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Research papers

Implications for sustainable water consumption in Africa by simulating five decades (1965–2014) of groundwater recharge

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ABSTRACT

Groundwater stands as a vital water resource for both present and future generations in Africa. This underscores the importance of examining the sustainability of current groundwater consumption across the continent, along with its capacity to fulfill the current human and essential environmental water needs. Groundwater sustainable yield is a suitable indicator for assessing groundwater sustainability but has not yet been quantified properly across Africa. A thorough quantification of groundwater sustainable yield necessitates a profound comprehension of the spatio-temporal fluctuations in surface hydrology, groundwater recharge, environmental flow, and sectoral water use. In this study, high spatial resolution (10 km) land surface hydrology was simulated for five decades (1965–2014) across Africa by the Community Land Model version 5 at half-hourly time step and aggregated to monthly and annual temporal resolutions. Then, groundwater recharge and environmental flow were quantified based on the water balance approach for the whole continent. Finally, by including African sectoral water use data available for four decades (1971–2010) we obtained the long-term average of groundwater sustainable yield. Based on extensive simulations of long-term land surface hydrology, we discovered that the groundwater system in Africa experienced an average annual recharge of 57.8 mm yr^{-1} (with a standard deviation of 110.8 mm yr^{-1} serving as an indicator of spatial variability), corresponding roughly to an annual recharge volume of 1793.6 km^3 yr^{-1}. Furthermore, our analysis revealed that the entire continent possesses an annual average potential sustainable yield (with standard deviations) of 4.5 mm yr^{-1} (10.2), 20.6 mm yr^{-1} (42.9), and 37.3 mm yr^{-1} (75.7) under conservative, optimum, and suitable water consumption scenarios, respectively. This calculated annual groundwater sustainable yield corresponds to 141.9 km^3 yr^{-1}, 643.1 km^3 yr^{-1}, and 1160.5 km^3 yr^{-1} for the conservative, optimum, and suitable scenarios, respectively. Furthermore, the calculated sustainable yield volume is contrasted with the total water storage figures documented for 50 countries throughout Africa. The outcomes illustrate that our calculated annual sustainable yield equates to roughly 0.02%, 0.1%, and 0.17% of the reported groundwater storage across the entire continent. Based on the estimated long-term average sustainable yield and the reported total water storage at the national level, our conclusion is that the accessible groundwater resources could potentially satisfy the current water requirements of both humans and the environment in African countries. This study offers the first model-based estimation of groundwater availability across Africa, potentially serving as a catalyst to inspire further progress toward adopting more sustainable approaches to groundwater usage on the continent.

1. Introduction

Groundwater has been recognized as the predominant water supply source for diverse communities throughout Africa (Altchenko et al. 2011) due to its ubiquitous, perennial presence, large storage capacity, favorable water quality, and resilience to inter-annual and seasonal climate variability as compared to other alternatives (Adelana and Macdonald 2008, Döll and Fiedler 2008, Calow et al. 2010, MacDonald et al. 2012). Based on the total volume of water held in storage, groundwater is the most abundant water resource in Africa (UNEP 2010).

These favorable characteristics make groundwater an attractive

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resource and, as a consequence, create intense competition between various water users in Africa, particularly for food and energy production purposes. On average, 75% of the continent's population relies on groundwater for drinking water (UNECA, 2000). This is even higher in specific countries located in arid and semi-arid zones of Africa. For instance, in Libya 95% of the population depends on groundwater for their drinking supply (Margat 2008). The discharge of waste water (i.e., brine) can degrade groundwater quality. Given the significance of water quality, particularly for potable purposes, water should not be directly used for domestic and industrial applications (Panagopoulos 2022, Panagopoulos and Giannika 2022a, 2022b). Considering all water consumers, about 86% of the water withdrawal in Africa is utilized for agriculture, 10% for households, and 4% for industry, including energy production (FAO 2005).

Additional water consumption in the energy sector, for example, large scale green hydrogen production, has been planned in Africa and is gaining attraction. This intensifies the competition between local water consumers (e.g., agriculture, households and industry) in Africa, especially in arid and semi-arid regions. Therefore, a thorough investigation of groundwater availability that inspires sustainable water consumption and facilitates groundwater management is of great importance. Ideally, it can be used to foster beneficial energy, e.g., green hydrogen, production in Africa. Inadequate water management can lead to the over-exploitation and depletion of groundwater storage (Custodio 2002, Rohde et al. 2018, Bierkens and Wada 2019, de Graaf et al. 2019), and will create potential conflicts between various water consumers. As a result of excessive groundwater resource exploitation, the potential for increased risks of saltwater intrusion and land subsidence will considerably escalate in coastal regions (Galloway and Burbey 2011, Michael et al. 2017) in addition to the environmental concerns highlighted by Bierkens and Wada (2019), among others.

The concept of the "safe yield" introduced by Lee (1915), aims to address the aforementioned threats, confront associated challenges, and uphold the sustainability of groundwater resources. Initially, the concept of safe yield was defined to limit the pumping rate to less than or equal to groundwater recharge under steady-state conditions regardless of the contribution from aquifer discharge. However, this concept is known as the 'water budget myth' in the hydrology community (Bredehoeft 2002, Devlin and Sophocleous 2005) and is an obvious over-simplification that can lead to overexploitation of an aquifer. Human activities can affect the system, and the total water budget, which must be considered in water projects and management. Theis (1940) concludes that the water being pumped from a groundwater system will be balanced by a loss of water elsewhere, mostly from storage, possibly induced recharge (e.g., re-infiltration from irrigation), reduced discharge, or a combination of these. Consequently, the concept of "safe yield" shifted to "sustainable yield" (Alley and Leake 2004) in the groundwater community. Groundwater sustainable yield is the available resource yield that enables the normal exploitation for a long time without adverse impacts while making maximum economic, societal, and environmental benefits (Freeze 1971, Fetter 1972, 2001, Sophocleous 2000, Sophocleous and Perkins 2000, Alley and Leake 2004, Kalf and Woolley 2005, Shi et al. 2012). Comprehensive details regarding the historical context and progression of sustainable yield are accessible within the community (e.g., Alley and Leake 2004, Maimone 2004, Rudestam and Langridge 2014). Moreover, substantial effort has been made to understand various aspects of groundwater sustainability. For instance, Gleeson et al. (2020) reviewed global groundwater sustainability, resources, and systems, Condon et al. (2021) explored monitoring opportunities and challenges, and Elshall et al. (2020) discussed the interactions between science and policy. Hence, for the purpose of sustainable planning and utilization of groundwater resources, it is crucial to possess recharge information as a key indicator of resource renewability.

Groundwater recharge is a crucial variable for evaluating groundwater sustainability and developing and predicting future changes (Taylor et al. 2013, Gleeson et al. 2020). Recharge can occur either locally from local water bodies or in diffuse form from precipitation over an unsaturated soil zone. Considering the long-term mean, the diffuse recharge is a part of precipitation that neither evaporates nor runoff to surface water bodies via surface runoff or interflow (Döll and Fiedler 2008). In the current study, we focus on diffuse recharge and hereafter, the term groundwater recharge refers mainly to diffuse recharge. The spatio-temporal estimation of groundwater recharge is difficult since there is currently no globally applicable and well-known approach that can capture the amount of rainfall directly reaching the groundwater table (Scanlon et al. 2002, Healy 2010). However, several methods can provide an indirect estimation of groundwater recharge at various scales. The most widely-used methods are chloride mass balance, environmental and isotopic tracers, groundwater-level fluctuation methods, and the estimation of baseflow to rivers and water balance (hydrological) models (Macdonald et al. 2021). At the global scale, the generation of the first groundwater recharge study dates back to 1979 by L'vovich. A baseflow component of measured river discharge to generate a global map of groundwater recharge was used (L'vovich, 1979). Later, global groundwater recharge has mainly been estimated by utilizing hydrological models. For instance, Döll et al. (2002) obtained a global groundwater recharge map using the hydrological model WGHM (WaterGAP Global Hydrology Model (Alcamo et al. 2003, Döll et al. 2003)), and updated simulations with the WGHM2 model (Döll and Fiedler 2008). Hydrological models can assist in obtaining spatio-temporal variations of groundwater recharge at selected spatial resolutions, albeit with uncertainties. If available, ground-based estimates of recharge can be used to validate the model simulations and quantify the errors.

In Africa, considerable research has been performed to investigate various aspects of groundwater recharge in several regions, for instance, in southern Africa (Xu and Beekman 2003, 2019, Abiye 2016), northern Africa (Edmunds and Wright 1979, Guendouz et al. 2003, Sturchio et al. 2004) and western Africa (Edmunds and Gaye 1994, Leduc et al. 2001, Leblanc et al. 2008, Favreau et al. 2009). Recently, the first long-term groundwater recharge map for the whole of Africa was generated for the period 1970 – 2019 through estimates collected from ground-based measurements (MacDonald et al., 2021). In this contribution, MacDonald et al. (2021) adopted a statistical approach to quantify long-term average groundwater recharge for Africa using a robust dataset of 134 long-term ground-based estimates. They have shown that at the continental scale, the long-term average rainfall is related to groundwater recharge through a linear mixed model. However, other climate and terrestrial factors were found to be important in the modeling of groundwater recharge, mainly at the local scale. This study by MacDonald et al. (2021) provides a valuable ground-based approximation of groundwater renewability in Africa and can also serve as a useful baseline for investigating water security. However, there is still strong interest in: (i) utilizing a physically-based land surface process modeling to comprehend the land surface hydrology and map groundwater recharge across Africa, and (ii) Investigating the feasibility of using groundwater recharge as a means to fulfill existing human and environmental water demands. The former is of particular significance to scientists, as employing a model-based approach can comprehensively capture spatio-temporal variations (such as atmospheric forcings, land cover, and soil texture), thereby offering insights into land surface hydrology (including evapotranspiration and surface runoff). The latter holds notable importance, particularly for water managers and local consumers, as it represents a stride towards fostering sustainable groundwater consumption in Africa. This progress is especially relevant in sectors like agriculture, where substantial water is utilized for food production through irrigation (Abd-Elaty et al., 2023; Khafaji et al., 2022; Pandey et al., 2020). The current study specifically concentrates on these two aspects. For the first time, we computed the long-term groundwater sustainable yield in Africa, incorporating five decades of land surface hydrology and natural groundwater recharge simulations at a spatial resolution of 10 km using the Community Land Model [ver. 5] (CLM) (Lawrence et al. 2019) and four decades of available records on sectoral water use in Africa.

To extend previous research, this study is driven by three specific objectives: (i) estimating the long-term average (1965–2014) of land surface hydrology in Africa through the application of the CLM model (Lawrence et al., 2019), (ii) evaluating the long-term average of groundwater recharge across the entire African continent, serving as an indicator of groundwater renewability, and (iii) calculating the long-term average of groundwater sustainable yield, which serves as an indicator of groundwater availability. This calculation takes into account sectoral water use (namely agriculture, household, and industry) as well as environmental flow (minimum ecological water requirements) in Africa. Lastly, the integration of these indicators furnishes the data necessary for the subsequent discussion on the sustainability of groundwater resources and their utilization in Africa.

2. Material and data

2.1. CLM model

The land surface model CLM was developed by the National Center for Atmospheric Research (NCAR) (Lawrence et al., 2019). In this study, version 5.0 of CLM has been used. CLM simulates the key biophysical and biogeochemical processes that includes the interaction of incoming radiation with the canopy and soil, exchange fluxes of sensible heat, latent heat and carbon between the land and atmosphere. Additionally, it simulates snow accumulation and melting, water and energy transport in the soil including infiltration, surface runoff, deep infiltration, and stomatal physiology and photosynthesis (Oleson et al., 2008, 2004). This makes it possible to estimate the evapotranspiration and surface runoff required for our study. The CLM model captures the spatial heterogeneity by a designed nested subgrid hierarchy (Oleson et al., 2008). Each grid cell is divided into various land units (notably: glacier, lake, urban, vegetated, and crop) with each land unit being able to include various numbers of snow/soil columns. Moreover, each column is composed of multiple plant functional types (PFTs) with PFT-specific plant physiological parameters (Bonan et al., 2002; Oleson et al., 2008). Going from the first subgrid level (i.e., the land unit) to the last one (PFTs) allows for capturing subgrid heterogeneity to a certain degree. For detailed information about CLM surface characterization and vertical discretization, the reader is referred to Oleson et al. (2010a, 2010b).

2.2. CLM model input data

2.2.1. Atmospheric forcing data

The CLM model requires extensive atmospheric forcing data including precipitation, air temperature, shortwave and longwave incoming radiation, humidity, surface air pressure, and wind speed. For our CLM simulations, long time series (1965–2014) of such data was obtained from the third Global Soil Wetness Project (GSWP3; Kim, 2017). The GSWP3 provides 3-hourly forcing data at global scale at 0.5° spatial resolution (https://hydro.iis.u-tokyo.ac.jp/GSWP3/; last access: 10 January 2023). The GSWP3 data is originally based on the second version of the 20th Century Reanalysis (20CR) created by the National Centers for Environmental Prediction (NCEP) land–atmosphere model (Compo et al. 2011). The 20CR was translated to 0.5° spatial resolution by means of downscaling techniques, the Global Spectral Model (GSM), and data assimilation (Yoshimura and Kanamitsu 2008). To derive the GSWP3 dataset from 20CR, a bias correction has been performed for precipitation (using the Global Precipitation Climatology Centre GPCC v6 dataset), temperature (using Climate Research Unit CRU TS v3.21 dataset), longwave and shortwave incoming radiation (using Surface Radiation Budget SRB dataset) (Guimberteau et al. 2018).

2.2.2. Land cover and soil texture data

Moderate Resolution Imaging Spectroradiometer (MODIS) land cover type product (MCD12Q1) has been used to feed the CLM model. The MCD12Q1 version 5 provides annual global coverage at 500 m resolution that is available from 2001 till 2015. The MCD12Q1 product is generated by means of a supervised classification approach from MODIS surface reflectance data (Friedl et al. 2010) and incorporates five land cover classification schemes (https://modis.gsfc.nasa.gov/data/dataprod/mod12.php; last access: 10 January 2023).

Soil texture and properties information is obtained from the International Geosphere-Biosphere Program Data and Information System (IGBP-DIS; GSD Task, 2014). IGB-DIS is an international initiative aiming to generate a soil information database accessible to the scientific community. It provides reliable soil properties information at the global scale for various soil layers. This makes it possible to extract soil information and maps for a particular geographic region at various soil depths (e.g., from a few centimeters top-soil up to 3.4 m sub-surface) and favorable spatial resolution (https://daac.ornl.gov/cgi-bin/dsviewer.pl?ds_id = 565; last access: 10 January 2023). The IGB-DIS data is made available as the CLM model soil texture at 8 km spatial resolution.

2.3. Supplementary data

2.3.1. Sectoral water use

Human water use data were derived from the first reconstructed gridded global water use data (Huang et al. 2018). This dataset includes the global monthly water withdrawal by various sectors (i.e., irrigation, domestic, electricity generation, livestock, mining, and manufacturing purposes) on a grid with 0.5° spatial resolution for the period 1971–2010 (https://zenodo.org/record/1209296#; last access: 10 January 2023). Several models (e.g., global hydrological models), algorithms (e.g., spatial and temporal downscaling), and data sources (e.g., water withdrawals from Food and Agriculture Organization (FAO) AQUASTAT) have been used to generate this global dataset. For irrigation water use, we considered the average of four estimates made by four global hydrological models, i.e., Water Global Assessment and Prognosis (WaterGAP: Döll and Siebert 2002, Alcamo et al. 2003, Döll et al. 2009, Müller Schmied et al. 2014), Lund-Potsdam-Jena managed Land (LPJmL: Rost et al. 2008), H08 (Hanasaki et al. 2008a, 2008b), PCRaster Global Water Balance (PCR-GLOBWB: Van Beek et al. 2011, Wada et al. 2011, 2014).

2.3.2. Groundwater recharge and storage

The long-term average of CLM simulated groundwater recharge in this study is compared to the reported average groundwater recharge (Macdonald et al. 2021) and total storage (MacDonald et al. 2012) for Africa. MacDonald et al. (2021) published a long-term (1970–2019) average groundwater recharge map which is generated from a robust dataset of 134 long-term groundwater recharge estimates using a statistical approach. Moreover, the reported groundwater storage has been estimated by integrating the aquifer saturated thickness and effective porosity for the whole of Africa.

3. Methods

As depicted in Fig. 1, this study involves four main steps. In the first step, the CLM model was employed to simulate half-hourly evapotranspiration, surface runoff and irrigation, which were then aggregated to monthly, annual, and long-term averages for the period 1965–2014 (this is in addition to five more years (1960–1964) discarded as a spin-up period) at 10 km spatial resolution. It should be noted that CLM aggregates the various input data in space and time toward the model resolution. The spatial aggregation of land cover, soil texture, and atmospheric forcing data was carried out using the nearest neighbor algorithm. Linear interpolation was employed to achieve half-hourly temporal intervals for variables such as temperature, pressure, specific

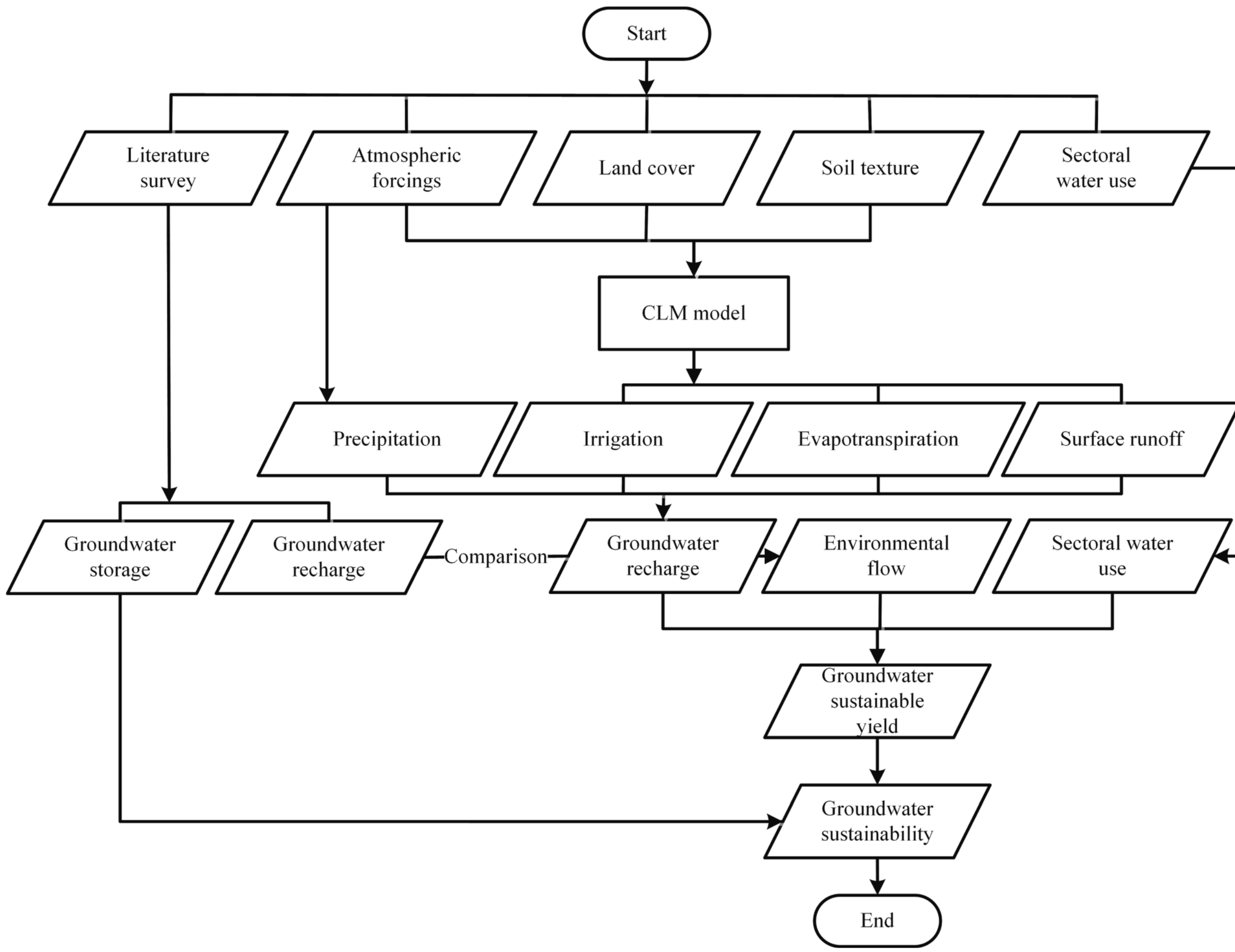

Fig. 1. Flowchart of the adopted methodology.

humidity, wind, and longwave radiation. The nearest neighbor algorithm was applied for precipitation, while cosine zenith angle was used for temporal resampling of shortwave radiation.

CLM simulations of evapotranspiration, surface runoff, and irrigation were used together with the annual and long-term average of precipitation from GSWP3 to compute the annual and long-term average of groundwater recharge for Africa based on a simple water balance approach. This was then compared with the reported groundwater recharge by MacDonald et al. (2021) for Africa. In the second step, the annual and long-term average of environmental flow was calculated under three different water consumption scenarios (conservative, optimum [also known as average, medium], and suitable [also known as less conservative]). The third step involved the resampling of sectoral water use data to a spatial resolution of 10 km, followed by analysis to derive the annual and long-term average of total human water withdrawal. As a result, the quantification of the annual and long-term average potential groundwater sustainable yield across Africa became feasible. In the final step, we compared the estimated groundwater sustainable yield with the documented total groundwater storage across Africa. This comparison was undertaken to facilitate a discussion regarding the sustainability of water consumption at the level of individual countries in Africa.

3.1. Groundwater recharge

The CLM model has been applied to simulate 50 years (1965–2014) of evapotranspiration and surface runoff across Africa at 10 km spatial resolution and monthly time step. Annual groundwater recharge and its long-term average were calculated from the CLM simulations based on general water balance approach (Meinzer 1920, Hahn et al. 1997, Rossi et al. 2022). Additionally, irrigation has been considered in the water balance, as an anthropocentric water supply, simulated by CLM based loosely on Ozdogan et al. (2010), for the period of 1965–2014, according to:

$$\mathrm{R} = (P + I) - \mathrm{ET} - Q \tag{1}$$

where R is groundwater recharge [mm yr^{-1}], P is the precipitation (rain and snow) [mm yr^{-1}], I is the simulated irrigation by CLM to account for all anthropocentric water supply [mm yr^{-1}], ET is evapotranspiration [mm yr^{-1}], and Q is surface runoff [mm yr^{-1}].

3.2. Environmental flow

Environmental flow, also referred to as the minimum ecological water requirement, denotes the minimal volume of water necessary to uphold ecosystems and the benefits they provide. Based on previous recommendations, the rational utilization rate of the water resources must not be more than 10%, 40%, and 70% of the total recharge based on conservative, optimum, and suitable scenarios (Alley et al. 1999, Sophocleous 2000, Alley and Leake 2004, Maimone 2004, Shi et al. 2012). Following these recommendations, we considered three different scenarios for assigning the environmental flow from simulated groundwater recharge: (i) conservative environmental flow (90% of recharge), (ii) optimum [also known as average, medium] environmental flow (60% of recharge), and (iii) suitable [also known as less conservative] environmental flow (30% of recharge).

3.3. Sustainability analysis

The quantification of the long-term average (1971–2010) groundwater sustainable yield is achieved through the utilization of Eq. (2), employing the concept of percentage of recharge [as proposed by Miles and Chambet (1995), Hahn et al. (1997)] and incorporating total human water withdrawal (sectoral water use). This approach serves to evaluate the sustainability of groundwater utilization in Africa. Here, we also considered three scenarios for sustainable yield originating from three scenarios designed for the environmental flow (i.e., conservative, optimal, and suitable):

$$SY = R - Q_{rest} - SWU \quad (2)$$

where SY is groundwater sustainable yield, Q_{rest} is environmental flow, and SWU is sectoral water use. The units of all variables in Eq. (2) can be expressed in mm yr^{-1}, and the maps are produced at 10 km spatial resolution. It should be noted that although the groundwater recharge and environmental flow simulations are available for 50 years (1965–2014), the long-term average of sustainable yield is calculated for 40 years (1971–2010) due to the limitation posed by the availability of sectoral water use data.

4. Results

This study has taken into account five distinct geographical regions, which serve as the framework for summarizing, reporting, and discussing findings specific to each area. These regions in Africa comprise eastern Africa, central Africa, northern Africa, southern Africa, and western Africa, as defined by geographical boundaries (https://www.mapsofworld.com/africa/regions/; last accessed: 10 January 2023). These regions are labeled accordingly in Fig. 2d.

4.1. Water balance components

The long-term average (1965–2014) of water balance components is depicted in Fig. 2, with precipitation shown in Fig. 2a, evapotranspiration in Fig. 2b, runoff in Fig. 2c, and irrigation in Fig. 2d. The precipitation map (Fig. 2a) provides a comprehensive depiction of the intricate patterns of precipitation across the vast continent of Africa. A significant portion of coastal regions and equatorial areas are characterized by a distinct propensity to receive higher levels of precipitation. The map illustrates that the most elevated precipitation values are concentrated around the equator, encompassing the tropical Africa region. In this zone, the annual average precipitation exceeds 1000 mm per year, indicative of a climatic region characterized by abundant rainfall.

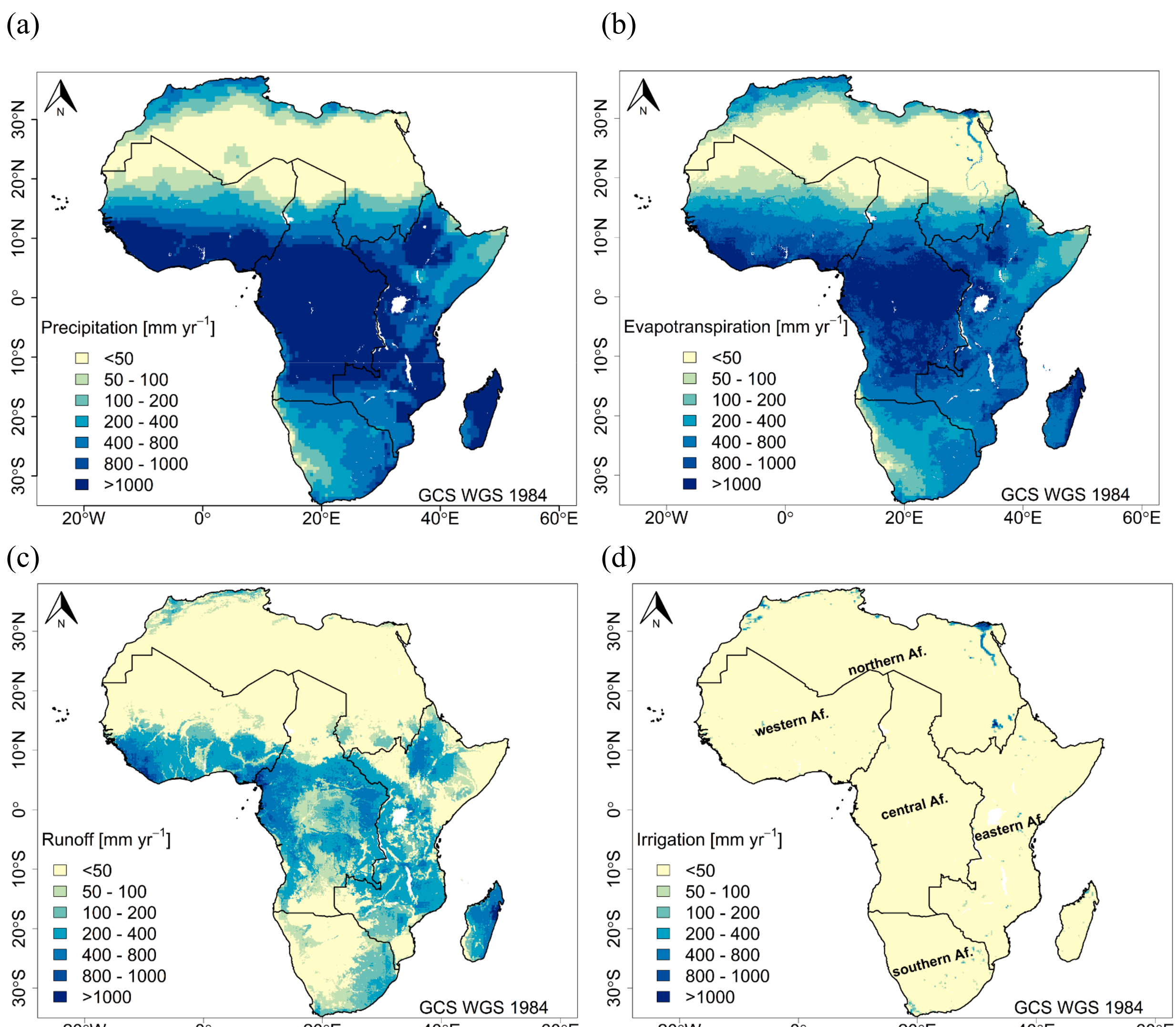

Fig. 2. The water balance components of the African continent: (a) long-term average (1965–2014) precipitation, (b) evapotranspiration, (c) runoff, and (d) irrigation, all mapped using the CLM model. The geographical regions of Africa are labeled in (d).

Nonetheless, Fig. 2a illustrates areas where precipitation values notably diminish, reaching their lowest points across the entirety of Africa. Significantly, the southern portion of the southwest coast and the Sahel zone encounter notably reduced levels of precipitation. A notable contrast arises when comparing coastal regions to inland areas. While the general trend suggests a decrease in precipitation as one moves away from the equator and tropical Africa, certain coastal regions exhibit a divergent pattern.

Evapotranspiration (Fig. 2b) and runoff (Fig. 2c) are closely related to precipitation. The quantity and intensity of precipitation play a direct role in influencing evapotranspiration and runoff rates, which subsequently affect the rate of groundwater recharge. The findings indicate a remarkable likeness and significant correspondence between the spatial distribution of precipitation and evapotranspiration across the entire continent. Similar to precipitation patterns, central Africa along the equator displays elevated evapotranspiration values, whereas the northern and southern regions, particularly the Sahel zone and Sahara desert, exhibit considerably lower evapotranspiration values.

Upon examining the runoff map (Fig. 2c), analogous patterns to those of evapotranspiration and precipitation become evident. However, the spatial manifestation of runoff is notably less distinct in comparison to evapotranspiration. Additionally, our observations indicate that the simulated irrigation by CLM (Fig. 2d), serving as an indicator of anthropocentric water supply, is relatively limited within the central and tropical regions, in contrast to northern and southern Africa. The majority of irrigated areas are concentrated in northern and southern Africa, signifying a prominent focal point for irrigation activities in these regions.

Upon investigating these five geographical regions, the outcomes (Fig. 3) indicate that central Africa receives the most substantial amount of precipitation (median: 1162 mm yr^{-1}), whereas northern Africa records the lowest precipitation (median: 37 mm yr^{-1}) when contrasted with the other regions. The eastern, southern, and western Africa experience median precipitation values of 776 mm yr^{-1}, 701 mm yr^{-1}, and 72 mm yr^{-1}, respectively. A similar pattern, although with varying magnitude, was noted for evapotranspiration. Central and northern Africa showcased the highest and lowest evapotranspiration rates, registering medians of 894 mm yr^{-1} and 38 mm yr^{-1}, respectively. In contrast, eastern, southern, and western Africa recorded median evapotranspiration values of 594 mm yr^{-1}, 575 mm yr^{-1}, and 62 mm yr^{-1}, respectively. Additionally, the median simulated surface runoff exhibited regional variations: 123 mm yr^{-1} in eastern Africa, 106 mm yr^{-1} in central Africa, 54 mm yr^{-1} in southern Africa, 8 mm yr^{-1} in western Africa, and 3 mm yr^{-1} in northern Africa. While a median of

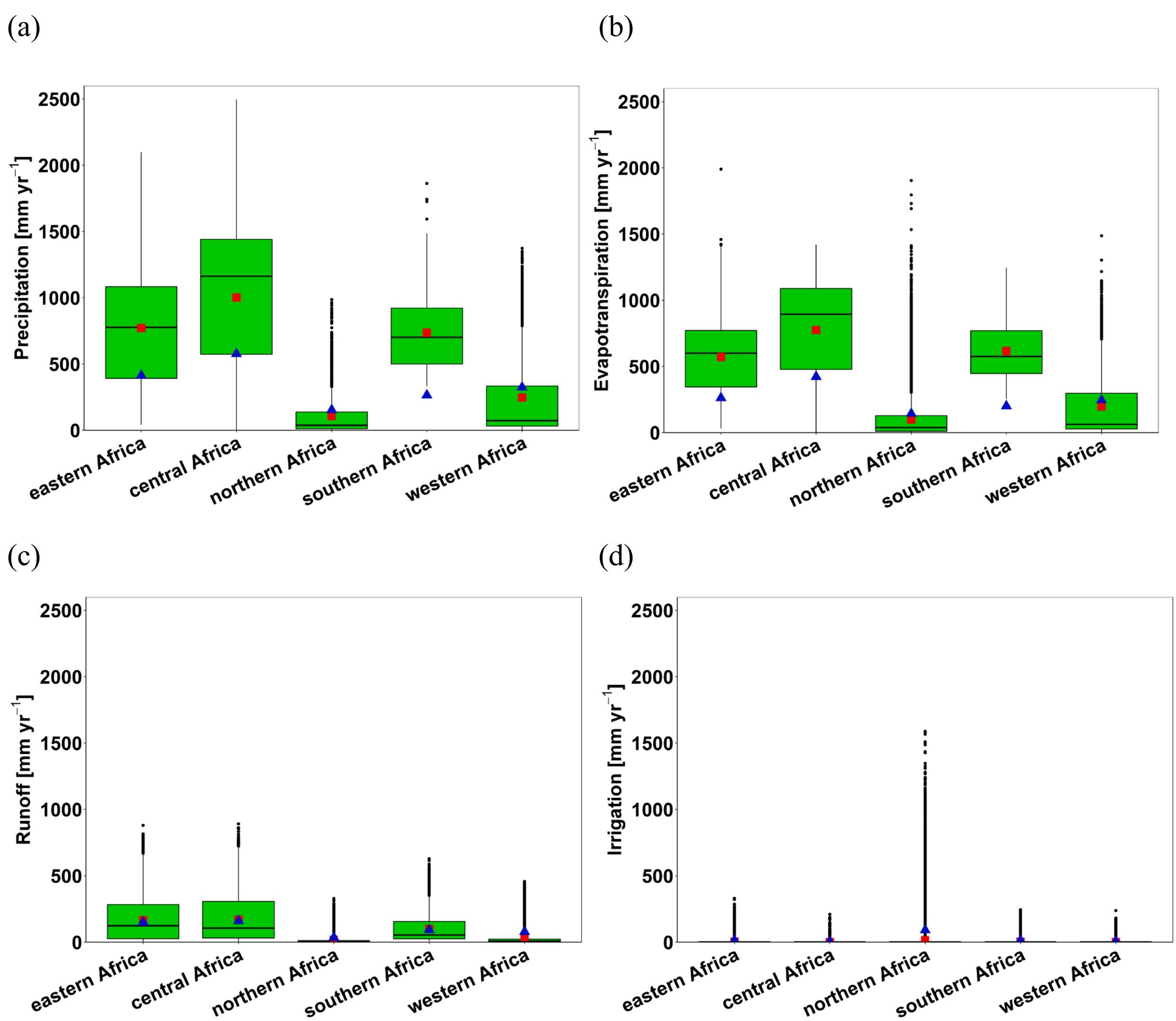

Fig. 3. The distribution of water balance components in Africa: (a) precipitation, (b) evapotranspiration, (c) runoff and (d) irrigation derived from the maps presented in Fig. 2. The individual point values in the plots correspond to the model grid cells. The average values are represented by red squares, while the standard deviation (as an indicator of spatial variability) values are indicated by blue triangles. (For interpretation of the references to colour in this figure legend, the reader is referred to the web version of this article.)

zero was apparent for the irrigation component in all regions, a considerable amount of irrigation was simulated specifically in the northern Africa region.

4.2. Groundwater recharge

The long-term average of simulated groundwater recharge is shown in Fig. 4a. The variability of groundwater recharge across the entire continent becomes evident, highlighting the formation of distinct zonal key areas. The groundwater recharge values are notably minimal and predominantly fall below 2.5 mm yr^{-1}, particularly in the vicinity of the Sahel zone and the Sahara. It is only in the western region of the Sahelian zone where a relatively higher annual groundwater recharge is observed on average, with values ranging between 2.5 mm yr^{-1} and 10 mm yr^{-1}. Moving further south from the Sahel, groundwater recharge values exhibit a steady increase and reach their peak in central Africa near the equator. In this area, the values range between 50 mm yr^{-1} and over 250 mm yr^{-1}, with the 100–250 mm yr^{-1} classification prevailing. An observable trend is the presence of notably higher groundwater recharge values in the proximity of coastal regions and directly along coastal areas. Moreover, the recharge values in Madagascar are strikingly elevated, with only the southwestern region registering values below 50 mm yr^{-1} on average. Across the remainder of Madagascar, the groundwater recharge values surge significantly, reaching average levels of 100–250 mm yr^{-1} or even surpassing 250 mm yr^{-1}. In Central Africa, the most elevated levels are observed in the Democratic Republic of Congo and its neighboring countries. These areas all fall within the tropical zone and experience substantial groundwater recharge due to elevated levels of precipitation. For detailed information of groundwater recharge values specific to individual countries (extracted from Fig. 4a), the readers are referred to Table 1.

The spatial distribution of simulated recharge (Fig. 4a) reveals median recharge values of 43 mm yr^{-1} in central Africa, 32 mm yr^{-1} in eastern Africa, 27 mm yr^{-1} in southern Africa, 6 mm yr^{-1} in western Africa, and 4 mm yr^{-1} in northern Africa (Fig. 5a). This underscores that substantial portions of Africa, such as Northern and Western Africa, experience notably limited recharge in comparison to the average recharge of 57.8 mm yr^{-1} calculated for the entire continent in this study.

Furthermore, we conducted a comparison between groundwater recharge data from this study and that of MacDonald et al. (2021), which represents the latest advancement in this field (Fig. 4b). Similarly, they documented higher groundwater recharge levels in tropical Africa in contrast to the northern and southern regions. Nonetheless, as evidenced by the outcomes (Fig. 4a & b), both maps exhibit a certain degree of similarity. Notably, this study offers more detailed spatial information compared to the findings of MacDonald et al. (2021). Summarizing their estimated recharge for the five geographical regions, their results (Fig. 5) showcase median recharge values of about 100 mm yr^{-1} in central Africa, 58 mm yr^{-1} in eastern Africa, 48 mm yr^{-1} in southern Africa, 2 mm yr^{-1} in western Africa, and 1 mm yr^{-1} in northern Africa.

4.3. Environmental flow

The long-term average of environmental flow is depicted in Fig. 6, accounting for three distinct water consumption scenarios: conservative (Fig. 6a), optimum (Fig. 6b), and suitable (Fig. 6c). The findings reveal that coastal regions in the northern areas, as well as those near the equator and more broadly across tropical Africa, consistently exhibit a propensity to receive elevated levels of environmental flow in all three scenarios (Fig. 6a, 6b, and 6c). The accumulation of precipitation and groundwater recharge in these coastal and equatorial zones surpasses that of other parts of Africa, contributing to the higher values of environmental flows observed. While an identical spatial pattern emerged in the environmental flow maps, particularly for the conservative (Fig. 6a) and optimum (Fig. 6b) scenarios, variations in magnitudes were observed, contingent upon the specified percentage of groundwater recharge for each scenario. For instance, it is evident that the highest environmental flow values were identified in central Africa, clustered around the equator within the confines of the tropical Africa region, across all three scenarios. However, there is a notable difference in the extent of areas receiving mean annual environmental flows: more than 250 mm yr^{-1} in the conservative scenario (Fig. 6a), 100–250 mm yr^{-1} in the optimum scenario (Fig. 6b) and 50–100 mm yr^{-1} in the suitable scenario (Fig. 6c). This consistent spatial pattern in the environmental flow maps, coupled with variations in magnitudes, is also discernible in western Africa.

The median optimum environmental flow values were determined as 26 mm yr^{-1} for central Africa, 19 mm yr^{-1} for eastern Africa, 16 mm yr^{-1} for southern Africa, 4 mm yr^{-1} for western Africa, and 3 mm yr^{-1} for northern Africa. Under the conservative scenario, these median values increased to 39 mm yr^{-1} (central), 29 mm yr^{-1} (eastern), 24 mm

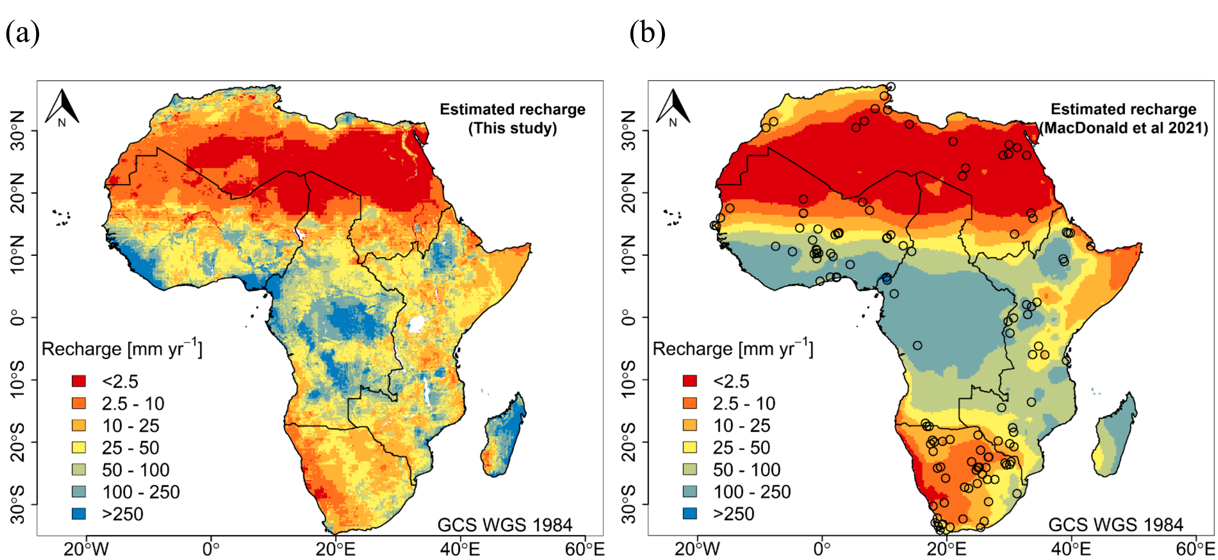

Fig. 4. Long-term average (50 years) of simulated recharge for the African continent: (a) The average of CLM model simulated recharge for 1965–2014 in this study and, (b) the average of recharge estimated for 1970–2019 by MacDonald et al. (2021). The circles depict the spatial distribution of 134 ground-based stations employed by MacDonald et al. (2021) for groundwater recharge estimation.

Table 1
The annual estimates for groundwater recharge and sustainable yield (both average depth and total volume) are provided for each country in Africa. Standard deviations (as an indicator of spatial variability) are indicated within parentheses. Groundwater sustainable yield values are presented for three scenarios: conservative, optimum, and sustainable. For comparison purposes, groundwater storage data is extracted from MacDonald et al. (2012).

Country	Recharge		Sustainable yield						Storage volume best estimate (km^3)
	Depth (mm yr^{-1})	Volume (km^3 yr^{-1})	Depth (mm yr^{-1})			Volume (km^3 yr^{-1})			
			Conservative	Optimum	Suitable	Conservative	Optimum	Suitable	
Algeria	10.5 (23.4)	23.3	0.5 (1.1)	3.1 (7.3)	5.9 (14.1)	1.1	6.8	13.2	92,000
Angola	87.8 (93.9)	109.8	8.3 (9.2)	33.9 (36.8)	59.5 (64.3)	10.3	42.3	74.3	17,000
Benin	42.1 (27.5)	4.9	3 (2.1)	15.2 (9.9)	27.4 (17.8)	0.4	1.8	3.2	720
Botswana	20.7 (8.8)	11.9	2 (1)	8.8 (3.8)	15.6 (6.5)	1.2	5.1	9	18,000
Burkina Faso	33.7 (28)	9.1	2 (2.6)	11.6 (10.4)	21.5 (18)	0.6	3.1	5.8	980
Burundi	63.9 (28.1)	1.6	1.6 (2.7)	17.7 (12.1)	35.5 (20.6)	0	0.5	0.9	47
Cameroon	178.8 (221.8)	83	16.4 (21.1)	68.3 (85.6)	120.4 (150)	7.6	31.8	56	1600
Cen. African Rep.	51.2 (25.3)	31.7	4.9 (2.4)	20 (9.6)	35.1 (16.8)	3.1	12.4	21.7	4200
Chad	28.3 (39.9)	36	2.5 (3.6)	10.3 (14.7)	18.2 (25.9)	3.1	13.1	23.2	46,000
Congo	143.3 (107.4)	49.5	14 (10.4)	56.6 (41.6)	99.1 (72.9)	4.9	19.5	34.2	6700
Côte d'Ivoire	57.2 (60.9)	18.6	2.9 (5.9)	18.1 (23.8)	33.8 (41.5)	0.9	5.9	11	240
Dem. Rep. of Congo	139.2 (114.7)	321.6	13.6 (11.5)	55 (45.6)	96.4 (79.8)	31.4	127	222.7	38,000
Djibouti	12.1 (6)	0.3	0.6 (0.6)	3.6 (2.8)	6.8 (4.9)	0	0.1	0.2	170
Egypt	4.9 (14)	4.8	0.1 (0.5)	0.7 (2.8)	1.3 (5.2)	0.1	0.6	1.3	55,000
Equatorial Guinea	409 (489.4)	11.4	39.1 (48.4)	157.3 (193.6)	275.5 (338.8)	1.1	4.4	7.7	48
Eritrea	19.1 (22.2)	2.3	1 (2.3)	5.9 (9.6)	11.4 (16.7)	0.1	0.7	1.4	330
Eswatini	37.8 (20.6)	0.6	0 (0)	1.8 (4.9)	6.4 (11.7)	0	0	0.1	24
Ethiopia	75.9 (83.2)	85.3	5.6 (8)	26.3 (33)	47.8 (57.9)	6.3	29.5	53.6	13,000
Gabon	194.5 (175.6)	50.7	18.4 (17)	74.5 (68.4)	130.6 (119.7)	4.8	19.4	34.1	1200
Gambia	109.2 (55.7)	1.2	6.9 (3.7)	37.5 (18.9)	68.1 (34.4)	0.1	0.4	0.7	750
Ghana	92.8 (73.1)	22.2	7.4 (8.1)	34 (31.7)	61.2 (55.1)	1.8	8.2	14.7	1400
Guinea	248.7 (235.2)	61.9	21.4 (21.8)	92.4 (89.7)	163.3 (157.7)	5.3	23	40.7	540
Guinea Bissau	296.1 (168.4)	9.3	25.2 (16)	111 (64.2)	196.8 (112.5)	0.8	3.5	6.2	1200
Kenya	43.2 (31.8)	24.9	2.5 (3.1)	13.3 (12.3)	24.8 (21.4)	1.4	7.7	14.3	8800
Lesotho	45 (24.7)	1.4	2.7 (2.2)	16.7 (9.8)	30.9 (17.6)	0.1	0.5	0.9	290
Liberia	427.8 (233.1)	41.1	38.4 (21.6)	157 (86.2)	275.5 (150.8)	3.7	15.1	26.5	86
Libya	8.4 (27.8)	13.3	0.6 (2.3)	2.9 (10.2)	5.4 (18.3)	0.9	4.6	8.5	100,000
Madagascar	259.7 (278.8)	155.4	15.8 (26.5)	87.1 (114.6)	163.7 (201.3)	9.5	52.3	98.1	1100
Malawi	79.2 (87.9)	8.5	5.3 (7.9)	27.9 (34.8)	51.3 (61.4)	0.6	3	5.6	270
Mali	22.9 (29.5)	29.1	1.6 (2.4)	7.5 (10.2)	13.7 (18.3)	2.1	9.6	17.4	27,000
Mauritania	10.4 (9.6)	10.8	0.7 (0.8)	3.3 (3.2)	6 (5.7)	0.8	3.5	6.3	23,000
Morocco	28.7 (44.2)	16.5	0.4 (1.1)	3.8 (9)	9.1 (19.1)	0.2	2.2	5.3	7400
Mozambique	70.1 (68.3)	54.8	6.4 (6.9)	27.7 (27.6)	49.2 (48.3)	5	21.6	38.5	6300
Namibia	15.4 (11.5)	12.7	1.4 (1)	5.9 (4.3)	10.4 (7.7)	1.1	4.9	8.6	7700
Niger	17.6 (33.1)	21.1	1.4 (2.8)	6.4 (12.4)	11.6 (22.1)	1.6	7.7	13.9	36,000
Nigeria	154.7 (213.6)	140.8	10.6 (20)	55.7 (84)	100.6 (147.6)	9.7	50.1	91.6	12,000
Rwanda	50 (27.6)	1.2	1.1 (2)	13.3 (10.2)	27.4 (17.9)	0	0.3	0.7	49
Senegal	76.7 (68.1)	15.2	5.4 (5.2)	25.9 (24.7)	47 (44.2)	1.1	5.1	9.3	13,000
Sierra Leone	632.8 (263.7)	45.4	58.5 (25.1)	242.3 (103.7)	426 (182.4)	4.2	17.4	30.6	330
Somalia	24.6 (9.4)	11.6	0.7 (0.8)	6.4 (3.4)	13.4 (5.8)	0.3	3	6.3	12,000
South Africa	28 (25.3)	34.3	0.6 (1.4)	6.4 (8.8)	14 (16.8)	0.7	7.9	17.2	17,000
South Sudan	37.9 (18.9)	23.7	1.7 (1.9)	12.8 (7.3)	24.2 (12.7)	1.1	8	15.1	13,000
Sudan	14.2 (20)	26.6	0.5 (1.2)	3.5 (6)	7 (10.9)	0.9	6.6	13.1	50,000
Tanzania	57.2 (75.5)	51.2	3.9 (7.1)	19.3 (29.3)	35.4 (51.6)	3.5	17.3	31.7	5300
Togo	66.4 (54)	3.8	4.5 (5.5)	23.4 (22.2)	42.4 (38.7)	0.3	1.3	2.4	300
Tunisia	33.3 (43.3)	5.1	0.5 (1.2)	5.1 (11.1)	12.9 (23)	0.1	0.8	2	7600
Uganda	40.7 (32.2)	8.7	2.8 (3.3)	14.4 (12.8)	26.2 (22.4)	0.6	3.1	5.6	340
Western Sahara	4.1 (0.9)	0.4	0.4 (0.1)	1.5 (0.4)	2.7 (0.7)	0	0.1	0.2	6800
Zambia	60.9 (53.4)	45.6	5 (5.4)	22.8 (21.1)	40.9 (36.6)	3.8	17	30.6	4000
Zimbabwe	26.4 (27.4)	10.2	1 (2.5)	7.6 (11.5)	15.1 (20.4)	0.4	2.9	5.9	2000

yr^{-1} (southern), 6 mm yr^{-1} (western), and 4 mm yr^{-1} (northern). Conversely, they decreased to 13 mm yr^{-1} (central), 10 mm yr^{-1} (eastern), 8 mm yr^{-1} (southern), 2 mm yr^{-1} (western), and 1 mm yr^{-1} (northern) under the suitable scenario across the five regions.

4.4. Groundwater sustainable yield

Three groundwater sustainable yield maps for Africa, corresponding to the three aforementioned environmental flow scenarios, are depicted in Fig. 7. The findings illustrate that under the conservative scenario (Fig. 7a), sustainable yield values are relatively small across most African countries. Sustainable yield experiences a significant increase from the optimum to the suitable scenario. The spatial distribution of sustainable yield in the optimum and suitable scenarios remains consistent with that of the conservative scenario when guided by the patterns of environmental flow and groundwater recharge. Sustainable yield is notably diminished in the vicinity of the Sahel zone and the Sahara, while it is primarily expanded in tropical Africa across all scenarios. Certainly, commencing from the southern region of the Sahel, sustainable yield values progressively rise, attaining their peak levels within central Africa around the equatorial belt (Fig. 7). Furthermore, elevated sustainable yield values are evident along the western coastal regions (e.g., Gambia, Guinea, Sierra Leone, Liberia, and Cote d'Ivoire), while relatively higher values are observed along the northern coast (e.g., Libya, Algeria, and Morocco), especially in the optimum (Fig. 7b) and suitable (Fig. 7c) scenarios.

The regional analysis (Fig. 8) reveals that central Africa exhibits the highest potential sustainable yield, with median values across the three scenarios (conservative: 4 mm yr^{-1}, optimum: 16 mm yr^{-1}, suitable: 29 mm yr^{-1}). For northern Africa, the minimum estimated sustainable yield

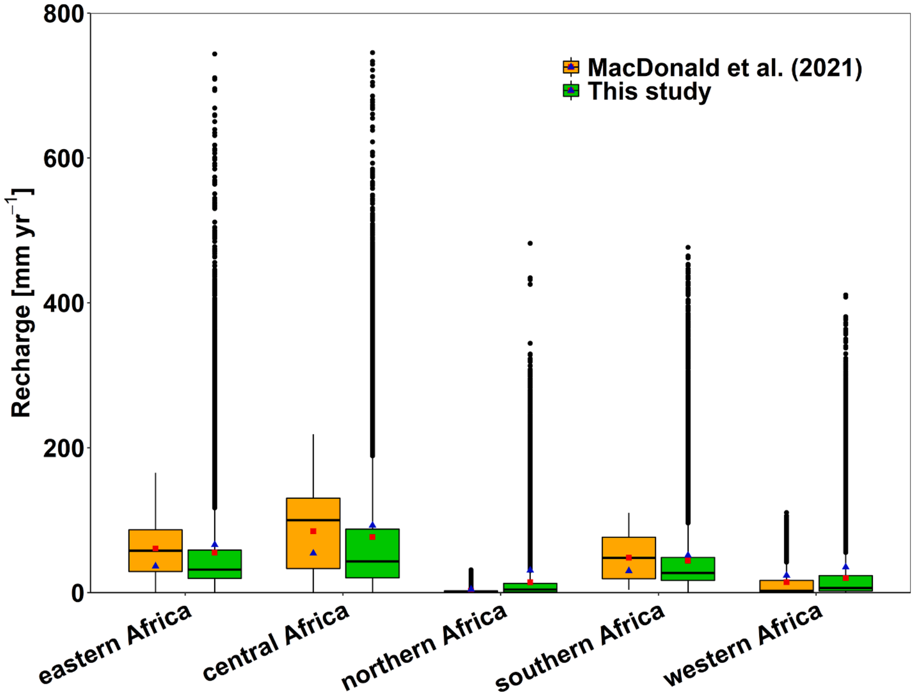

Fig. 5. The distribution of the long-term average (50 years) estimated recharge (both from this study and MacDonald et al. (2021)) for the African continent derived from recharge maps (Fig. 4): The average values are represented by red squares, while the standard deviation (as an indicator of spatial variability) values are indicated by blue triangles. (For interpretation of the references to colour in this figure legend, the reader is referred to the web version of this article.)

is 0 mm yr^{-1} in the conservative scenario, 1 mm yr^{-1} in the optimum scenario, and 2 mm yr^{-1} in the suitable scenarios. Comparable sustainable yield values were derived for eastern Africa (conservative: 2 mm yr^{-1}, optimum: 10 mm yr^{-1}, suitable: 18 mm yr^{-1}) and southern Africa (conservative: 2 mm yr^{-1}, optimum: 10 mm yr^{-1}, suitable: 19 mm yr^{-1}). In western Africa, there is a relatively small variation in median sustainable yield across the scenarios (conservative: 0 mm yr^{-1}, optimum: 2 mm yr^{-1}, suitable: 4 mm yr^{-1}). It is important to highlight that mean regional values surpass their respective median values in both the estimated recharge (Fig. 5a) and sustainable yield (Fig. 8) assessments. This can be attributed to the presence of positive outliers in the statistical distribution. The distribution exhibits a right-skewed pattern, leading to a longer tail in the upper range of values. As a result, the mean values are influenced and shifted towards the higher end of the distribution.

Taking into account the entire continent, our findings underscore Africa's potential for sustainable yield with annual volumes of 141.9 km^3 yr^{-1} (conservative scenario), 643.1 km^3 yr^{-1} (optimum scenario), and 1160.5 km^3 yr^{-1} (suitable scenario). These figures correspond to approximately 0.02%, 0.1%, and 0.17% of the reported groundwater storage for the entire continent (MacDonald et al. 2012). When considering average depth, Africa's groundwater sustainable yield equates to average values (along with their standard deviations as an indicator of spatial variability) of 4.5 mm yr^{-1} (10.2) in the conservative scenario, 20.6 mm yr^{-1} (42.9) in the optimum scenario, and 37.3 mm yr^{-1} (75.7) in the suitable scenario.

Furthermore, we have included a "rough reference" indicating the global average percentage of sustainable yield over groundwater storage. This reference serves to enhance the reader's comprehension of the African sustainable yield estimates within the broader context of global assessment.

Taking into account the reported average global groundwater recharge of 234 mm yr^{-1} (Moeck et al., 2020), the total surface area of continents worldwide at 1.48 × 10^{14} m^2 (https://education.nationalgeographic.org/resource/Continent; last access: 10 January 2023), the average global human water usage of 2268 km^3 yr^{-1} (https://www.annualreviews.org/doi/https://doi.org/10.1146/annurev.energy.28.040202.122849#_i11; last access: 10 January 2023), and the average global groundwater storage of 7 × 10^6 km^3 (Richey et al., 2015; UN World Water Assessment Program, 2003), we can calculate the average global sustainable yields using the methodology presented in this study. For the conservative, optimum, and suitable scenarios, the calculated sustainable yields are 1195.2 km^3 yr^{-1}, 11584.8 km^3 yr^{-1}, and 21974.4 km^3 yr^{-1}, respectively. These calculated figures represent roughly 0.008%, 0.077%, and 0.146% of the reported groundwater storage across the entire planet. These percentages are lower than the African average percentages of sustainable yield over groundwater storage, which are 0.02% for the conservative scenario, 0.1% for the optimum scenario, and 0.17% for the suitable scenario.

Table 1 presents a comprehensive overview of the annual volume and average depth of groundwater recharge and sustainable yield for each African country. To enhance context and facilitate comparisons, we have included the groundwater storage estimate for each country, as extracted from MacDonald et al. (2012). A closer examination of Table 1 reveals that the total annual volume (along with the associated average depth) of sustainable yield in central Africa is quantified at 66.3 km^3 yr^{-1} (14.6 mm yr^{-1}), 269.9 km^3 yr^{-1} (59.5 mm yr^{-1}), and 473.9 km^3 yr^{-1} (104.3 mm yr^{-1}) for the conservative, optimum, and suitable scenarios, respectively. This corresponds to 0.06%, 0.24%, and 0.41% of the reported groundwater storage for the central Africa region. When focusing on the volume of sustainable yield within the central African region, it becomes apparent that the Democratic Republic of Congo boasts the highest sustainable yield figures (conservative yield: 31.4 km^3 yr^{-1}, optimum yield: 127 km^3 yr^{-1}, suitable yield: 222.7 km^3 yr^{-1}), while Equatorial Guinea exhibits the smallest sustainable yield values (conservative yield: 1.1 km^3 yr^{-1}, optimum yield: 4.4 km^3 yr^{-1}, suitable yield: 7.7 km^3 yr^{-1}). In eastern Africa, the annual sustainable yield exhibits a range from 31.5 km^3 yr^{-1} (3.8 mm yr^{-1}), 159 km^3 yr^{-1} (20.9 mm yr^{-1}), to 293.4 km^3 yr^{-1} (39.2 mm yr^{-1}) for the conservative, optimum, and suitable scenarios. This corresponds to 0.06%, 0.3%, and 0.55% of the reported groundwater storage for the eastern Africa region. Notably, Madagascar emerges with the highest annual yield, reaching

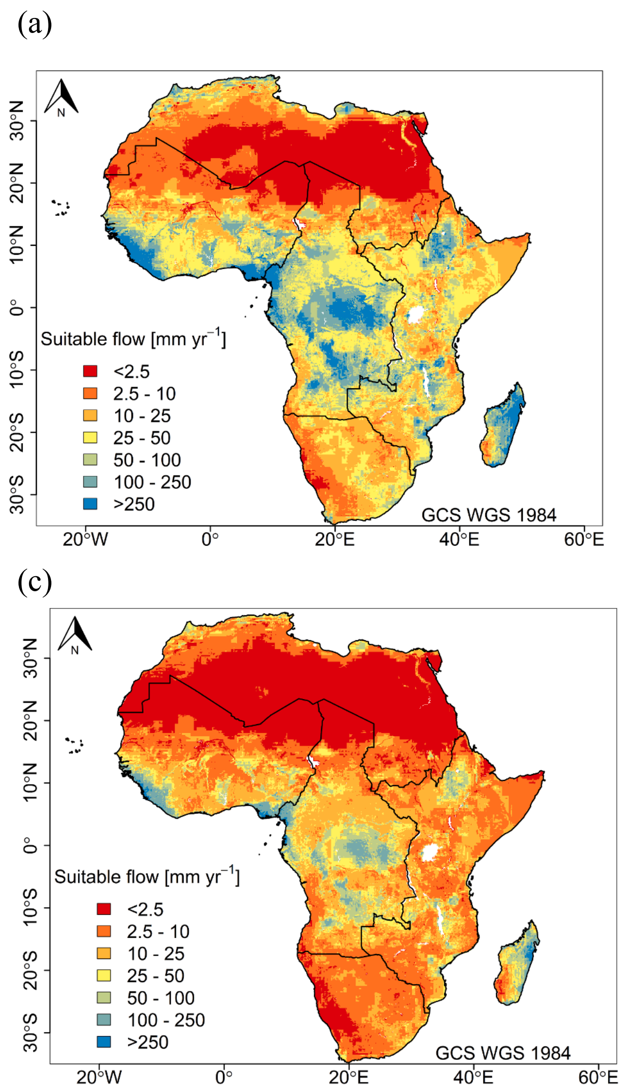

Fig. 6. The long-term (1965–2014) average environmental flow across the African continent considering three scenarios: (a) conservative, (b) optimum, and (c) suitable conditions.

9.5 km^3 yr^{-1}, 52.3 km^3 yr^{-1}, and 98.1 km^3 yr^{-1} for the conservative, optimum, and suitable scenarios. Conversely, Djibouti presents the lowest annual yield values of 0 , 0.1 km^3 yr^{-1}, and 0.2 km^3 yr^{-1}, respectively. In northern Africa, the simulated annual sustainable yield encompasses 4.4 km^3 yr^{-1} (0.6 mm yr^{-1}), 29.7 km^3 yr^{-1} (4.2 mm yr^{-1}), and 58.7 km^3 yr^{-1} (8.5 mm yr^{-1}) for the conservative, optimum, and suitable scenarios. These are equal to 0%, 0.01%, and 0.02% of the reported groundwater storage for the northern Africa region. Noteworthy is South Sudan, exhibiting the highest annual sustainable yield figures of 1.1 km^3 yr^{-1}, 8 km^3 yr^{-1}, and 15.1 km^3 yr^{-1} for the conservative, optimum, and suitable scenarios. Conversely, Western Sahara demonstrates the lowest annual sustainable yield values, with 0 , 0.1 km^3 yr^{-1}, and 0.2 km^3 yr^{-1} for the conservative, optimum, and suitable scenarios. Moving to southern Africa, the annual sustainable yield varies from 3.1 km^3 yr^{-1} (1.3 mm yr^{-1}), 18.4 km^3 yr^{-1} (7.9 mm yr^{-1}), to 35.8 km^3 yr^{-1} (15.5 mm yr^{-1}) for the conservative, optimum, and suitable scenarios. These figures represent approximately 0.01%, 0.04%, and 0.08% of the reported groundwater storage for the southern Africa region. Within this region, South Africa stands out with the highest sustainable yield values, reaching 0.7 km^3 yr^{-1}, 7.9 km^3 yr^{-1}, and 17.2 km^3 yr^{-1} for the conservative, optimum, and suitable scenarios. On the other hand, Eswatini demonstrates the lowest sustainable yield, with value of 0 (for both conservative and optimum scenarios), and 0.1 km^3 yr^{-1} for the suitable scenario. Turning our attention to western Africa, the annual sustainable yield ranges from 33.4 km^3 yr^{-1} (12.6 mm yr^{-1}), 155.7 km^3 yr^{-1} (56 mm yr^{-1}), to 280.3 km^3 yr^{-1} (99.6 mm yr^{-1}) under the conservative, optimum, and suitable scenarios. These values correspond to approximately 0.03%, 0.13%, and 0.24% of the reported groundwater storage for the western Africa region. Within this region, Nigeria emerges with the highest sustainable yield values, reaching 9.7 km^3 yr^{-1}, 50.1 km^3 yr^{-1}, and 91.6 km^3 yr^{-1} for the conservative, optimum, and suitable scenarios. In contrast, Gambia presents the lowest calculated sustainable yield, with values of 0.1 km^3 yr^{-1}, 0.4 km^3 yr^{-1}, and 0.7 km^3 yr^{-1} for the conservative, optimum, and suitable scenarios.

5. Discussion

Groundwater holds a pivotal role as a primary water resource in Africa, vital for meeting the escalating demands for water, food, and energy. This significance is particularly pronounced in the northern and southern regions of the continent, where groundwater often stands as the sole dependable water source (UNEP 2010). Hence, conducting an in-depth examination of groundwater resource sustainability, encompassing prevailing groundwater recharge, human water consumption, and ecological water needs, emerges as an imperative necessity across Africa.

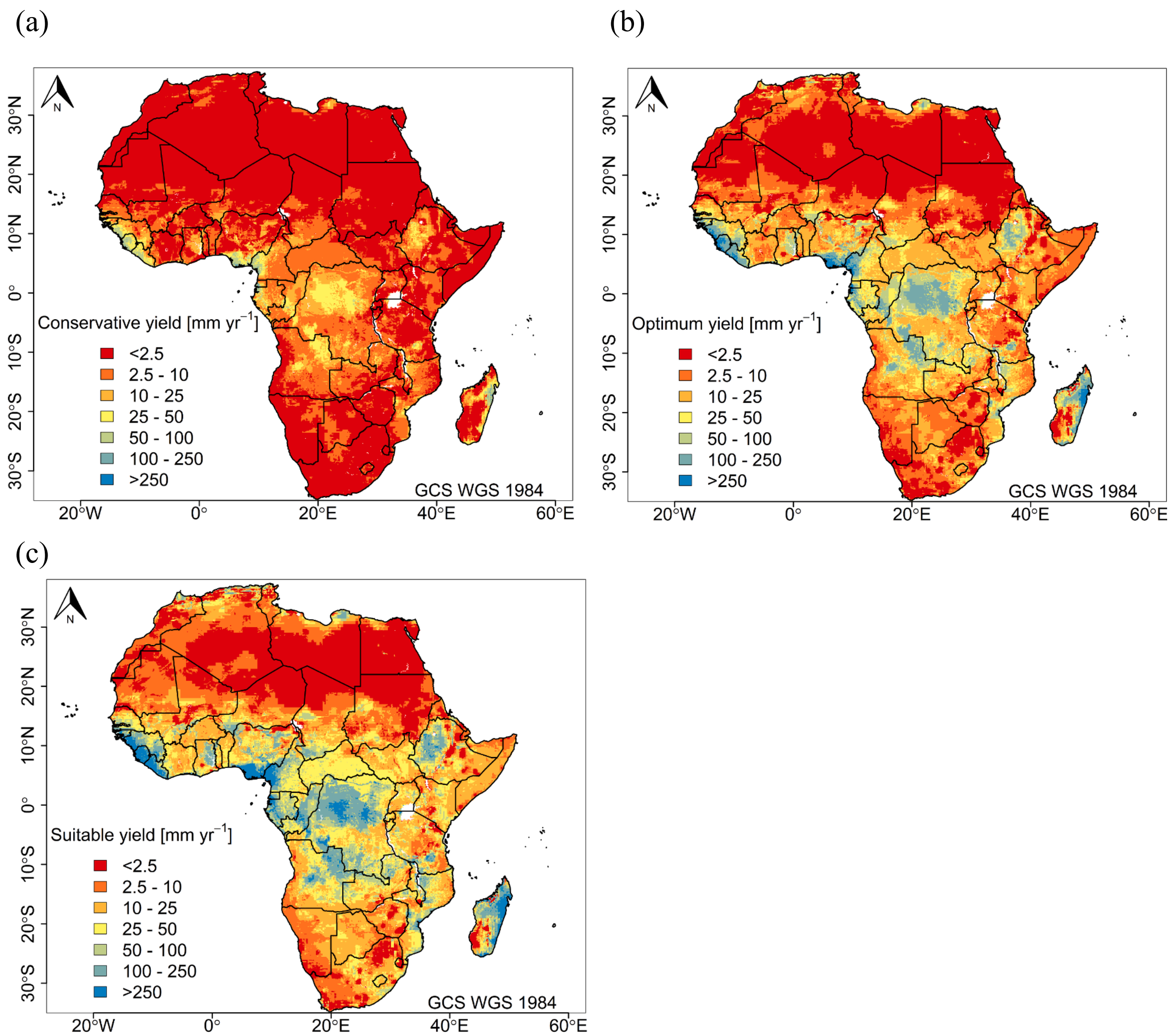

Fig. 7. The long-term (1971–2010) average sustainable yield across the African continent considering three scenarios: (a) conservative, (b) optimum, and (c) suitable conditions. The lines on the map denote country borders.

The long-term average groundwater recharge, as simulated by the CLM model, reaches its peak in tropical Africa, aligning with regions characterized by elevated precipitation levels. This observation reinforces the robust correlation between the long-term average precipitation and groundwater recharge. This correlation has also been highlighted in previous research conducted by MacDonald et al. (2021) at the continental scale for Africa, where a substantial association between long-term average precipitation and recharge was identified. Nonetheless, in certain countries within tropical Africa, such as Niger, Central African Republic, Democratic Republic of Congo, Uganda, Tanzania, and Kenya, our simulation outcomes revealed a noteworthy surplus of surface runoff in comparison to groundwater recharge. This phenomenon is likely influenced by parametrization and constraints of the CLM model, especially in terms of surface runoff simulation, as well as local variables including the land cover type, soil characteristics, geomorphology and the temporal distribution of precipitation. For instance, it has been noted that the distribution of surface runoff in Niger has been influenced by factors such as vegetation type and local geomorphology (Bromley et al. 1997). Furthermore, previous studies have highlighted the significance of land cover and soil types in moderating the connection between precipitation and recharge (Ibrahim et al., 2014; Sami and Hughes, 1996; Scanlon et al., 2005). Land cover attributes, including factors such as vegetation density and the presence of impervious surfaces, exert a considerable influence on the movement of water and the process of infiltration. Vegetation enhances groundwater recharge through improved infiltration, while impervious surfaces impede infiltration and increase surface runoff (Siddik et al., 2022). In our study, we observed that for the majority of vegetated land units, the percentage of surface runoff was either comparable to or even slightly higher than the percentage of groundwater recharge. As an example, in crop grid cells where at least 80% of the pixel purity was achieved, an average of 14% of the rainfall was directed towards surface runoff and groundwater recharge. For broadleaf evergreen trees in tropical grid cells, the proportion of surface runoff (20%) was comparatively higher than that of groundwater recharge (11%) (results not shown). This phenomenon could potentially be attributed to an overestimation of land surface runoff within the CLM model, underscoring the necessity for further refinement of land surface runoff parameterization in the model. Soil characteristics, notably soil texture and permeability, play a significant role in regulating infiltration rates and groundwater recharge. Our study revealed a distinct pattern where grid cells with at least 50% clay soil coverage exhibited a higher proportion of surface runoff (14%) and a lower proportion of groundwater recharge (6%) (results not shown). Hence, the interplay between land cover, soil characteristics, and water movement is of paramount importance in shaping groundwater recharge dynamics (Owuor et al., 2016).

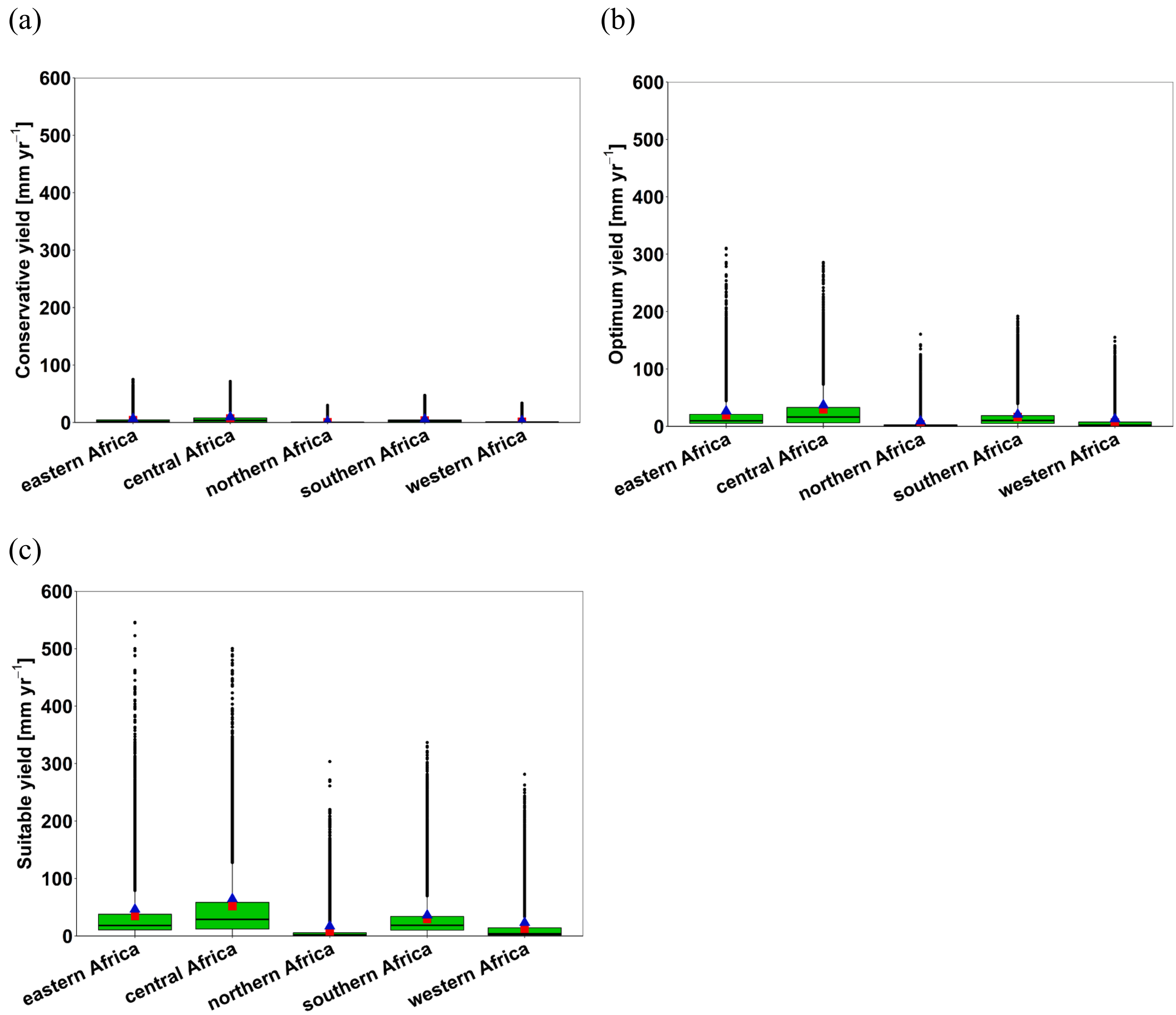

Fig. 8. The distribution of the long-term average (40 years) estimated sustainable yield in Africa: (a) conservative sustainable yield, (b) optimum sustainable yield, and (c) suitable sustainable yield, derived from the maps of sustainable yields (Fig. 7). The individual point values in the plots correspond to the model grid cells. The average values are represented by red squares, while the standard deviation (as an indicator of spatial variability) values are indicated by blue triangles.

The average simulated groundwater recharge over a span of 50 years (1965–2014) using the CLM model in this study is compared with the most recent groundwater recharge map for Africa published by MacDonald et al. (2021). Their study involved upscaling of 134 ground-based groundwater recharge estimates over a 50-year period (1970–2019) and aimed to quantify the spatial distribution of recharge across the entire continent. While our findings exhibit certain degrees of similarities in terms of the overarching patterns when comparing the two estimates (Fig. 6a & b), it is important to note that our model-derived map offers exhaustive spatial (0.09°) and temporal (monthly to annual time steps) information (ranging from monthly to annual time steps). Our model simulations offer distinct advantages in two key aspects: (i) they facilitate the potential for conducting comprehensive time series analyses. This enables, for instance, the exploration of how the decadal mean of groundwater recharge evolves over time and the quantification of anomalies across the entire time series, and (ii) the spatial resolution of the model simulations can be improved depending on the availability of higher resolution input data. This makes it possible, for instance, to make use of higher resolution atmospheric forcings, soil and land use data to better describe the land surface hydrology at local level and produce a higher resolution (e.g., 1–3 km) groundwater recharge map. Moreover, the CLM model offers a comprehensive depiction of all water balance components—precipitation, evapotranspiration, and surface runoff—at consistent resolutions across the entire continent. This serves as a valuable complement to the statistical approach employed in estimating long-term groundwater recharge, which operates at coarser spatial and temporal resolutions (0.28° spatial resolution and decadal time steps), relying on unevenly distributed ground stations (MacDonald et al., 2021).

Overall, our findings reveal that the median of groundwater recharge estimates derived from the CLM model tends to be lower than the median of statistical-based estimates reported by MacDonald et al. (2021) for the entire continent. This discrepancy can likely be attributed to two primary factors: Firstly, the groundwater recharge data used by MacDonald et al. (2021) encompass both diffuse and focused recharge types, whereas our CLM simulations solely consider natural diffuse recharge. This distinction could potentially affect the estimated recharge magnitude and its spatial distribution. Secondly, the CLM model tends to overestimate surface runoff, leading to a reduction in groundwater recharge. This is due to the fact that water diverted to surface runoff is subsequently unavailable for infiltration and deep percolation into the groundwater system.

From our simulated groundwater recharge (Fig. 4a), we derived an average (standard deviation as an indicator of spatial variability) value of 57.8 mm yr^{-1} (110.8) for the entirety of the African continent. In contrast, the recharge map presented by MacDonald et al. (2021) (Fig. 4b) yielded an average (standard deviation) value of 47.7 mm yr^{-1} (53.5). By pooling together 134 ground-based estimates collected from various locations across Africa spanning the period from 1970 to 2019 (as depicted by the circles in Fig. 4b), we computed a continental average value of 64.05 mm yr^{-1} (111.53). Considering the groundwater recharge data collected at these ground stations as the in situ (reference) data for Africa, it is clear that the average simulated groundwater recharge in this study is close to the average of the reference recharge data. Furthermore, in order to understand the role of African groundwater recharge within the context of global recharge dynamics, it is meaningful to compare our estimated and in situ continental average values (57.8 mm yr^{-1} and 64.05 mm yr^{-1}) with the average global groundwater recharge (234 mm yr^{-1}). This global recharge value is derived from a recent comprehensive dataset comprising over 5000 locations and is freely available for analysis (Moeck et al., 2020). The ratio between our estimated recharge and the global average (24.7%) closely resembles that of the reference data and global recharge (27.3%). This correspondence underscores the capacity of our estimated recharge values to effectively elucidate the contribution of African recharge to the global recharge dynamics.

Environmental flow is central to ensuring the sustainability of ecosystems. Moreover, it is a fact that a part of the available groundwater cannot be economically exploited due to the low hydraulic conductivity. In this study, three strategies are considered for analyzing the environmental flow; conservative, optimum, and suitable water consumption scenarios. In all three scenarios, the spatial patterns of groundwater recharge were captured since the calculation of environmental flow was based on a specific percentage of recharge. Transitioning from a conservative to an optimum scenario, and subsequently to a suitable scenario, leads to an increase in potential water availability for human utilization. However, this comes at the expense of compromising sustainability considerations. Among various scenarios, we assumed that the optimum one is more sustainable for the environment. This is also in line with other studies where 60% of recharge or surface runoff was proposed as the ecological water demand (Tennant 1976, Costanza et al. 1997, Alley et al. 1999, Sophocleous 2000, Alley and Leake 2004, Maimone 2004, Hurditch 2005, Shi et al. 2012).

From the comparison of estimated sustainable yield in this study and the reported amount of groundwater total storage from previous studies, four types of conditions could be identified for African groundwater resources at the regional scale: (i) regions with a higher range of sustainable yield and higher amount of groundwater total storage (i.e., western and central Africa); (ii) a region with a relatively lower range of sustainable yield but a very high amount of total storage (i.e., northern Africa); (iii) a region with a higher range of sustainable yield but a relatively lower amount of total storage (i.e., eastern Africa); and (iv) a region with both lower range of sustainable yield and relatively lower amount of groundwater total storage (i.e., southern Africa). Among the factors driving these various conditions, the most important ones are mainly the amount of precipitation in the region, local hydrogeological conditions, and human groundwater withdrawal. For instance, the lower range of estimated sustainable yield in northern Africa can be explained by very low precipitation there; however, its higher total storage can be explained by the dominant sedimentary aquifers and fossil groundwater related to different climate conditions in the past. Lower groundwater recharge and higher total storage in northern Africa have also been explained by the aquifer type in this region (Macdonald et al. 2021). The relatively low storage but high sustainable yield, for example, in eastern Africa, can be linked to the crystalline-rock basement and volcanic aquifers producing more runoff from the precipitation and limiting the effective infiltration rate. In southern Africa, relatively low precipitation, dominant intergranular and fractured geology, higher surface runoff, and higher water pumping especially in domestic and agricultural water sectors, make the groundwater status of the region more sensitive, resulting in both lower sustainable yield and lower total storage. For detailed information about African geology and aquifer types, the reader is referred to Fig. 2 in MacDonald et al. (2012).

In African regions and countries where both storage and sustainable yield are high, the groundwater resources are resilient to changes in climate. However, in countries where both storage and sustainable yield are low, groundwater pumping can easily become unsustainable and perhaps very sensitive to short and long-term environmental stressors and climate change. Moreover, in case the total storage is high and long-term average sustainable yield is relatively low, groundwater could be considered resilient to a short-term change in climate but possibly vulnerable to long-term depletion. However, in countries with lower storage and higher sustainable yield, the groundwater resources can be more sensitive to drought events but resilient to long-term depletion. It should be noted that the groundwater security in Africa is shown and discussed by MacDonald et al. (2021) mainly by comparison of the magnitude of groundwater storage and variation of groundwater recharge.

Based on national-level long-term average sustainable yield statistics (Table 1) obtained in this study, the available groundwater resources could potentially meet current human water use and environmental water requirement, not only for the optimum (medium) case but even considering the conservative (lower extreme) and suitable (upper extreme) scenarios in African countries. This is due to the fact that we found a considerable amount of sustainable yield (water availability) for most of the investigated countries in Africa at the national level. However, in some countries (particularly in Eswatini, Djibouti, Western Sahara, Rwanda, São Tom. Príncipe, Gambia, Burundi, Lesotho, Eritrea, Tunisia, Somaliland, Togo, Egypt, Benin, Morocco, Zimbabwe, Malawi, Somalia, Burkina Faso, Uganda, Guinea Bissau, Mauritania, Equatorial Guinea, Libya, Namibia), the long-term average sustainable yield is quite low (optimum scenario values: <5 mm yr^{-1}). Typically, in water security analyses, the consideration of total storage is often overlooked, focusing primarily on other factors that contribute to sustainability (Taylor 2009), or it is common to primarily rely on the ratios between groundwater abstraction and recharge in such analyses (Zhou 2009). In order to make a more comprehensive assessment of groundwater sustainability over a long period, we need to consider the total storage besides our calculated sustainable yield in such countries. This is also emphasized in recent groundwater recharge estimation, where the main focus was placed on water security aspects (Macdonald et al. 2021). For instance, the long-term average optimum sustainable yield calculated in this study for Libya is 4.6 km^3 yr^{-1}; however, the value of 100,000 (64,600–234,000) km^3 is reported as the best estimate (and possible variation range) of total storage in this country (Edmunds and Wright 1979, Ahmad 1983, Macdonald et al. 2021). This demonstrates that while investigating renewable water, human water use, and environmental water requirement is crucial for groundwater resource sustainability analysis (Vörösmarty et al. 2010), these factors alone are not sufficient. For a comprehensive understanding of sustainability, it is imperative to also consider the dynamic changes in groundwater storage (Damkjaer and Taylor 2017, Bierkens and Wada 2019).

Based on the data presented in this study, the assessment of current sustainable yield and total storage at the national level suggests that water use in Africa appears to be sustainable, yet substantial differences exist between countries in terms of sustainable yield and storage. The *current* spatial distribution of sustainable yield at the national level, with considerable groundwater storage, support this sustainability. However, water availability and demand in Africa can significantly be affected by *future* climate change projections just like other parts of the globe. This stresses the need to investigate future groundwater sustainable yield in Africa according to projected precipitation, evapotranspiration, population growth, and water demand. This aspect is under investigation by the authors.

The outcomes of this study are poised to provide valuable insights for (policy) decision-makers, aiding them in the pursuit of effective water resources management in Africa. The values presented in Table 1, depicting national-level groundwater recharge and sustainable yield, offer a comprehensive and invaluable overview of groundwater availability for distinct countries in Africa. This information is essential for informing the endeavors of (policy) decision-makers. As an example, this information underscores a critical point: in countries where the groundwater's optimum sustainable yield is below a specific threshold (e.g., 0.6 [mm yr^{-1}], as evidenced in Egypt, Eswatini, and Western Sahara), the planning of additional water consumption demands meticulous attention, or even a complete reevaluation. The rationale behind this caution lies in the recognition that pursuing such consumption may lack long-term sustainability. This holds significant importance as it effectively integrates scientific insights into the decision-making process, thereby enhancing the capacity for managing water resources at a national level. This approach paves the way for fostering sustainable water consumption practices on a national scale.

More investigations are strongly recommended to reduce potential uncertainties in the current analysis, particularly with the use of recent sectoral water use data. Additionally, practical implementation warrants consistent monitoring of rapid fluctuations in either groundwater's sustainable yield or storage, attributed to pumping activities. This vigilance stands as a pivotal measure in upholding water sustainability throughout Africa.

In this study, we used the CLM land surface modeling approach for the estimation of long-term average groundwater recharge in Africa. We made use of MODIS data to describe the land cover type of the continent which has been widely-used in environmental research (Javadinejad et al. 2019, Abdollahi et al. 2021). We obtained time series of actual evapotranspiration and surface runoff that enabled us to calculate recharge. Physically-based land surface models (such as CLM) present a suitable framework for encompassing crucial hydrological components, and they have been effectively employed in previous research to enhance our comprehension of hydrological processes. Previously, such hydrological models have been employed to capture groundwater recharge variations at regional, continental, and global scales (Döll and Fiedler 2008). However, there is still room for improvement concerning the modeling approach. For instance, lateral groundwater flow is not considered in the CLM model which is important particularly at local scale. The exclusion of lateral water flow in a land surface model can lead to over/under estimation of groundwater recharge as infiltrated water at a specific location can move laterally to reemerge somewhere else, adding to the recharge at such locations (Maxwell and Condon, 2016). Moreover, the spatial distribution of soil moisture, which is influenced by both timing and magnitude of streamflow, is affected by lateral water flow exclusion (Fan et al., 2019). For including lateral groundwater movements, detailed geological information at the local scale is needed, as well as intensive computations at a very high spatial resolution. In addition, we propose to evaluate local factors affecting African groundwater resources. Groundwater recharge has high spatial variability related to microtopography and enhanced infiltration can occur from local depressions for instance. Our diffuse groundwater recharge estimates based on the water balance approach cannot capture this variability properly. Most importantly, detailed groundwater modeling for the areas demonstrating high potential groundwater sustainable yield is required for a thorough assessment of the resources at the local scale. Therefore, although the CLM model is a useful tool that can provide water balance components needed for the initial groundwater recharge estimation, it needs to be coupled with a proper subsurface model to directly calculate groundwater recharge and improve the simulations. Fully integrated subsurface-surface flow modeling can better describe the system and improve the simulation performance (Talebmorad and Ostad-Ali-Askari, 2022).

It is crucial to underline that, even when utilizing a standard coupled model, it's imperative to account for uncertainties stemming from diverse sources. In general, uncertainty of hydrological models originates from: (i) model input and calibration data, (ii) model structure, and, (iii) model parameters (Moges et al., 2021). In case of coupled models, potential uncertainty can propagate from one sub-model to another, and affect the overall performance of the coupled system. For instance, Moges et al. (2020) explored the uncertainty propagation in a coupled hydrological model including a surface [i.e., Precipitation-Runoff Modeling System (PRMS)] and a sub-surface [i.e., modular three-dimensional finite-difference ground-water flow model (MODFLOW)] model. They showed how uncertainty in a specific input variable (e.g., precipitation) of surface water and sub-surface water models could affect the different parts of a hydrograph. They concluded that a better description of input uncertainty could improve high flows estimation, but it is mainly the sub-surface and surface water sub-models that influence the uncertainties in baseflow and recession (Moges et al., 2020).

6. Conclusions

Groundwater sustainable yield is the available resource yield that enables the normal exploitation for a long time without adverse impacts while making maximum economic, societal, and environmental benefits. Land surface modeling is one of the possible approaches to quantify water balance components, estimate groundwater recharge and produce a groundwater sustainable yield map. These quantitative maps serve as tools for assessing the sustainability of African groundwater resources. Through the utilization of the CLM model, our investigation revealed that the groundwater systems across the entirety of Africa have experienced an average annual recharge of 57.8 mm yr^{-1} (with a standard deviation of 110.8 mm yr^{-1} serving as an indicator of spatial variability). This volumetrically translates to approximately 1793.6 km^3 yr^{-1} in terms of annual recharge. Upon incorporating additional factors such as environmental flow and total sectoral water use, our findings highlighted that the African continent possesses the potential for annual sustainable yield across various scenarios. Specifically, under conservative, optimum, and suitable water consumption scenarios, the continent's potential annual sustainable yields are estimated at 4.5 mm yr^{-1} (with a standard deviation of 10.2 mm yr^{-1}), 20.6 mm yr^{-1} (standard deviation of 42.9 mm yr^{-1}), and 37.3 mm yr^{-1} (standard deviation of 75.7 mm yr^{-1}), respectively. In terms of volume, these sustainable yield values correspond to 141.9 km^3 yr^{-1} 643.1 km^3 yr^{-1}, and 1160.5 km^3 yr^{-1}. These assessments of the overall volume of sustainable yield, on average, represent approximately 0.02%, 0.1%, and 0.17% of the documented groundwater storage across the entire continent. This groundwater sustainable yield essentially represents the residual water volume that remains once current human needs and potential environmental water demands are taken into consideration. As a result, this yield has the capacity to augment and contribute to the overall storage if left unused or unutilized for additional purposes such as food and energy production. When taking into account both the African groundwater sustainable yield and the reported storage of 660,814 km^3, it can be inferred that the available resources have the potential to satisfactorily fulfill existing human and environmental water needs in Africa while maintaining sustainability. Moreover, our findings in the current study can potentially contribute to both scientific-based research and application-oriented projects across Africa. Furthermore, it has the potential to address the deficiency of in-situ data in Africa, especially in the domain of groundwater recharge and sustainable yield mapping. However, it is crucial to recognize that climate change will have a substantial impact on groundwater recharge and sustainable yield. Therefore, it is imperative to consider *future* climate projections for the assessment of future groundwater resources and their sustainability.

List of abbreviations

20CR	The 20th Century Reanalysis
BMBF	German Federal Ministry of Education and Research
CLM	Community Land Model
CRU	Climate Research Unit
ET	Evapotranspiration

(*continued on next page*)

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List of abbreviations	
FAO	Food and Agriculture Organization
GPCC	The Global Precipitation Climatology Centre
GSM	The Global Spectral Model
GSWP3	The third Global Soil Wetness Project
H_2ATLAS	Hydrogen Atlas
I	Irrigation
IEK	Institut für Energie- und Klimaforschung
IGB-DIS	International Geosphere-Biosphere Program Data and Information System
LPJmL	Lund-Potsdam-Jena managed Land
MCD12Q1	MODIS Land Cover Type
MODFLOW	Modular three-dimensional finite-difference ground-water flow model
MODIS	Moderate Resolution Imaging Spectroradiometer
NCAR	The National Center for Atmospheric Research
NCEP	The National Centers for Environmental Prediction
P	Precipitation
PCR-GLOBWB	PCRaster Global Water Balance
PFT	Plant Functional Types
PRMS	Precipitation-Runoff Modeling System
Q	Surface runoff
R	Recharge
SASSCAL	The Southern African Science Service Centre for Climate Change and Adaptive Land Management
SRB	Surface Radiation Budget
SWU	Sectoral Water Use
SY	Sustainable Yield
WASCAL	West African Science Service Centre on Climate Change and Adapted Land Use
WaterGAP	Water Global Assessment and Prognosis
WGHM	WaterGAP Global Hydrology Model

Credit authorship contribution statement

Bagher Bayat: Conceptualization, Methodology, Software, Formal analysis, Visualization, Interpretation, Validation, Writing – original draft, Writing – review & editing. **Bamidele Oloruntoba:** Methodology, Software, Writing – review & editing. **Carsten Montzka:** Methodology, Interpretation, Writing – review & editing. **Harry Vereecken:** Methodology, Interpretation, Writing – review & editing. **Harrie-Jan Hendricks Franssen:** Supervision, Methodology, Interpretation, Writing – review & editing.

Declaration of competing interest

The authors declare that they have no known competing financial interests or personal relationships that could have appeared to influence the work reported in this paper.

Data availability

The long-term average (LTA) of groundwater recharge and sustainable yield data generated in this study are openly accessible through the Zenodo repository as follows:–
https://zenodo.org/uploads/10003315.–
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