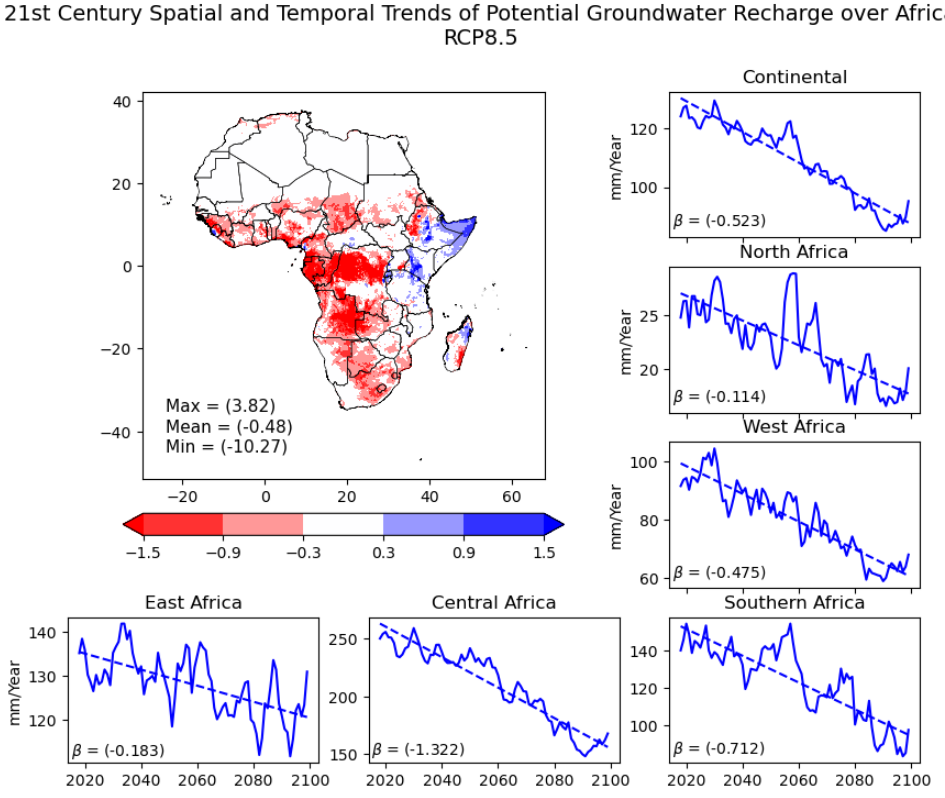


Figure 4: Spatial variation and temporal trends in PGWR across Africa throughout the 21st century under RCP8.5. Central map displays spatial variation trends in annual PGWR (mm/year2), with red shades indicating decreasing trends and blue shades indicating increasing trends. The white areas/without colour represent areas where trend values are within the +/- 0.03mm/year2 range or insignificant (p>0.005). The time series panels on the right of and below the map show regionally averaged PGWR trajectories with associated linear trends (dashed lines) and corresponding slopes (β) for six domains: Continental, North Africa, West Africa, East Africa, Central Africa, and Southern Africa

In stark contrast, the RCP8.5 scenario (Fig. 4) presents a widespread and accelerated decline in PGWR across all domains, with a continental trend of −0.523 mm/year^2 which is more than ten times the decline observed under RCP2.6. The most intense reductions are projected in Central Africa (−1.322 mm/year^2) and Southern Africa (−0.712 mm/year^2), followed closely by West Africa (−0.475 mm/year^2) whose declines are respectively 9 times, 4 times and 11

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times faster than for the RCP2.6 scenario. Also, North Africa (−0.114 mm/year^2) and East Africa (−0.183 mm/year^2), which had shown slight increases under RCP2.6, exhibit declining trends under RCP8.5. These declining trajectories align with the spatial patterns shown in the trend maps, where the dominance of red shading particularly over Central, West, and Southern Africa illustrates broad-scale negative trends in PGWR.

To further elucidate the drivers and nature of the observed change in Africa's PGWR, we computed annual rates of change in rainfall (SRAIN) and potential evapotranspiration (SPET) over the period 2015–2100 (Fig S5 and S6) (Table 1) and examined in addition the Pearson correlation coefficients between differences in rainfall (ΔRAIN), potential evapotranspiration (ΔPET), and groundwater recharge (ΔGWR) across the NF and FF climate windows (see Fig. S3 and S4). The results reveal the predominant role of rainfall variability in shaping PGWR patterns throughout the 21st century (Ani et al., 2022; Kotchoni et al., 2019; West et al., 2022). For RCP2.6 in nearly all regions, ΔRAIN consistently demonstrates a very strong correlation (>= 0.8) (Walizada, 2021) with ΔPGWR, affirming precipitation as the primary recharge driver. However, the influence of ΔPET appears to be regionally modulated, with West Africa, Central Africa, and Southern Africa exhibiting strong (>=0.5) to very strong negative correlations between ΔPET and ΔPGWR, alongside discernible increasing PET trends. This pattern suggests that rising evaporative demand is acting as a constraint on recharge in these regions, exacerbating the effects of declining rainfall and aligning with the pronounced negative PGWR trends observed under both climate scenarios.

Table 1: ***Correlation coefficients and trend slopes of change in rainfall (ΔRAIN), change in potential evapotranspiration (ΔPET), and change in potential groundwater recharge (ΔPGWR) under the RCP2.6 scenario.*** *The table presents the Pearson correlation coefficients between changes in RAIN, PET, and PGWR, along with the annual rates of change (slopes) for RAIN and PET (mm/year) from 2015 to 2100 for the continental average and five African regions.*

Region	Slope (S_{RAIN}) mm/year^2	Slope (S_{PET}) mm/year^2	Correlation (ΔRAIN-ΔGWR)	Correlation (ΔPET-ΔGWR)
Continental	-0.05	0.16	0.96	-0.68
North Africa	0.06	-0.01	0.94	-0.65
West Africa	-0.09	0.42	0.95	-0.47
East Africa	0.12	-0.02	0.92	-0.67
Central Africa	-0.16	0.29	0.94	-0.76
Southern Africa	-0.46	0.24	0.96	-0.80

In contrast, East Africa and North Africa do not display decreased PGWR under the RCP2.6 scenario, which is supported by either favourable or stable rainfall and PET trends. Overall, these findings reinforce the central role of sustained and adequate rainfall in maintaining PGWR, while also highlighting the compounding impact of rising PET in regions where precipitation is concurrently declining. Areas facing simultaneous rainfall reduction and PET increase, particularly in West, Central, and Southern Africa confront escalating risks of groundwater depletion and water stress over the long term.

Under the RCP8.5 climate scenario (Table 2), precipitation declines strongly across all African regions compared to the RCP2.6, while potential evapotranspiration (PET) increases more strongly. This combined effect leads to widespread reductions in PGWR. The amplified role of evaporative stress, alongside declining rainfall, underscores the heightened vulnerability of groundwater resources in West, Central, and Southern Africa under high-emission conditions.

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In contrast, North Africa and East Africa exhibit the lowest PET trends among all regions. These relatively modest increases in evaporative demand, coupled with less severe rainfall reductions, suggest less impact on PGWR under RCP8.5 than for other regions. The weaker negative correlations between ΔPET and ΔPGWR in these regions, when compared to RCP2.6, point to a diminished influence of evaporative demand. Overall, the findings highlight that while RCP8.5 universally exacerbates climate-induced stress on PGWR, regional variability in evaporative demand and rainfall decline play a critical role in mediating the severity of impacts.

*Table 2: **Correlation coefficients and trend slopes of rainfall (RAIN), potential evapotranspiration (PET), and potential groundwater recharge (PGWR) under the RCP8.5 scenario.** The table presents the Pearson correlation coefficients between changes in RAIN, PET, and PGWR, along with the annual rates of change (slopes) for RAIN and PET (mm/year) from 2015 to 2100 for the continental average and five African regions.*

Region	Slope (RAIN) mm/year^2	Slope (PET) mm/year^2	Correlation (RAIN-GWR)	Correlation (PET-GWR)
Continental	-1.32	0.31	0.92	-0.62
North Africa	-0.4	0.1	0.92	-0.24
West Africa	-1.87	0.48	0.93	-0.53
East Africa	-0.35	0.1	0.88	-0.48
Central Africa	-2.69	0.61	0.89	-0.64
Southern Africa	-1.8	0.39	0.95	-0.6

3.3 Inter annual variability of potential groundwater recharge

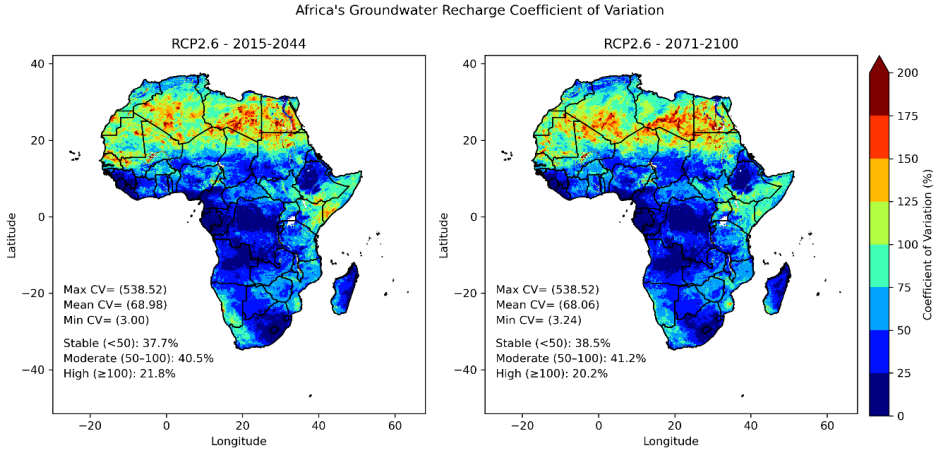


Figure 5: Coefficient of variation (CV) of annual PGWR over Africa under the RCP2.6 climate scenario for the two climate windows: Near Future (2015–2044, left) and Far Future (2071–2100, right). Higher CV values (warm colors) indicate stronger year-to-year fluctuations relative to mean PGWR, while lower CV values (cool colors) denote more stable recharge regimes.

Beyond PGWR availability and long-term trends, assessing its interannual variability is essential for evaluating its stability, resilience and recovery potential. To this end, we analyzed the spatial variation of the PGWR coefficient of variation (CV) across the continent. For the

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NF (2015–2044) and FF (2071–2100) under the RCP2.6 scenario (Fig. 5) the CV hardly changes (from 69% to 68%) implying that fluctuations relative to mean PGWR are stable at the continental scale. The maximum and minimum CV values remain unchanged between the two climate windows showing the persistence of localized extreme values. The annotated stability classes further illustrate the distributional changes. In the near future, 37.7% of grid cells fall into the "Stable" class (CV < 50%), 40.5% into the "Moderate" class (50% ≤ CV < 100%), and 21.8% into the "High" variability class (CV ≥ 100%). By the far future, the share of "Stable" grid cells increases slightly by 0.8 percentage points (pp), "Moderate" rises by 0.7pp, and the proportion of "High" variability decreases by 1.6pp.

In contrast to the relatively stable or mildly declining variability observed under RCP2.6, the RCP8.5 climate scenario reveals a marked intensification of PGWR variability across Africa. (Fig. 6). At the continental scale, the mean CV increases from 68% in the NF to 83% in the FF showing a clear increase of interannual fluctuations relative to the mean PGWR. The minimum CV values remain low at approximately 3% and 4% for both climate windows suggesting that highly stable localities still exist in the far future but the growth in the mean values shows a widespread shift towards more volatile PGWR regimes under the pessimistic climate scenario. The distribution of grid cells among the three stability classes emphasizes this aggravation. In the NF, 40.2% of grid cells are classified as stable, 37.9% as moderate and 21.9% as high. By the FF however, the stable localities in Africa decline by 14.8pp (25.4%), moderate localities increase by 6.3pp (44.2%) and the highly unstable localities increase by 8.5pp (30.4%). This change indicates that nearly one-third of Africa will experience highly unstable PGWR dynamics by 2100 having only fewer places maintaining low interannual variability.

Together, the CV results indicate that while RCP2.6 offers a stable PGWR variability, RCP8.5 on the other hand projects an amplified decline in stability with a significant reshuffling of localities towards moderate and high variability classes.

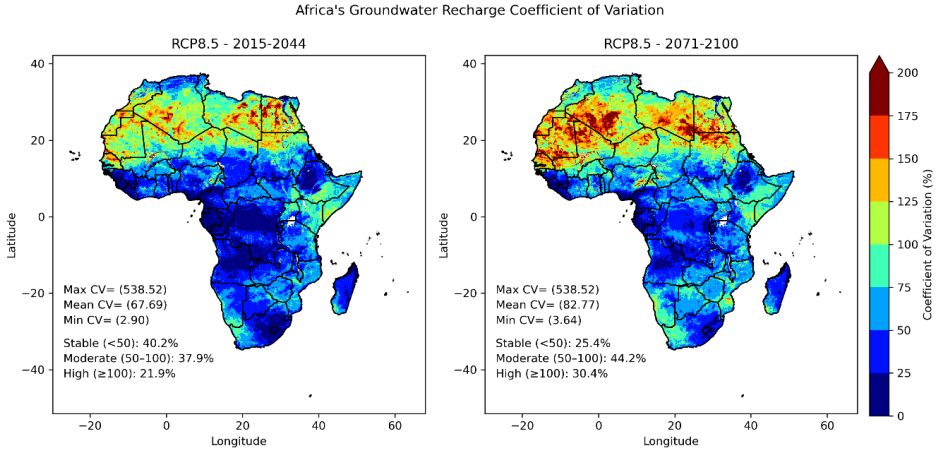


Figure 6: Coefficient of variation (CV) of annual PGWR over Africa under the RCP8.5 climate scenario for the two climate windows: Near Future (2015–2044, left) and Far Future (2071–2100, right). Higher CV values (warm colors) indicate stronger year-to-year fluctuations relative to mean recharge, while lower CV values (cool colors) denote more stable recharge regimes.

3.4 Comparison of Simulated PGWR with other datasets

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Figure S7 shows a generally weak agreement at the grid cell level between CLM5 and the reference datasets, with large proportions of the continent showing both low and negative correlations, reflecting differences in climate forcing, model structure and process representation. Due to this, a strong year to year agreement is not expected.

On the other hand, analysed trend sign agreement as shown in Figure 7 and Table 3 reveal better consistency between CLM5 and the reanalysis reference datasets (ERA5-Land and GLDAS) but less than 50% agreement with WaterGAP-GFDL projection dataset.

Table 3: Percentage of gridcells showing trend sign agreement and mismatch between the CLM5 ensemble mean and the reference datasets.

Climate scenario	Reference dataset	Agreement in decreasing trend (%)	Agreement in increasing trend (%)	Total trend-sign agreement (%)	Mismatch (%)
RCP2.6	ERA5-Land	37.7	19.2	56.9	43.0
RCP2.6	GLDAS	28.7	23.7	52.4	47.6
RCP2.6	WaterGAP-GFDL	32.1	17.2	49.3	50.6
RCP8.5	ERA5-Land	32.9	22.9	55.8	44.2
RCP8.5	GLDAS	24.0	27.5	51.5	48.5
RCP8.5	WaterGAP-GFDL	26.8	17.2	44.0	55.9

Considering both climate scenarios, 24% to 37% of grid cells agree on decreasing recharge trends while 17% to 27% of grid cells agree on increasing recharge trends. Considered together, both positive direction and negative direction agreement classes show that approximately 51% to 57% of grid cells agree with CLM5 among the reanalysis datasets while 44% to 49% of projected PGWR from WaterGAP-GFDL agree with CLM5.
. Mismatch regions account for 43% to 48% of grid cells among reanalysis datasets while accounting for 50% to 55% with the climate projection datasets (WaterGAP-GFDL) in both climate scenarios. This shows that there is a generally higher coverage of trend direction agreement over Africa than mismatches especially when compared with reanalysis reference datasets.

The reanalysis datasets under RCP2.6 show negative trend agreement in the Mediteranean region, and Central Africa region including Angola while positive trend agreement was observed over the Sahara and Southern Africa especially, Namibia. For RCP8.5, most of the Republic of South Africa and parts of tropic west and East Africa agreed on positive PGWR trends.

In terms of the coefficient of variation class agreement (Figure S8), there is an agreement on spatial organisation of recharge regimes. The regions characterised by “stable”, “moderate” and “high” variability display agreement with reference datasets especially in the Sahel and Southern Africa. Mismatches are however pronounced in the transitional climatic regions which include zones between wet regions and dry regions such as the Sahel belt, the Kalahari boundary and margins of the Congo Basin.

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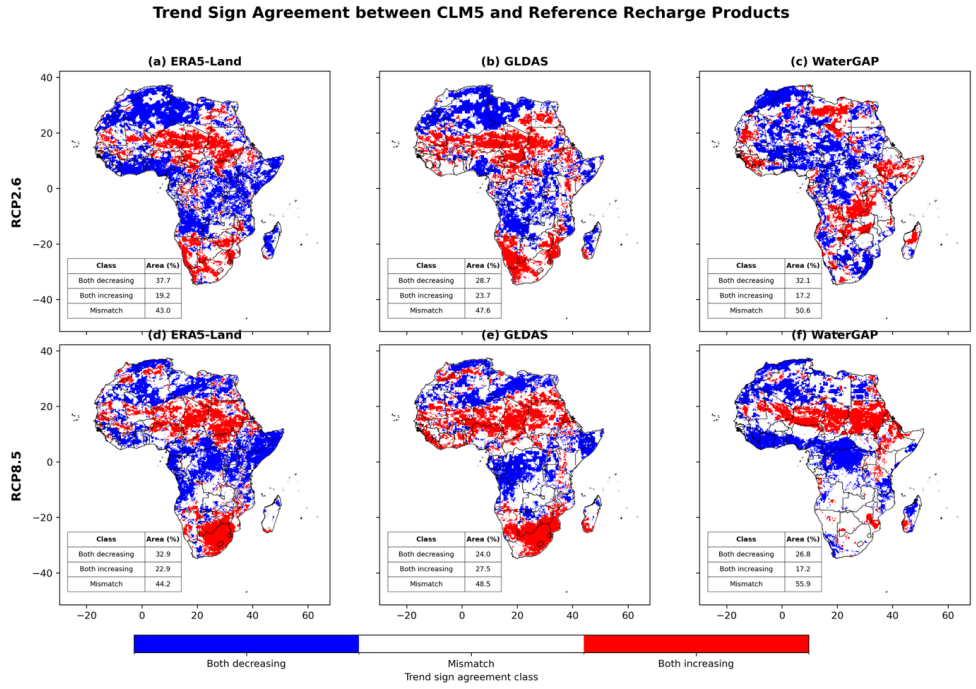


Figure 7: Spatial agreement in the direction of long-term groundwater recharge trends between CLM5 and three reference datasets (ERA5-Land, GLDAS, and WaterGAP) across Africa for RCP2.6 (top row) and RCP8.5 (bottom row). Blue indicates agreement in decreasing trends, red indicates agreement in increasing trends, and white indicates disagreement (mismatch). Insets show the percentage of continental area corresponding to each category.

3.5 Projected Growth in Human Water Use under RCP2.6 and RCP8.5 Climate Futures

Based on the assessment of Africa's PGWR sensitivity to climate dynamics, it is equally necessary to understand how anthropogenic pressures may affect future trajectories. Projections under both RCP2.6 (Fig S9) and RCP8.5 (Fig S10) depict that domestic water use dominates across most of Africa, contributing more than 90% of sectoral demand in nearly all regions. Irrigation, livestock, and industrial water use remain comparatively small, with irrigation exhibiting localized importance in parts of North and East Africa. However, given scenario assumptions such as constant irrigated land after 2050, long-term sectoral projections should be interpreted with caution.

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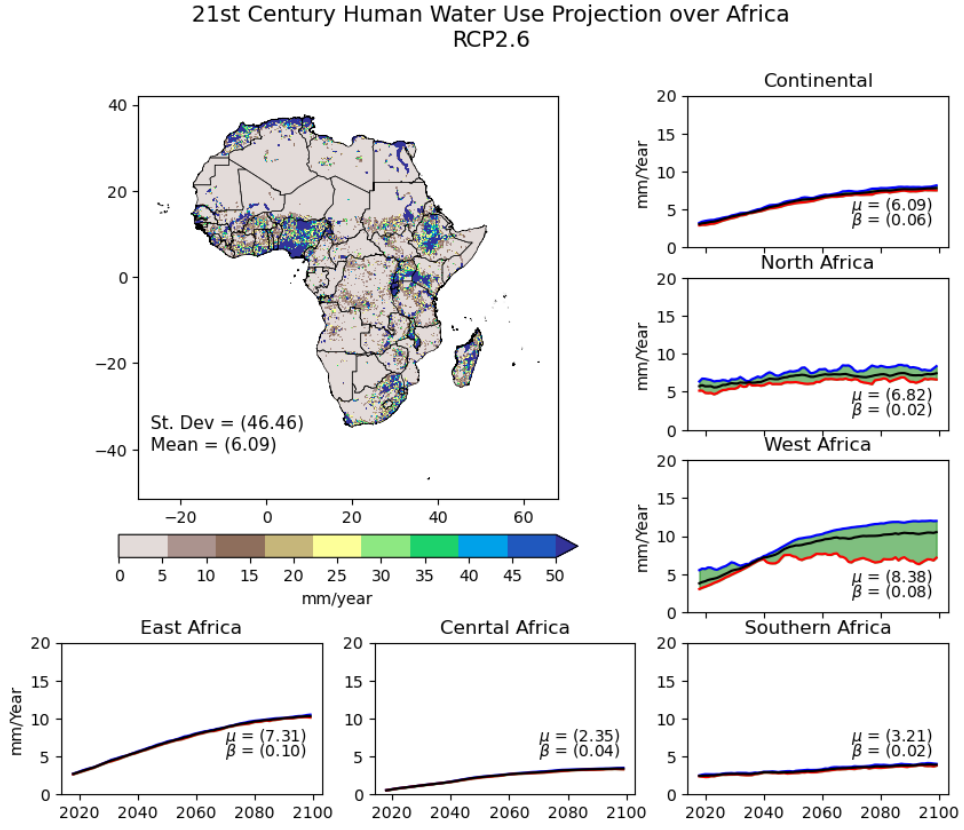


Figure 8: Projected spatial and temporal dynamics of total human water use across Africa during the 21st century under RCP2.6 climate scenario. Central map displays both the average annual human water use (mm/year) and its standard deviation from 2020 to 2100 calculated over all grid cells, with color gradients representing spatial variation. Accompanying time series plots illustrate ensemble mean trajectories (black line), spread (shaded green area), and extremes (blue and red lines) of water use for six domains: North Africa, West Africa, East Africa, Central Africa, Southern Africa and values for the complete continent. Labels on each panel show the domain-specific mean (μ) and linear trend slope (β), indicating both magnitude and rate of change.

A spatial assessment of total human water use (HWU) under the RCP2.6 climate scenario reveals through the combination of its continental mean (6.1mm/year) and standard deviation (46.5mm/year) that Africa's human water use is spatially heterogeneous, meaning that while most of the continent uses relatively little water, there are hotspots of intense water use, in densely populated urban centres, irrigated agricultural zones and industrial regions (e.g., parts of Nigeria, Egypt, and South Africa). Most of the African continent records consumption levels in the range of 0–5 mm/year (Fig. 8). However, several countries exhibit notably higher demands. In West Africa, countries such as Nigeria, the Republic of Benin, Togo, Ghana, Côte d'Ivoire, Burkina Faso, Liberia, and Sierra Leone have human water use levels exceeding 5 mm/year. Similarly, elevated consumption is observed in parts of East Africa, including Ethiopia, Rwanda, Burundi, and Madagascar. In Southern Africa, particularly in the south-eastern corridor of South Africa as well as Swaziland and Lesotho, greater water use is also evident. Countries such as Morocco, northern Algeria, and northern Tunisia show substantial human water consumption.

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HWU across Africa under RCP2.6 follows a consistent upward trajectory throughout the 21st century, with notable regional variation in the pace and magnitude of increase. North and Southern Africa exhibit moderate growth trends, while West and Central Africa show more pronounced increases. East Africa records the steepest rate of change, highlighting it as the region with the most rapidly growing water demand. It is noteworthy however that West Africa has the highest HWU average across the century with 8.4mm/year and Central Africa exhibits the least water use with 2.4mm/year. These patterns underscore the spatial heterogeneity in anthropogenic water pressures, even under a low-emissions scenario.

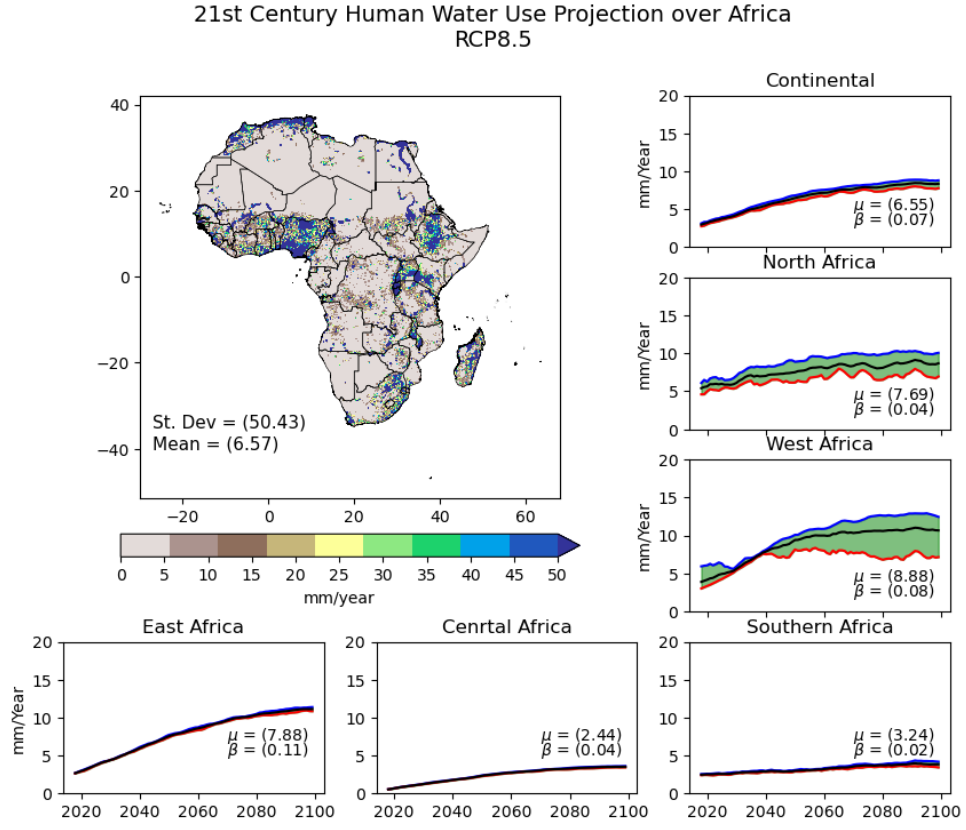


Figure 9: Projected spatial and temporal dynamics of total human water use across Africa during the 21st century under RCP8.5 climate scenario. Central map displays both the average annual human water use (mm/year) and its standard deviation from 2020 to 2100 calculated over all grid cells, with color gradients representing spatial variation. Accompanying time series plots illustrate ensemble mean trajectories (black line), spread (shaded green area), and extremes (blue and red lines) of water use for six domains: North Africa, West Africa, East Africa, Central Africa, Southern Africa and values for the complete continent. Labels on each panel show the domain-specific mean (μ) and linear trend slope (ß), indicating both magnitude and rate of change.

Under the RCP8.5 climate scenario (Fig. 9), total water use over Africa increases more than under RCP2.6, reflecting the influence of higher temperatures in a high-emissions, low-mitigation future. The mean continental use differs from RCP2.6 by 7.8% while its spatial heterogeneity (standard deviation) is increased by 8.5% compared to RCP2.6. Notably, the rate of increase in HWU under RCP8.5 is 0.07 mm/year, 13% more than under RCP2.6. This acceleration underscores the amplified pressure that would accompany a pessimistic emissions

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pathway. At the regional level, North Africa shows a doubling of the growth rate (β = 0.040 mm/year under RCP8.5 vs. 0.020 mm/year under RCP2.6), indicating intensified demand in an already water-stressed region. West Africa exhibits a marginal increase in growth rate (0.085 vs. 0.083 mm/year), while East and Central Africa experience slightly faster increases at 0.09mm/year and 0.03mm/year, respectively. Interestingly, Southern Africa displays a slight deceleration in HWU growth under RCP8.5, decreasing by 0.1% compared to the RCP2.6 scenario. These findings suggest that, although both climate scenarios project a consistent rise in water demand, the pace and magnitude of growth are amplified under RCP8.5, particularly in North and East Africa.

3.6 Fractional Use of Groundwater Recharge by Human Water Use in Africa

Following the temporal and spatial assessment of HWU across Africa, it becomes crucial to evaluate the fraction of PGWR consumed by anthropogenic demands as an indicator of PGWR stress and sustainability, hereafter referred to as Stress Ratio (SR).

The spatial and temporal patterns of HWU as a fraction of PGWR under both RCP2.6 (Fig. S11) and RCP8.5 (Fig. S12) climate scenarios are presented. These reveal that, while a vast majority of the continent (in terms of land mass) maintains relatively low stress (<20%), several locations across the continent are projected to experience severe and critical stress (>80%) due to human water demand.

Under the RCP2.6 climate scenario, 94% of the African continent falls below the 20% threshold, suggesting low stress in most areas. However, localized hotspots in West Africa, parts of North Africa, and urbanized or irrigated zones in East and Central Africa exhibit significantly higher values. Particularly in West Africa, a region previously identified with high sectoral and total human water use, the average proportion of groundwater recharge to human water use is markedly elevated. This is consistent with the observed concentration of demand and relatively low recharge in parts of the Sahel and Sudanian regions. The temporal trajectory across the century shows a steady rise, with regional means and trends suggesting gradually intensifying pressure, especially in West, East, and Southern Africa.

Under the RCP8.5 scenario, the stress on groundwater resources intensifies. The percentage of African continent consuming more than 80% of their recharge and therefore under severe and critical stress increases slightly by 12% (from 1.99% to 2.23%) compared to RCP2.6. Most notably, West Africa exhibits a sharp increase in both the average HWU fraction and its rate of change, reflecting compounded effects of increased demand and diminished recharge under the high-emissions scenario. Similarly, Southern Africa, already experiencing vulnerability under RCP2.6, demonstrates a substantial increase in the proportion of recharge consumed. In contrast, Central Africa, which is characterized by relatively abundant recharge and lower water demand, maintains the lowest levels of stress under both scenarios. The data highlights that even under an optimistic climate scenario (RCP2.6), specific regions are on a trajectory toward high groundwater dependency. The situation is exacerbated under RCP8.5, where reduced recharge and increased demand amplify the SR, especially in regions already predisposed to water scarcity.

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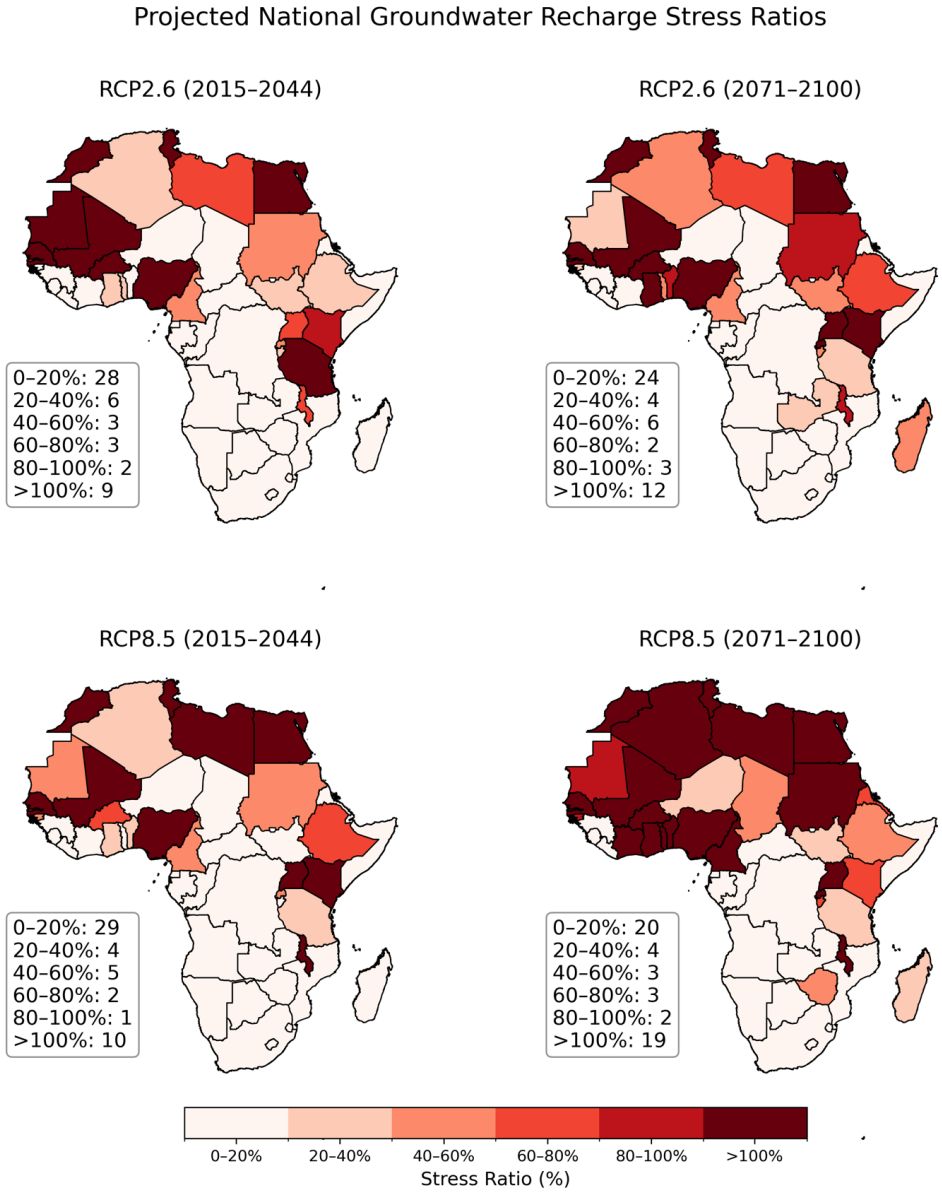


Figure 10: Projected National PGWR stress ratio for Africa under two emissions pathways and climate windows. Maps show the 2015–2044 and 2071-2100 national-mean stress ratio for RCP2.6 (top) and RCP8.5 (bottom). Colors denote classes Low (<20%), Moderate (20–40%), High (40–80%), Severe (80–100%), and Critical (>100%, i.e., withdrawals exceed PGWR).

At national level (Fig. 10), both climate induced change and climate trajectory have a negative impact on Africa's PGWR stress ratios. Comparing NF and FF under RCP2.6, the number of countries under low to moderate stress ratios reduced by 17.6% from 34 (NF) to 28 (FF) while the number of countries under the high to critical stress ratios increase by 35.2% from 17 (NF) to 23 (FF). For RCP 8.5, the reduction in the low to moderate classes is 22.5% (from 31 to 24) while the increase in high to critical stress ratio classes is by 50% (from 18 to 27). This shows

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that as time progresses under both climate scenarios, less countries could experience low to moderate stress ratios while more countries would experience high to critical stress ratios. Regarding climate trajectory, only one country transitions from the low-to-moderate stress class to the high-to-critical stress class under the NF scenario, compared with four countries under the FF scenario. This suggests that over Africa at national levels, two types of changes can be identified. First, within each RCP scenario, transition from NF to FF results in a more pronounced shift of countries from low-to-moderate stress classes towards high-to-critical stress classes. This is evident under both RCP2.6 and RCP8.5 but more pronounced under RCP8.5. Second, when comparing RCP2.6 and RCP8.5 within the same climate window differences in stress classification are smaller in the NF and become more apparent in the FF.

Because the RCP framework (van Vuuren et al., 2011) does not specify explicit national population trajectories, exposed population was estimated by combining groundwater stress projections under RCP2.6 and RCP8.5 with national population projections from the SSP framework (van Vuuren et al., 2014) as shown in Table S1. Both frameworks share common radiative forcing endpoints (e.g. 2.6 and 8.5 W m^{-2}, as in RCP2.6/SSP1-2.6 and RCP8.5/SSP5-8.5). Specifically, country-level projections for SSP1-2.6, which emphasizes sustainable development and human well-being, and SSP5-8.5 (O'Neill et al., 2017; Riahi et al., 2017), which assumes rapid economic growth accompanied by declining fertility in most developing countries, were employed. Under SSP1-2.6, the results indicate that by 2045 (end of NF), approximately 783 million people (53. 7% of Africa's population from 11 countries) will reside in countries experiencing severe and critical groundwater stress associated with RCP2.6, increasing to over 1.45 billion (71% from 15 countries) by 2100 (end of FF). Under SSP5-8.5 combined with RCP8.5, 685 million people (52.9% from 11 countries) are projected to be exposed by 2045 and 1.03 billion (72.4% from 21 countries) by the end of the century. This shows that under the high mitigation pathway, more people will be affected by the increasing stress on Africa's PGWR than in the high emissions scenario. On the other hand, under the high emissions scenario, while less humans are affected given less population growth, the affected proportion of African population is higher than under the mitigation pathway especially at century end, meaning that PGWR stress will become more nationally widespread and entrenched relative to population size. This also signals a need to consider population exposure when interpreting future groundwater stress particularly in countries where projected HWU becomes large compared to PGWR. Table S9 provides the projected national GWR Stress Ratios and population under the different climate windows and climate trajectories across African countries.

4 Discussion

4.1 Interactions Between Climate-Driven PGWR and Human Water Demand under RCP2.6

The consideration of multiple diagnostic metrics (Table S2) including PGWR availability, PGWR trends, its interannual variability, HWU and human water use fraction of PGWR under the RCP2.6 climate scenario provides understanding into the complex interplay between climate-induced variations in PGWR and rising anthropogenic water demand across Africa. This synthesis reveals that first, a low-emission climate trajectory does not necessarily imply an absence of future water pressure across Africa. This is because relatively stable groundwater recharge may coincide with rising anthropogenic demands. This finding is consistent with the

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studies of Jones et al., (2024), Liu et al., (2024) and Zhang et al., (2025). These works demonstrate that apart from climate change itself, socio-economic development, urbanisation and demographic expansion are drivers of potential future water stress. Particularly, Mazzoni et al., (2018) highlights that some nations having low gross domestic product per capita might be exposed to the highest water deficit per capita partly because of heavy reliance on domestic agriculture as a primary source of food supply leading to increased water demand. Secondly, beyond the continental scale pressures, considerable regional disparities emerge in both hydroclimatic and socio-economic dimensions, with important implications for groundwater sustainability. The disparity shows that Africa's water scarcity has a socio-economic dimension (Fukuda et al., 2026) as it is driven by distict geographical variations such as population (Tamoffo et al., 2025) socio-economic developments and infrastructure accessibility (Yitageasu et al., 2026; Zhang et al., 2025a). Therefore, groundwater related stress under low emission scenario cannot be explained by climatic changes alone but must be considered within the context of changing demographic and socio-economic pressures.

North Africa diverges from the slightly negative continental trend, showing an increase in PGWR coupled with the highest average fraction of recharge used by humans (27.6%), more than five times the continental average fraction. Historical conditions indicate the possible contributions of irrigation-induced recharge suggesting that precipitation is not the only source of water input (Khemiri et al., 2026). This anthropogenic addition of water to the soil however does not translate into reduced groundwater pressure as irrigation demands including climate induced evapotranspiration connected to agricultural intensification can increase water demand faster than natural recharge (Adeyeri, 2025; Trigui et al., 2026a). This high reliance on groundwater is compounded by longstanding patterns of limited surface water availability and population demand in arid and semi-arid zones (Frappart, 2020). Consequently, despite a comparatively low difference in HWU between NF and FF, its positive trend suggests that groundwater resources in the region can become more vulnerable, especially under prolonged stress.

West Africa, while showing a declining PGWR amount (–2.78 mm/year between NF and FF), also exhibits the steepest increase in the fraction of recharge used by humans (+0.12% per year). This increasing pressure reflects the region's rapidly increasing HWU (+0.08 mm/year) connected to rapid population growth and increased urbanization (Macharia et al., 2020). A study over Niger Republic even notes that population is expected to double every 25 years (Boko et al., 2020). The pressure noted in the study is consistent with the observed dominance of domestic and irrigation use in countries such as Nigeria and Ghana. Sokeng et al., (2026) noted that ecosystem degradation is a contributor to the regional stress. The concept of compound events which is the co-occurrence or rapid succession of two or more climate drivers in this case drought-heatwave, have also been noted to impact groundwater recharge in the sudan and sahel zones (Adeyeri, 2026). Such compound events may constrain recharge by reducing soil moisture availability and increase evaporative losses. The declining recharge, coupled with rising demand considering the variation between NF and FF, signal a mounting groundwater sustainability challenge in West Africa driven by the interaction of climatic, environmental and demographic forces.

Southern Africa emerges as a region of concern due to its steep decline in PGWR even under RCP2.6. This observed decline is related to a projected decline in rainfall due to a lengthening of dry season spells (Wainwright et al., 2022). Adeyeri, (2026) further notes that shallow unconfined acquifers capable of providing baseflow during dry spells can experience a sharp

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reduction in groundwater recharge rates in periods of compound drought. Wankie et al., (2026) notes the occurrence of an assymetric warming pattern in the region where minimum temperature increased faster than maximum temperatures. This could create higher atmospheric moisture demand leading to higher irrigation water withdrawals. While the average fraction of recharge used by humans remains low (Fig. S6), the projected increase in HWU by 39.6% comparing FF and NF and 52.0% change in stress ratio between NF and FF, suggests increasing exposure to groundwater insecurity, especially in highly populated or irrigated catchments. This imbalance is consistent with the concept of socio-economic draught expressed by Wang et al., (2025). It happens when the imbalance between water demand and water supply affects society leading to growing agricultural urban and industrial demand, increasing groundwater stress. The relatively low stress ratio should therefore not prevent the recognition of possible localised groundwater related stress in places where declining recharge and concentrated demand coexist.

In Central Africa, the combination of high recharge rates and relatively low HWU ensures that the average fraction of PGWR used by humans remains minimal at 1.0%, even though both HWU and SR are expected to be more than twice its NF values in the FF. Raouf et al., (2024) highlights that poor water governance practices, inadequate infrastructure and lack of coordination explains the mismatch between Central Africa's water availability and low human water use. Nounkeu et al., (2021) identifies poor access to water sources, which necessitates considerable effort to obtain water. Meunier et al., (2019) also identifies lower industrialization leading to minimal competition for water resources. Differences in consumption patterns also show a socio-economic dimension. L. Zhang et al., (2025b) report that Central African countries exercise lower dietry water footprint (DWF) compared to rapidly evolving economies of the North and Southern Africa. In the furture however, Central Africa's DWF is expected to rise as a result of rapid population growth and resource-intensive diets under low emission scenarios. This suggests that Central Africa's currently low pressure on GWR may increase as the demography, infrastureal development and consumption patterns evolve.

East Africa, in contrast, demonstrates positive trends in both PGWR and HWU, reflecting the dynamic balance between expanding water needs and climate-induced recharge responses. Despite recording a rise in HWU (0.10 mm/year), the region maintains a relatively moderate average fraction of recharge used (5.6%) even though the stress ratio changes by 111.8% in the FF compared to NF. This projected increase in PGWR is consistent with other hydroclimatic studies which indicate increased precipitation over the region under low-emission scenarios. Ochwo et al., (2025) attributes the the projected increase in groundwater recharge to the rise in yearly rainfall under the low and moderate emission scenarios. Sebaziga et al., (2025) explains further that the combination of consecutive wet days, maximum one-day precipitation and precipitation from very wet days would contribute to the groundwater recharge under low emission scenarios. MacLeod et al., (2024) deepens the explanation indicating that the reason for the increased wetness and subsequent rise in groundwater recharge is associated with the positive Indian Ocean Dipole index which causes a reversal of the typical walker circulation leading to deeper convective events. Nonetheless, the increasing slope of usage and demand fraction warrants attention, particularly as socio-economic development accelerates in the region with Kenya and Uganda being the fastest growing economies in East Africa (Renner, 2020). This increase in stress ratio despite the positive PGWR trends indicate that anthropogenic demand would be a determinant of futire groundwater related stress in the region,

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Overall, these findings imply that under RCP2.6, future PGWR stress across Africa may be largely driven by anthropogenic water demand and less by climate-induced changes. The divergent regional responses show that groundwater pressure arises from a combination hydroclimatic and socio-economic forces: high demand relative to limited recharge in North Africa, declining recharge and increasing demographic pressure in both West and Southern Africa and expanding Water requirements despite abundant PGWR in Central and East Africa. These interactions are shown in the increase in stress ratio between NF and FF especially in West, Central and East Africa having increases of 112%, 170% and 111% projected respectively. These findings therefore suggest that emissions mitigation alone may not be sufficient to prevent increasing groundwater stress. Instead, sustaining Africa's groundwater will also involve understanding how population growth, sectoral water demand, infrastructure development and water management practices affect the balance between anthropogenic demand and groundwater recharge availability.

4.2 Amplified Climate and Human Pressures on Groundwater Resources under RCP8.5

RCP8.5 accentuates the vulnerability of groundwater systems through the compound effects of declining recharge, rising interannual variability, and accelerating anthropogenic demand. This interplay shows the combined influence of climate driven changes and socio-economic factors that increase pressure on renewable groundwater resources (Table S3), underscoring the emergent risk of unsustainable groundwater exploitation in several African subregions. Rising temperatures as characteristic of RCP8.5 and associated increase in evaporative demand in combination with declining precipitation can constrain groundwater renewal. On the other hand, population growth and agricultural intensification increase water demand (Adeyeri, 2025, 2026). Regional groundwater recharge assessments also show that the combination of declining recharge and increased abstraction can contribute to groundwater level decline and aquifer depletion where abstraction persistently exceeds replenishment (Selim et al., 2025a; Zerouali et al., 2026).

North Africa emerges here as a region of elevated concern. Despite a modest decline in interannual PGWR variability, the region experiences a marked reduction in average recharge and a significant rise in human dependency on groundwater. Given the region's (semi)arid climate, heavy irrigation footprint, and dependence on groundwater reserves, the results reflect not only climatic pressures but also indicate systemic water use challenges (Halipu et al., 2022) exacerbated by intensive water abstraction and distribution systems required for drinking and irrigation(Lucca et al., 2023). Rising temperatures and decreasing precipitation may further intensify these pressures through potential evaporation and crop evaporation leading to heightened irrigation demand and groundwater abstraction (Trigui et al., 2026b). Experiences from Souss-Massa Basin in Morocco suggest that the persistence of water-intensive irrigation could reinforce dependence on groundwater especially in arid conditions thus creating a cycle of increasing abstraction and depletion of the aquifer (El-Yazidi et al., 2026). The studies of the El-Moghra aquifer in Egypt showed the effects of intensive pumping in combination with climate change as a projected acceleration of the groundwater-level decline and possible salination (Selim et al., 2025b). The relative modest decline in the interannual recharge variability therefore does not indicate improved water security. This is because persistent recharge deficit in groundwater recharge can place a sustained pressure in groundwater system.

West Africa shows also a concerning profile under RCP8.5. Recharge is projected to decline sharply, while HWU increases to an 8.9 mm/year average, the highest among all regions. This

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results in a 12.6% consumption of available recharge by human use, with a growth trend of +0.21% per year. The projected decline in PGWR can be explained by changes in the West African monsoon especially changes in the seasonality of rainfall, increased dry-spell duration and intensified evaporative demand which can reduce soil moisture availability and groundwater replenishment (Adeyeri, 2025; Granata & Di Nunno, 2025). In line with these mechanisms, Kabo-Bah et al. (2025) also projects reduced precipitation and increased temperature over the Black Volta Basin of Ghana. Godwin et al. (2026) identified reductions in dry season flows and intensified hydrological variability in the Benue Basin of Nigeria. On the socio-economic side, rapid population growth, urbanization and agricultural expansion can increase domestic and irrigation water requirements whereas, land use and land cover changes have potential to alter infiltration, surface runoff leading to modified groundwater replenishment (Togbévi et al., 2026). In West Africa, PGWR is essential for sustaining dry season irrigation which directly impacts food security (Kwoyiga & Stefan, 2018). The concurrent reduction in PGWR and increase in HWU therefore suggest that in the future, groundwater related stress will arise from the interaction of hydroclimatic and socioeconomic pressures.

Southern Africa remains notable for its hydrological volatility. It records one of the steepest negative trends in recharge and a substantial increase in interannual variability between NF and FF, reflecting heightened climatic instability. The projected recharge decline agrees with changes in the atmospheric circulation, especially the intensification of the subtropical high pressure systems and poleward displacement of the westerlies which have the potential to suppress precipitation and reduce frontal rainfall across parts of Southern Africa (Engelbrecht et al., 2024a; Taguela et al., 2025). Also, the El Nino-Southern Oscillation (ENSO) and Indian Ocean sea surface temperature anomalies contribute to regional rainfall variability via changes in atmospheric circulation potentially leading to the occurrence of dry conditions (Adeyeri, 2026; Cai et al., 2025). Some results from the Limpopo River Basin further show that high emission scenarios can result in declining groundwater contributions to subsurface runoff and groundwater levels. This illustrates that regional groundwater systems are sensitive to changing hydroclimatic conditions.
Although HWU remains relatively low, the increase in PGWR variability and consumption fraction trend still flags the region as highly sensitive to climate and anthropogenic drivers.

Previous assessments have consistently identified North and Southern Africa as regions of heightened water stress, driven by limited renewable resources (Ferreira et al., 2024). Future projections in this work also align with these patterns, revealing that these same regions are likely to experience intensified stress due to declining PGWR and increasing human water use, particularly under RCP8.5. The underlying mechanisms however differ between the two regions. In North Africa, low recharge, increasing aridity, sustained agriculture-related and domestic water withdrawals contribute to the persistent imbalance between renewable water availability and anthropogenic demand (Adraoui & Jaafar, 2024; Hamlat et al., 2024). This is illustrated in the Eastern Mitidja Plain in Algeria study where declining recharge and intensified groundwater abstraction altered groundwater and surface water relationship leading to the acceleration of groundwater level decline (Kastali et al., 2024). Southern Africa in contrast, has its vulnerability more closely associated with increasing hydroclimatic instability including droughts, changes in precipitation patterns and rising evaporative demand (Berghuijs et al., 2024; Engelbrecht et al., 2024b).

Central Africa, while traditionally endowed with abundant water resources, is expected to experience significant PGWR decrease and growing variability under RCP8.5. This reduction

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may reflect the interaction of hydroclimatic processes such as declining precipitation, increasing atmospheric evaporative demand and changes in the regional moisture transport which are known to constrain soil moisture availability and groundwater replenishment (Nath et al., 2024; Stojanovic et al., 2026). Some results from the congo basin associate the declining rainfall with weaker atmospheric moisture convergence and warming of the tropical Atlantic Ocean (Wongchuig et al., 2025). Adeyeri, (2026) and Chawanda et al., (2024) also suggest that these climatic pressures may be further amplified by land-atmosphere feedbacks associated with forest degradation and deforestation which are known to weaken atmospheric moisture recycling. Nkaba et al., (2025) also projected declining groundwater contributions to baseflow and surface runoff in the Inkisi River catchment in the future climate scenarios. Despite these projected hydroclimatic changes, the region still maintains relatively low human water use (2.4 mm/year) and only 1.3% of PGWR is consumed by human activity, indicating a more buffered system. Still, the observed positive slope in demand and fractional use suggests that future vulnerabilities may emerge, especially under population growth and infrastructural expansion.

East Africa is expected to have a comparatively modest decline in PGWR and a rise in demand resulting in increased stress (6.2% of recharge used). The region also records one of the highest slopes of HWU increase and fractional consumption growth . The relatively moderate decline in PGWR could reflect the response of East African rainfall regimes to climate change especially the contrasting behaviour of the long and short rainy seasons (Adeyeri, 2026; Tafesse et al., 2025). Increasing rainfall in some seasons however do not necessarily translate to groundwater recharge as increased temperatures and rising atmospheric demand can reduce the proportion of precipitation contributing to recharge (Abdulahi et al., 2025; Birhan et al., 2026). Also, changes in rainfall intensity and frequency can alter the partitioning of precipitation between surface runoff, evapotranspiration and infiltration thereby introducing additional spatial heterogeneity in recharge responses (Blake et al., 2025). These climatic pressures are further compounded by growth in population, urbanisation, agricultural intensification and increasing industrial requirements (Georgiou et al., 2024; Guyasa et al., 2025). As a result of these, simultaneous increase in HWU and relatively modest decline in PGWR suggest that groundwater related stress in East Africa may be intensified even when there is recharge resilience.

Under the RCP8.5 climate scenario overall, future pressure on Africa's groundwater resources would likely arise from the interplay of declining recharge, increased hydroclimatic variability and rising human water demand, even though the relative importance of the pressures aren't the same in each region. North Africa would combine sustained low recharge with high water demand, West Africa would face recharge decline and increasing pressures from both demography and agricultural expansion, Southern Africa would face increased hydroclimatic instability. Both Central and East Africa while retaining comparatively more recharge could remain vulnerable to increasing future demand. The observed stronger deterioration under RCP8.5 compared to RCP2.6 thus indicates potential benefits of climate mitigation. However, rising human water demand demonstrates that mitigation alone may not eliminate groundwater stress.

4.3 Limitations of the study

Despite the robust framework employed in this study, some limitations are noteworthy. The PGWR assessment is inherently dependent on the CLM5 Land Surface Model and its underlying parameterizations. Different land surface models may provide divergent outcomes to a certain extent. Furthermore, all simulations in this work are strongly influenced by the

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quality of the climate forcing dataset which carries uncertainties (Bichet et al., 2020) over data-scarce regions of Africa.

Secondly, the uncertainties in sectoral water use employed for the calculation of human water use assume that there is no increase in irrigated area after 2050. This may cause future irrigation water demand in the second half of the century to be underestimated. Furthermore, the PCR-GLOBWB2.0 model has been shown to systematically underestimate industrial and domestic water withdrawals due to the absence of thermos-electric cooling demand and its proportional allocation methods which do not show sectoral prioritization during water shortages. Industrial demand is said to be underestimated by at least 25% while domestic demand is underestimated by at least 8% (Sutanudjaja et al., 2018b).

Thirdly, while the SR metric offers a focused assessment of pressure on renewable potential groundwater fluxes, it does not account for withdrawals from non-renewable groundwater storage, which may temporarily buffer stress in some regions especially in countries like Egypt with extensive irrigation network (Barnes, 2017; ElGamal et al., 2019). Also, since PGWR is derived from a land surface water balance, it does not resolve aquifer storage or groundwater level dynamics. Thus, this metric only conveys pressure on renewable recharge potential rather than a direct calculation of groundwater depletion.

Lack of direct observation data to validate estimates may be compounded by aggregated national, regional and continental values which may obscure important local heterogeneities and stress hotspots.

5 Conclusions

This study examines the changes in potential groundwater recharge (PGWR), human water use (HWU) and their joint implications for groundwater stress over Africa for the period 2015-2100. PGWR was simulated with the Community Land Model version 5 (CLM5), driven by six CORDEX-Africa GCM-RCM climate forcing combinations under RCP2.6 and RCP8.5. HWU projections from PCR-GLOBWB 2.0 (PCRaster GLOBal Water Balance model version 2.0) were used to calculate the fraction of renewable PGWR potentially consumed by human demand.

The results indicate that PGWR changes in the future depend strongly on climate scenario. PGWR remains relatively stable at the continental scale under RCP2.6 declining by only 2.9 mm/year equivalent to 2.3% between near future (2015-2044) and far future (2071-2100). RCP8.5 however shows a strong decline of 30.9mm/year (25.1%) in PGWR across the continent mostly noticeable in Central Africa, West Africa and Southern Africa. Also, the analysis shows that change in rainfall is the main driver of PGWR variability but PET also affects PGWR especially in regions with joint rainfall decline and evaporative demand increase.

Interannual variability of PGWR is also different between RCP2.6 and RCP8.5. The coefficient of variation of PGWR is broadly stable under RCP2.6 changing by only 1%, comparing near future (NF) and far future (FF), while it increases by 15% under RCP8.5 showing a shift towards less stable PGWR conditions across parts of Africa. This suggests that a future of unrestrained high emissions may not only affect PGWR but also its reliability over time.

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Both climate scenarios record increased HWU although stronger under RCP8.5. Consequently, several regions demonstrate rising PGWR stress ratio (which indicates the fraction of PGWR consumed by anthropogenic demands) especially in places where both increasing demand and declining PGWR occur. North Africa shows the highest average stress ratio of 35.6% while West Africa follows at 12.6% due to the combination of its increasing HWU and declining PGWR. Nationally, the number of countries classified as high-to-critical stress increased from 17 to 23 under RCP2.6 and from 18 to 27 under RCP8.5. Over the same period, the number of countries in the low-to-moderate stress classes decreased from 34 to 28 under RCP2.6 and from 31 to 24 under RCP8.5.

This work and its findings show that groundwater recharge assesssments in the future should advance beyond examining changes in recharge magnitude alone but jointly consider recharge variability and human water demand. This is because increasing pressure may arise even where PGWR maginitude appears stable. Also, PGWR stress ratio used in this study only provides a useful screening index for recognizing places where human water use increases relative to the PGWR renewal. It therefore does not represent storage or groundwater level dynamics. Future research should progress towards assessments that integrate groundwater level observations, recharge measurements and local hydrological properties. Altogether, these developments can provide a stronger basis for realizing projected gropundwater stress into assessments of actual groundwater sustainability and locally relevant adaptation strategies.

Data Availability

The CORDEX-Africa climate projections used to force the CLM5 simulations are publicly available through the corresponding CORDEX/ESGF data repositories (https://esg-dn1.nsc.liu.se/search/cordex/). ERA5-Land data are available from the Copernicus Climate Data Store (Copernicus Climate Change Service, 2019; DOI: 10.24381/cds.e2161bac), and the GLDAS Noah version 2.1 data are available from the NASA Goddard Earth Sciences Data and Information Services Center (Beaudoing and Rodell, 2020; DOI: 10.5067/E7TYRXPJKWOQ). The WaterGAP-GFDL and PCR-GLOBWB2.0 datasets used in this study are available from https://data.isimip.org/10.48364/ISIMIP.398165.11 and https://globalhydrology.nl/research/datasets/ respectively. The population data was also obtained from https://doi.org/10.7927/H49C6VHW. The processed datasets and CLM5-derived potential groundwater recharge data required to reproduce the analyses, figures and tables presented in this study are available at Zenodo under https://doi.org/10.5281/zenodo.22915107.

Competing Interests

At least one of the (co-)authors is a member of the editorial board of Hydrology and Earth System Sciences.

Author Contribution

BO: data curation, methodology, formal analysis, investigation, software, visualization, writing (original draft preparation). BB: conceptualization, methodology, writing (review and editing), EHS: Data curation, methodology, writing (review and editing), SFK: conceptualization and methodology, CM: methodology, writing (review and editing), HV: conceptualization, methodology, writing (review and editing). & HJHF: conceptualization, methodology, supervision, writing (review and editing).

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