Groundwater for Sustainable Development 27 (2024) 101374

Contents lists available at ScienceDirect

Groundwater for Sustainable Development

journal homepage: www.elsevier.com/locate/gsd

Research paper

Mapping the potential of managed aquifer recharge in Africa: GIS-based multi-criteria decision analysis approach

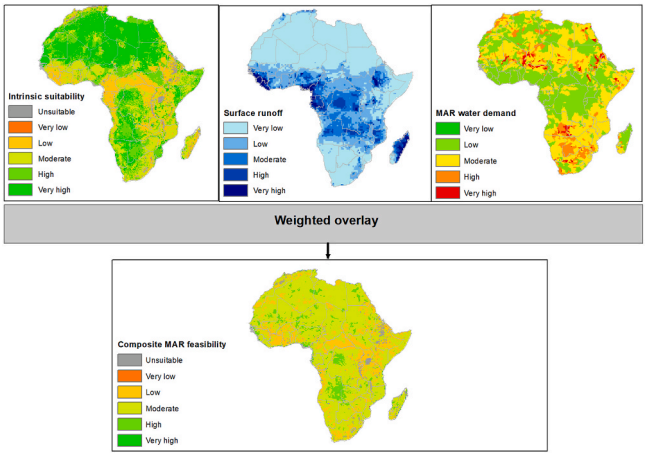
Girma Yimer Ebrahim [a,*], Catalin Stefan [b], Jana Sallwey [b], Jonathan Lautze [c]

[a] International Water Management Institute, P.O. Box 5689, Addis Ababa, Ethiopia
[b] Research Group INOWAS, Department of Hydro Sciences, Technische Universität Dresden, 01069, Dresden, Germany
[c] International Water Management Institute, Private Bag X813, Silverton, Pretoria, 0127, South Africa

HIGHLIGHTS

- GIS-MCDA was used to assess MAR feasibility.
- MAR feasibility was assessed based on biophysical factors, water availability, and demand.
- This is the first continent-wide MAR feasibility assessment in Africa.
- Nearly three-quarters of Africa has moderate MAR feasibility.
- The map aids in raising awareness, planning, and decision-making.

GRAPHICAL ABSTRACT



ARTICLE INFO

Keywords:
Africa
GIS-MCDA
Managed aquifer recharge
MAR feasibility mapping
MAR suitability mapping

ABSTRACT

Africa faces numerous challenges related to rainfall variability, droughts, water scarcity, and climate change. Managed Aquifer Recharge (MAR)- groundwater recharge and underground water storage for later use or environmental support presents a viable alternative for water storage and may provide an effective tool for coping with such challenges. However, the potential area where MAR can be feasibly implemented has not been identified. This study mapped MAR feasibility using a Geographic Information System-based Multi-Criteria Decision Analysis (GIS-MCDA) and assessed MAR potential in Africa. The methodology focused on three key pillars of MAR feasibility: intrinsic suitability based on biophysical parameters, water source availability, and water demand. Maps responding to these pillars were developed and combined to create a composite MAR feasibility map. Results show that 18% of the continental area falls into the low feasibility class, 73% into the moderate feasibility class, and 7% into the high feasibility class. The feasibility map was validated against 17 existing MAR schemes in Africa, demonstrating a good correlation between their locations and areas with MAR potential. Results of sensitivity analysis of criteria weights of the biophysical parameters show that geology is the

* Corresponding author.
E-mail address: g.ebrahim@cgiar.org (G.Y. Ebrahim).

https://doi.org/10.1016/j.gsd.2024.101374
Received 31 May 2024; Received in revised form 15 October 2024; Accepted 8 November 2024
Available online 12 November 2024
2352-801X/© 2024 The Authors. Published by Elsevier B.V. This is an open access article under the CC BY-NC-ND license (http://creativecommons.org/licenses/by-nc-nd/4.0/).

most influential criterion, followed by slope. In general, this first feasibility assessment shows good potential for MAR implementation in Africa. Therefore, MAR should be considered prominently among other water storage options for resilience building in Africa and policymakers should ensure adequate resource allocation for its implementation. The feasibility map can be used to guide MAR planning and investment decisions.

1. Introduction

Groundwater is a vital resource for billions of people worldwide. It provides drinking water, supports agriculture, and buffers against climate change. Besides that, it is important for securing the biodiversity of ecosystems. Globally, groundwater supplies half of the domestic water supply (UN, 2022) and 40% of the water used for irrigated agriculture (GEF, 2024; Jasechko and Perrone, 2021; Siebert et al., 2010). It also supplies 24% of industrial water (GEF, 2024) and buffers rainfall variability, providing a reliable water supply during extended periods of drought (Burke et al., 2023; Vaux, 2011). The rising pressures of population growth, climate change, and economic development are straining groundwater resources worldwide, resulting in unsustainable extraction levels (Gleeson et al., 2010) and potentially harming aquatic ecosystems (de Graaf et al., 2019). Groundwater depletion is a significant issue in many parts of the world, particularly in North Africa, the Middle East, South and Central Asia, North China, North America, and Australia (Konikow and Kendy, 2005). This depletion is affecting many vital agricultural regions worldwide, threatening food security and livelihoods (Wada et al., 2010).

Groundwater is a critical resource for many Africans, especially in dryland regions, where it may be the only reliable water source for growing cities (World Bank, 2018). Over 75% of the African population depends on groundwater for drinking water (Braune and Xu, 2010; Carter and Parker, 2009). However, rapid urbanization and pollution are posing significant threats to groundwater resources across the continent (Gaye and Tindimugaya, 2019; Giordano, 2009; Oiro et al., 2020). As cities expand and populations grow, increasing water demand depletes groundwater levels. Simultaneously, various pollutants are contaminating groundwater supplies, jeopardizing the sustainability of water resources for millions of people across the continent (Braune and Xu, 2010; Gaye and Tindimugaya, 2019; Ouedraogo et al., 2016). Coastal aquifers in Africa are threatened by saltwater intrusion, while groundwater contamination by fluoride and nitrate is widespread. Saltwater intrusion is particularly affecting coastal areas, contaminating freshwater supplies (Steyl and Dennis, 2010). Additionally, 15% of Africa's landmass faces a high risk of excessive fluoride levels in groundwater, exceeding safe drinking water standards (Podgorski and Berg, 2022). Furthermore, nitrate pollution is a significant problem in many African countries, contaminating groundwater sources (Abascal et al., 2022). The Cape Town water crisis of 2018 is a typical urban water crisis that resulted in a ''Day zero'' municipal water supply (Olivier and Xu, 2019). The city's exclusive reliance on a surface reservoir, exacerbated by severe drought, resulted in a Day of zero municipal water supply. Investing in groundwater could have been a crucial solution to mitigate the crisis (Olivier and Xu, 2019).

Africa is particularly vulnerable to climate change due to its heavy reliance on rainfed agriculture and limited adaptation capacity (Ayugi et al., 2022; Collier et al., 2008; MacDonald et al., 2009; Praveen and Sharma, 2019). As climate change intensifies, the continent is likely to experience more frequent and severe droughts and floods (Gizaw and Gan, 2017; Serdeczny et al., 2017; Trisos et al., 2022). These extreme weather events, combined with climate change impacts, pose a significant threat to food security in Africa (Connolly-Boutin and Smit, 2016; Gregory et al., 2005; MacDonald et al., 2009). In the face of increasing rainfall variability and climate change, irrigation is key to increasing resilience in Africa. However, in areas where surface water resources are scarce, water availability is becoming a limiting factor in intensifying irrigation (Iglesias et al., 2018; Koech and Langat, 2018). More importantly, river runoff is typically unevenly distributed within years and across years, requiring interventions to regulate and store flows to improve the reliability of water availability over time and space (Balek, 2011; Mahé et al., 2013; Oyebande, 2001). While climate change will influence all water resources, groundwater systems will exhibit a slower response compared to surface water, potentially providing a buffer to support adaptation efforts (MacDonald et al., 2011). However, increasing water demand due to climate change and population growth increases the pressure on groundwater sustainability (Wada and Bierkens, 2014). Therefore, groundwater management interventions like Managed Aquifer Recharge are vital for ensuring water security and meeting growing water demands.

Managed aquifer recharge (MAR) is a potential solution for addressing groundwater management challenges (Dillon et al., 2009, 2019). MAR is increasingly important in arid and semi-arid regions with low natural recharge and high evaporation. If implemented correctly, it is one of the strategies that can contribute to water security. MAR is a nature-based approach to water management that is often overlooked (Seidl et al., 2024; Water, 2018). It offers a solution for water storage by using treated wastewater and surface water to replenish aquifers. Storing water in the aquifers when there is excess water or treated wastewater during the wet periods for use during dry periods is considered a viable water resource management option (Dillon et al., 2019; Stefan and Ansems, 2018). MAR can improve water storage and is useful for water reuse and improving water quality in soil aquifer treatment facilities (Grinshpan et al., 2021). Due to these benefits, MAR is considered an innovative approach to water reuse (Miller, 2006), enhancing water security (Dillon, 2005), and climate change adaptation (Tuinhof et al., 2011). Other benefits of MAR include flood control, preventing saltwater intrusion, and the safeguarding of ecosystems (Dillon, 2005). Further, the reduced energy demand for pumping may reduce carbon emissions and mitigate climate change (Escalante et al., 2019).

MAR in Africa contributes nearly 158 Mm^3/year of additional water storage to enhance water supply (Ebrahim et al., 2020). Although it represents a small fraction (0.4%) of total groundwater use across the continent, it plays a critical role in water security (Ebrahim et al., 2020). While MAR has been adopted in Africa for over three decades (Bouri and Dhia, 2010; Tredoux and Cain, 2010), its prevalence is notably lower than in other continents (Stefan and Ansems, 2018). There are nonetheless good examples that have more than 30 years of MAR practice in Southern Africa (e.g., Atlantis case study in South Africa (Tredoux and Cain, 2010)) and Northern Africa (e.g., Soukra case study, Tunisia (Chaieb, 2014)). The Atlantis scheme, South Africa, contributes approximately 25–30% of the water supply of Atlantis Town (Tredoux and Cain, 2010). The Windhoek case in Namibia is expected to provide a drought buffer of up to three years for the Windhoek city (Murray, 2017). By building upon these successful cases, the benefits of MAR can be further developed and scaled up, ultimately strengthening water security across the continent. However, MAR requires careful design and implementation and may not be feasible everywhere due to various constraints such as hydrogeological, water source, water quality, and cost limitations (Seidl et al., 2024). Therefore, identifying potential sites is the first step in MAR project planning (Government of India, 2007).

The application of GIS-based Multi-Criteria Decision Analysis (GIS-MCDA) with freely accessible remote sensing and surficial data has made it easier to identify suitable locations for MAR sites. This approach leverages readily available data to create maps that visualize regional MAR potential. The integration of GIS and MCDA has revolutionized site suitability analysis, offering a more comprehensive and accurate

approach than traditional map overlay methods (Rahman et al., 2012). Several studies used GIS-MCDA to map potential groundwater zones (Abdo et al., 2024; Ehsan et al., 2024; Magesh et al., 2012). However, existing literature on MAR potential (Bonilla Valverde et al., 2016; Daher et al., 2011; Ebrahim et al., 2017; Fathi et al., 2020; Ghayoumian et al., 2005, 2007; Rahman et al., 2012; Russo et al., 2015; Yosef et al., 2024) focuses mainly on intrinsic suitability.—i.e., the general capacity of an aquifer to be recharged, both naturally and through human intervention. While some studies used drainage density (Bonilla Valverde et al., 2016; Fathi et al., 2020), distance to a river or canal water (Xu et al., 2021), and distance to wastewater treatment plants (Riad et al., 2011) as a proxy for water availability, only Martins et al. (2024), Panagiotou et al. (2024), Aloui et al. (2022), Marwaha et al. (2021), and Goode (2021) considered the critical role of water availability and demand in determining MAR potential. This study, however, was geographically focused on the Mediterranean Basin and North America. There is no African-scale assessment of MAR potential that includes water availability and demand.

Within this context, the main objective of this study is to assess MAR potential in Africa using GIS-MCDA by explicitly considering the intrinsic suitability of aquifers, water source availability, and water demand. To generate the MAR feasibility map, we combined maps of intrinsic parameters (slope, soil, land use/cover, and geology) with maps of water source availability (surface runoff) and water demand (baseline water stress, seasonal and interannual variability in water availability). To generate the intrinsic suitability map, we combined slope, soil, land use/cover, and geology maps using mean criteria weight calculated using ranking, AHP (Analytic Hierarchy Process), and MIF (The Multi-Influencing Factor method). The water availability map was generated using surface runoff data from the Global Runoff Data Center (GRDC), and the water demand map was based on baseline water stress, seasonal variability in water availability, and interannual variability in water availability using equal weight. Finally, these maps were combined to create a composite MAR feasibility map using equal weights. This approach offers a holistic perspective, providing a more practical assessment of the potential benefits of incorporating MAR into local water resource management. This study separates MAR suitability from MAR feasibility by defining them as follows: *MAR suitability* refers solely to the aquifer's natural capacity for recharge and storage. *MAR feasibility* encompasses a broader perspective, considering the aquifer's suitability, the availability of water for recharge, and the existing water demand.

By establishing a continental perspective, we provide a framework for decision-makers to develop more targeted national or regional studies. In addition, policymakers can use this information to make informed decisions about MAR implementation, prioritize investments in infrastructure, and increase awareness of its potential for enhancing water security and resilience.

2. Methodology

2.1. Geographic Information System-based multi-criteria decision analysis

Geographic Information System based Multi-Criteria Decision Analysis (GIS-MCDA) offers a more comprehensive, efficient, and cost-effective approach to MAR potential mapping than conventional methods. Conventional methods, such as hydrogeological surveys, geophysical surveys, and well drilling, can be time-consuming and expensive (Abdo et al., 2024; Doke et al., 2021). In contrast, GIS-MCDA relies primarily on existing data and analytical tools, reducing the need for extensive fieldwork and associated costs (Bhuyan and Deka, 2022). Additionally, GIS-MCDA is easy to understand and intuitively appealing to decision-makers (Malczewski, 2004). It generates visually appealing maps that can be easily understood and communicated to stakeholders, facilitating informed decision-making. The rapid growth of digital spatial data and advanced GIS tools has made GIS-MCDA increasingly attractive (Malczewski, 2004). GIS-MCDA consists of seven steps: defining the problem, excluding infeasible sites, selecting criteria, classifying and standardizing criteria, assigning weights, combining criteria based on assigned weights, and sensitivity analysis. Subsequent sections describe each step.

2.1.1. Defining the problem

Africa, a continent characterized by diverse climates, rapid population growth, and urbanization (Chirisa, 2008; Hall et al., 2017), faces significant challenges in water resource management. In many arid and semi-arid regions of Africa, rainfall distribution is uneven, and most runoff is generated during the wet periods. Droughts are more common than elsewhere. Groundwater, a crucial resource for many communities, is increasingly stressed due to over-extraction, pollution, and climate change. Managed Aquifer Recharge offers a promising nature-based solution to these challenges. By strategically replenishing groundwater aquifers, MAR can help mitigate water scarcity, improve water quality, and enhance community resilience to drought.

Given its low cost, ease of maintenance, and reliance on readily available GIS data, surface spreading methods represent a common MAR approach in Africa (Ebrahim et al., 2020). These methods can be applied to various recharge techniques, including infiltration basins and controlled flooding. Surface runoff, captured through distributed water harvesting ponds, is a suitable water source for MAR in most watersheds. Unlike treated wastewater, primarily available in urban areas, surface runoff is accessible across a broader range of regions.

2.1.2. Exclusion of infeasible sites

Exclusion of infeasible sites that are not feasible for MAR application can be performed using boolean logic: if a location is considered suitable, it is assigned a value of 1; otherwise, it is assigned a value of 0 (Malczewski, 2004). This step is also known as constraint mapping. Using the spreading method, two criteria, slope threshold and land use/land cover, were used to eliminate areas deemed unsuitable for MAR. When the hydraulic gradient is large, the recharged water rapidly moves away from the recharge area, compromising the recovery of recharged water. Densely developed urban areas or locations with limited vacant land may not have the space to accommodate an infiltration pond and are unsuitable. Similarly, waterbodies are not suitable and are excluded.

Rahman et al. (2012) and Agarwal et al. (2013) used a 5% slope as a threshold where MAR using the surface spreading method is not feasible. Fathi et al. (2020) and Bonilla Valverde et al. (2016) adopted a slope threshold of 30%, and Massmann (2003) used a 15% slope as a threshold. This study used a slope threshold of 10%, a very conservative assumption compared to previous studies. Additional information can be found in section S1 of the Electronic supplementary material (ESM).

2.1.3. Criteria selection

The selection of criteria involves the choice of appropriate thematic maps as criteria for GIS-MCDA. Each selected criterion has to be quantifiable and non-redundant (Dodgson et al., 2009). The criteria for this study were selected based on literature review and data availability. The selected criteria and data sources are presented in Table 1. The selected criteria were grouped into three categories: criteria for intrinsic suitability analysis, criteria used for water source availability for MAR, and criteria for water demand analysis (Figs. 1 and 2). Four biophysical parameters, which include slope, soil, land use/land cover, and geology, were used for intrinsic MAR suitability mapping.

Water availability for MAR was evaluated using surface runoff data obtained from the Global Runoff Data Centre (GRDC). While rainfall and surface runoff are important factors in water availability, surface runoff often provides a more accurate and comprehensive indicator. Rainfall alone can be misleading, as it does not account for factors like soil type, slope, vegetation, and land use, which all influence how much rainfall becomes surface runoff. Surface runoff, on the other hand, represents the actual amount of water available for potential use, making it a better

Table 1
Selected criteria and source of data and their resolutions.

Categories	Thematic layers	Source	Resolution	Reference
Intrinsic suitability analysis	Slope	Derived from Africa DEM 30 arc-second, HydroSHEDS (USGS)	1 km	Consbio (2010)
	Soil texture at 2 m depth	ISRC-World Soil Information	250 m	ISRIC (2018)
	Geology	African Geological map from the British Geological Survey	30 km	(BGS, 2017; MacDonald et al., 2012)
	Land use/Landcover	European Space Agency (ESA)	20 m	ESA (2021)
Water source	Surface runoff	Global Runoff Data Center (GRDC)	55 km	Fekete et al. (2002b)
Demand	Baseline water stress	Aqueduct Global Maps 4.0	30 km	Kuzma et al. (2023)
	Seasonal variability in water availability	Aqueduct Global Maps 4.0	30 km	Kuzma et al. (2023)
	Inter-annual variability in water availability	Aqueduct Global Maps 4.0	30 km	Kuzma et al. (2023)

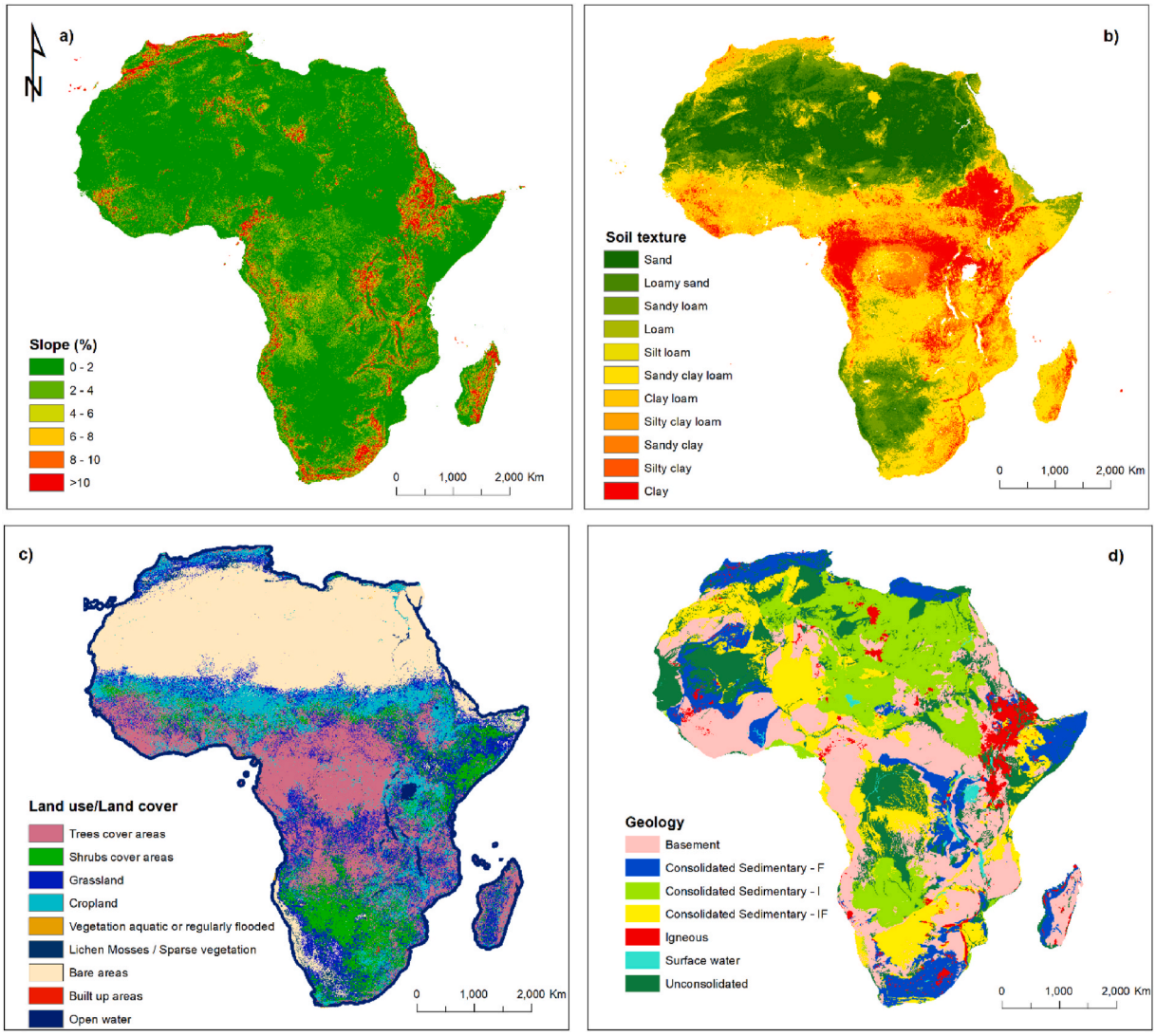


Fig. 1. Intrinsic criteria used for suitability mapping: slope in percent (a), soil texture classes (b), white color represent areas with no data, which are specifically water bodies, land use/land cover classes (c), and type of geology (d). Abbreviations used in the geology map legend represent dominantly fractured flow (F), dominantly intergranular flow (I), and mixed flow (IF). (For interpretation of the references to color in this figure legend, the reader is referred to the Web version of this article.)

indicator of water availability. Incorporating both rainfall and surface runoff would be redundant, as surface runoff already encapsulates the influence of rainfall. We used annual surface runoff data at a 30 × 30 arc min (~55 km) spatial resolution obtained from the Composite Runoff V1.0 database of Fekete et al. (2002a) to represent water availability. The runoff data was produced by combining observed river discharge

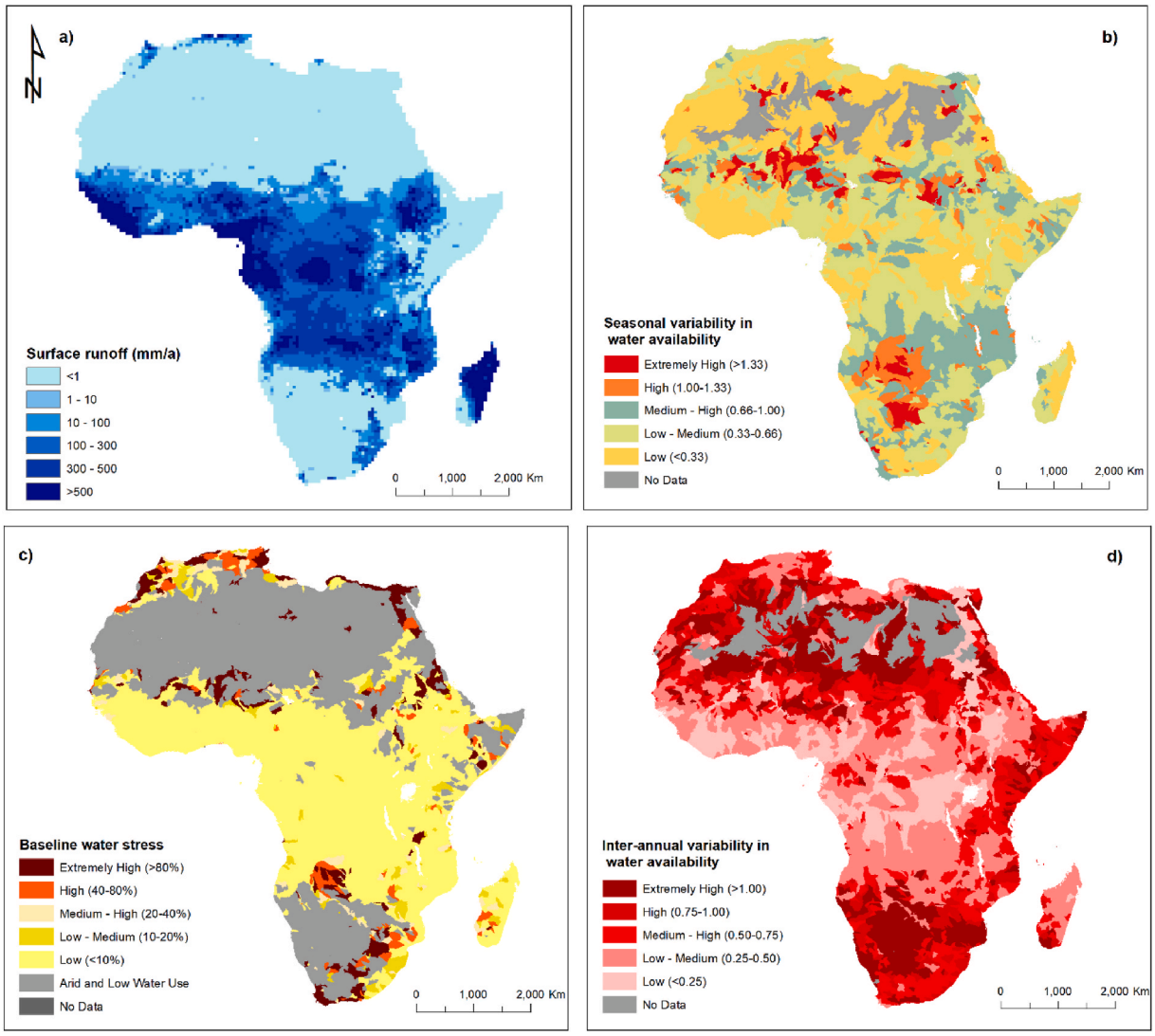


Fig. 2. Additional criteria used for feasibility mapping: surface runoff (a), seasonal variability in water availability (b), baseline water stress (c), and inter-annual variability in water availability (d). White colors (b, c, and d) represent areas with no data, which are specifically water bodies. (For interpretation of the references to color in this figure legend, the reader is referred to the Web version of this article.)

information from the GRDC with a climate-driven water balance model[1] (Fekete et al., 2002a).

Baseline water stress and seasonal and interannual variability in water availability data obtained from Aqueduct 4.0 global datasets[2] (WRI, 2023) were used as a proxy for water demand. Baseline water stress is the total water withdrawal divided by total renewable surface and groundwater supplies (Hofste et al., 2019a). The total available renewable water supplies are calculated as the total available water minus upstream water uses, which include consumptive water uses and water stored in dams. Seasonal variability in water availability measures how much a region's available water supply, including renewable surface and groundwater, changes within a year. Interannual variability in water availability measures how much a region's available water supply, including surface water and groundwater, fluctuates from the year-to-year. Water storage through MAR is essential to manage seasonal and inter-annual variability in water availability.

Baseline water stress, water depletion, seasonal variability, and interannual variability obtained from the Aqueduct global model were calculated using PCR-GLOBWB 2[3], the global, gridded hydrological model developed at Utrecht University, which has a grid resolution of 5 × 5 arc minutes. This equates roughly to 10 km × 10 km grids. Baseline water stress, water depletion, seasonal variability, and interannual variability indicators were aggregated at a spatial unit of hydrological sub-basins based on the model output for 1979–2019. The HydroBASINS level 6 hydrological sub-basins were used as spatial aggregation units. On average, a sub-basin in HydroBASINS level 6 covers roughly 5318 km^2 (WRI, 2023). For groundwater table decline, aquifers were used as spatial aggregation units. Since We developed the water demand map based on PCR-GLOBWB 2's baseline water stress data and seasonal/interannual variability information, limitations inherent to this global hydrological model, notably coarse grid resolution and a limited number of locations for model calibration, apply to these indicators. This highlights the importance of considering these limitations when interpreting the results, particularly at finer spatial scales.

All spatial datasets were projected using the Africa Sinusoidal (D-WGS_1984) projection system. Soil and land use/land cover data were

[1] https://grdc.bafg.de/GRDC/EN/03_dtprdcts/33_CmpR/unh_grdc.html?nn=201568.

[2] https://www.wri.org/data/aqueduct-global-maps-40-data.

[3] https://globalhydrology.nl/research/models/pcr-globwb-2-0/.

resampled to 30 km using the nearest neighbor algorithm to match the other dataset. Slope and surface runoff were resampled to 30 km resolution using the bilinear technique that involves continuous data sampling. Resampling to the average resolution was used as it offers an option to resample all data layers to an average resolution so that all data layers contribute some information. The 30 km resolution was decided based on the critical information geology and demand map holds to the overall feasibility map. The no-data values in the seasonal and inter-annual variability map were replaced with values of their nearest neighbor using the Nibble tool in ArcGIS.

2.1.4. Classification and standardization of criteria

Since criteria maps are in different units, each criterion needs to be expressed in the same measurement scale, which in this study is a scale from zero to one, with the highest value marking the most preferred areas (Jafari and Zaredar, 2010). This was undertaken by a step-wise standardization approach (Bonilla Valverde et al., 2016).

For surface infiltration MAR schemes, a high infiltration capacity is preferable as recharge is controlled by gravity-driven water flow into the soil. With a higher infiltration capacity, larger volumes can be recharged. Steeper slopes will result in more runoff, less infiltration, and a high hydraulic gradient that will influence the recovery of recharged water. Thus, slopes above 10% have been used as a constraint, and slopes from 0 to 2% are classified as having a suitability value of one. This study defined soil texture classes based on their hydrologic soil group classification and infiltration capacity (FAO, 1979; USDA, 1986). Generally, the lower the clay content in the soil, the higher the infiltration capacity. Land use/cover standardization was accomplished considering the ease of site clearing and preparation requirements necessary to implement surface infiltration MAR schemes. Hence, areas with dense vegetation are less preferred. Geology was standardized based on the information from MacDonald et al. (2010) and MacDonald and Davies (2000). Aquifers with high storage coefficients are the most suitable for MAR as they can store large amounts of water. Unconsolidated sedimentary aquifers are often targeted for MAR as they can hold a large volume of water due to the large volume of pore spaces (Dillon and Pavelic, 1996). In Africa, crystalline basement aquifers comprise approximately 40% of the land area (MacDonald and Davies, 2000). Storage in basement aquifers depends on the degree of fracture and interconnection of fractures (Kresic, 2006) and is usually characterized by low storage potential (Titus et al., 2009). Larger runoff volumes are advantageous as they indicate a higher potential for water availability. High values of water stress indicate more competition among water users (Gassert et al., 2014). Seasonal and interannual variability characterizes a strong demand for water, which would encourage MAR implementation to meet the high water demand and bridge the water availability gap during dry seasons and droughts.

All datasets were reclassified into six MAR suitability classes. Table 2 presents the reclassified values for the four biophysical parameters, water availability, and water demand; for supporting evidence for criteria classification and standardization, see section S2 of the ESM.

2.1.5. Assigning relative criteria weights

Assigning relative weights entails allocating weights for each criterion based on their importance to the problem definition. There are several methods for determining weights for GIS-MCDA. These include the equal weight method (Roszkowska, 2013), ranking methods (Roszkowska, 2013), the Multi-Influencing Factor (MIF) method (Bonilla Valverde et al., 2016; Fathi et al., 2020; Magesh et al., 2012), and the Analytic Hierarchy Process (AHP) technique (Saaty, 2008). In the equal weight method, weights are uniformly distributed, whereas in the ranking method, criteria are ranked based on their importance, and the weights are the individual ranks normalized by dividing by the sum of the ranks. The criteria weight in the equal weight's method is defined as one over a number of criteria (1/n). The method requires minimal knowledge from the decision-maker (Wang et al., 2009). The equal weights method has also been criticized because it ignores the relative importance of criteria (Wang et al., 2009). In the MIF technique, weights are determined based on cause-and-effect relationships between the criteria, and the weights are calculated by adding the major and minor effects score for each criterion and dividing this into the total score. The AHP technique (Saaty, 2004) involves the construction of a pairwise comparison matrix in which the weights of each parameter are determined by the relative importance of each parameter to the specific context (Bhuyan et al., 2024). The intrinsic MAR suitability map was created by averaging the weights calculated using three methods: ranking, MIF, and AHP (Table 3). See section S3 of the ESM for further details. For the water source, we used only one criterion: surface runoff potential. The water demand map was built by combining three elements: baseline water stress and seasonal and interannual variability in water availability. All three factors were weighted equally. Similarly,

Table 3
Criteria weights used for intrinsic MAR suitability mapping.

Criteria	Ranking method	AHP	MIF	Average weight
Soil	0.3	0.40	0.25	0.31
Geology	0.4	0.40	0.50	0.43
Land use/cover	0.1	0.04	0.13	0.09
Σ	1.00	1.00	1.00	1.00

Table 2
Selected criteria and their classified and standardized values.

	Suitability value	1.0	0.8	0.6	0.4	0.2
Intrinsic suitability	Slope (%)	0–2	2–4	4–6	6–8	8–10
	Soil texture	Sand, loamy sand, or sandy loam	Silt loam or loam	Sandy clay loam	Clay loam, silty clay loam, sandy clay,	silty clay, clay
	Geology	Unconsolidated	Consolidated sedimentary- dominantly inter-granular flow	Consolidated sedimentary-inter-granular flow and fractured flow	Igneous (volcanic rocks) and Consolidated sedimentary-dominantly fractured flow	Basement
	Land use/land cover	Bare areas	Grassland and Cropland	Lichen Mosses/Sparse vegetation	Shrubs cover areas	Trees cover areas
Water source	Surface runoff (mm/a)	>800	500–800	300–500	15–300	0–15
Demand	Baseline water stress classes	Extremely high stress (>80%)	High stress (40–80%)	Medium to high stress (20–40%)	Low to medium stress (10–20%)	Low stress (<10%) and Arid and low water use
	Seasonal variability in water availability	Extremely high (>1.33)	High (1.00–1.33)	Medium to high (0.66–1.00)	Low to medium (0.33–0.66)	Low (<0.33)
	Inter-annual variability in water availability	Extremely high (>1.00)	High (0.75–1.00)	Medium to high (0.50–0.75)	Low to medium (0.25–0.50)	Low (<0.25)

the overall feasibility map, which integrates intrinsic MAR suitability, water source, and water demand, was produced, assuming an equal weight of 33.3% for each map.

2.1.6. Criteria combination

One of the most widely used techniques in Geographic Information Systems for making decisions based on multiple criteria is Weighted Linear Combination (Eqn. (1)), often abbreviated as WLC (Sallwey et al., 2019). The intrinsic suitability map was produced based on the four thematic maps (slope, geology, soil, and land use/Land cover) and their respective weights calculated using the average of the three methods. The overall MAR feasibility map was created based on the intrinsic suitability, water source, and demand maps, assuming equal importance weights.

$$S = \sum w_i y_i \quad \text{(Eqn. 1)}$$

Where S= Suitability/feasibility, wi = weight for criterion i, yi = Criterion map.

2.1.7. MAR suitability/feasibility classifications

Similar to the approach used by Bonilla Valverde et al. (2016) all three maps (intrinsic suitability, water source availability, and water demand) were classified into six classes based on their suitability/feasibility for MAR (Table 4). We then determined the percentage area covered by each class.

2.1.8. Sensitivity analysis

Sensitivity analysis is an important step in GIS-MCDA. It assesses how a change in criteria weight affects the overall suitability analysis. The One-At-a-Time (OAT) approach is commonly used to assess the sensitivity of criteria weights (Chen et al., 2010). According to Chen et al. (2010), the criteria weight of the main changing criteria under consideration can be calculated using Eqn. (2). To meet the criteria weight sum constraint, the weight of other criteria is adjusted proportionally following the new weight of the main changing criteria weight using Eqn. (3). Following Chen et al. (2010) approach criteria weights were adjusted to 20% of their value (Table 5).

$$W(c_m, pc) = W(c_m, 0) + W(c_m, 0) \times pc, 1 \le m \le n \quad \text{(Eqn. 2)}$$

$W(c_m, pc)$, is the new weight of the main changing criteria, $W(c_m, 0)$ is the base weight of the main changing criterion C_m, at the base run, pc is the percentage change, and n is the number of criteria.

$$W(c_i, pc) = (1 - W(c_m, pc)) \times \frac{W(c_i, 0)}{(1 - W(c_m, 0))}, i \neq m, 1 \le i \le n \quad \text{(Eqn. 3)}$$

Where W (C_i 0) is the weight of the i-th criterion C_i at the base run.

3. Results

3.1. Intrinsic MAR suitability

To assess the intrinsic MAR suitability, we developed a comprehensive map that incorporated various biophysical factors. These factors included slope, soil type, geological characteristics, and land use/land cover. To determine the relative importance of each factor, we employed a multi-criteria decision analysis approach that combined ranking, AHP, and MIF methods. The mean criteria weight, calculated from the three methods, was employed in the final analysis to reduce the potential bias in criteria weight. This rigorous methodology ensured that our intrinsic suitability map accurately reflects the complex interplay of these factors in determining the intrinsic potential for MAR implementation across the continent. Results show that about 25.3% and 32.4% of Africa fall into the high and very high intrinsic suitability classes, respectively. As shown in Fig. 3, most Northern and Western African countries and some Southern African countries (e.g., Angola, Botswana) and Central African countries (e.g., Democratic and Republic of Congo) appear to be in very high suitability classes. Approximately 26.3% of the study area is classified as a moderate suitability class, and 0.1% of areas have been classified as very low suitability class (Table 6). In general, there is substantial intrinsic potential for MAR in Africa.

Table 4
MAR suitability/feasibility classification.

Map values	Suitability/Feasibility classes
0	Unsuitable
>0–0.2	Very low
>0.2–0.4	Low
>0.4–0.6	Moderate
>0.6–0.8	High
>0.8–1.0	Very high

3.2. Availability of water source

Recharge water for MAR can be obtained from various sources, including surface runoff, perennial or intermittent streams, and treated wastewater. However, the current study focuses solely on surface runoff as a source of recharge water. While other sources may also be viable, surface runoff is a readily available and widely distributed resource that can be effectively harnessed for MAR purposes. Fig. 4 depicts the water availability map of Africa derived based on GRDC runoff data. Results show that more than half of the continental area (55%) lies in the very low water availability class, and 7.7% of the area falls into high to very high water availability classes (Table 6). While the study focuses solely on surface runoff, it is important to note that treated wastewater can be a valuable source of recharge water, especially in areas with limited surface water availability. The advantage of treated wastewater as a source of water for MAR is its year-round availability, irrespective of the wet season, but it requires significant pre-and post-treatment, which can be costly (Murray and Tredoux, 1998).

3.3. Demand for water

MAR has the potential to address seasonal variability in water demand through seasonal storage (Dillon et al., 2009). Fig. 5 presents the MAR water demand map for Africa developed based on baseline water stress and seasonal and inter-annual variability in water availability. Results show that approximately 30.5% and 45.3% of the area belong to low and moderate water demand classes, respectively. 13.9% and 2.9% of the area are classified as high and very high water demand classes, respectively (Table 6).

3.4. MAR feasibility mapping

The composite MAR feasibility map was created by combining the intrinsic MAR suitability, water source availability, and water demand maps using equal weights in a weighted overlay analysis (Fig. 6). Following Bonilla Valverde et al. (2016), the resulting intrinsic suitability, water source availability, and water demand maps were classified into five classes, and the area of each class was calculated. The composite MAR feasibility mapping results show that 17.5% of Africa falls into the low feasibility class (Table 6). 73% of the area falls in the moderate feasibility class. 6.6% of the area is classified as highly feasible, and no area has been classified as very highly feasible.

3.5. Validation

The composite MAR feasibility map was validated using 17 existing spreading method MAR case studies reported by Ebrahim et al. (2020) (Fig. 7). The Receiver Operating Characteristic (ROC) curve and the Area Under the Curve (AUC) metrics are commonly used to validate

Table 5
Criteria weight sensitivity analysis.

Criteria	Base weight	Slope (+20%)	Slope (−20%)	Soil (+20%)	Soil (−20%)	Geology (+20%)	Geology (−20%)	Landuse (+20%)	Landuse (−20%)
Slope	0.17	**0.20**	**0.14**	0.15	0.19	0.14	0.20	0.17	0.17
Soil	0.31	0.30	0.32	**0.37**	**0.25**	0.26	0.36	0.30	0.32
Geology	0.43	0.41	0.45	0.39	0.47	**0.52**	**0.34**	0.42	0.44
Land use/ cover	0.09	0.09	0.09	0.08	0.10	0.08	0.10	**0.11**	**0.07**
Σ	1.00	1.00	1.00	1.00	1.00	1.00	1.00	1.00	1.00

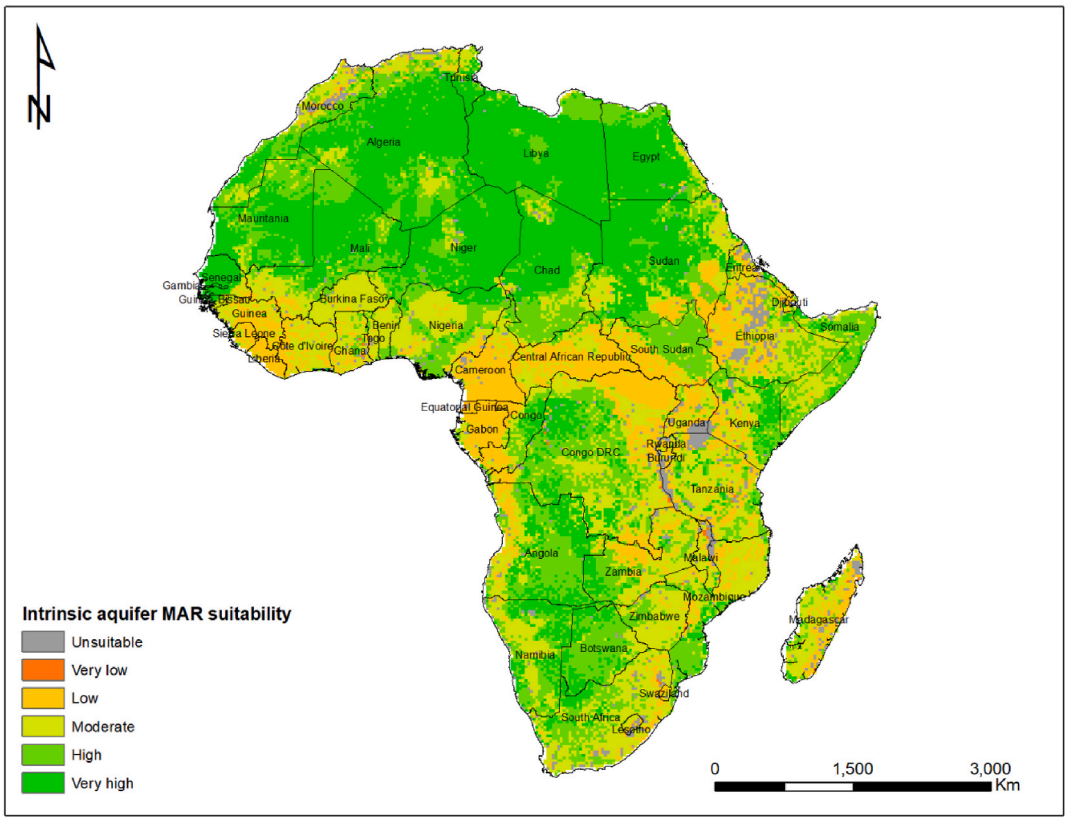


Fig. 3. Intrinsic MAR suitability for Africa.

Table 6
Feasibility classes of MAR and areas in each class.

Map values	Feasibility classes	Percentage of the continental area in each suitability & feasibility class			
		Intrinsic suitability	Water source availability	Demand for water	Composite MAR feasibility
0	Unsuitable	3.0			3.0
>0–0.2	Very low	0.1	55.2	7.5	0.0
>0.2–0.4	Low	12.8	24.7	30.5	17.5
>0.4–0.6	Moderate	26.3	12.4	45.3	73.0
>0.6–0.8	High	25.3	5.1	13.9	6.6
>0.8–1.0	Very high	32.4	2.6	2.9	0.0

suitability maps with classified field validation datasets (e.g., Abdo et al. (2024); Bhuyan and Deka (2022)), but our MAR scheme dataset lacks such classification. Therefore, we were unable to apply the ROC technique directly. Instead, we validated our feasibility map following the approach of Al-Ruzouq et al. (2019). 94% of existing MAR schemes fall under the moderate feasibility class and 6% under the high feasibility class, reinforcing our method's reliability and results. Generally, there is good agreement between the existing MAR scheme's locations and the feasible MAR sites obtained with GIS-MCDA. However, regional feasibility assessment may not be useful for local-scale MAR implementation due to the map's coarse resolution.

3.6. Sensitivity analysis

The results of the sensitivity analysis are presented in Table 7. Results show that geology is the most sensitive criterion, followed by slope. Increasing the weight assigned to geology by 20% results in a 4 % decrease in the moderate feasibility class due to the shift from the low to moderate feasibility class. Similarly, increasing the criteria weight by 20% decreases the moderate feasibility class by 2.3%. Soil and land use and land cover are less sensitive. In general, the maximum change in area due to changes in the criteria weight is only 4%, indicating the robustness of the chosen criteria weighting method. See section S4 of the ESM for further details.

4. Discussion

Africa faces myriad challenges of food insecurity, climate vulnerability, and poverty. Expanding water storage is widely seen as a crucial solution, but the potential of MAR to achieve this goal remains

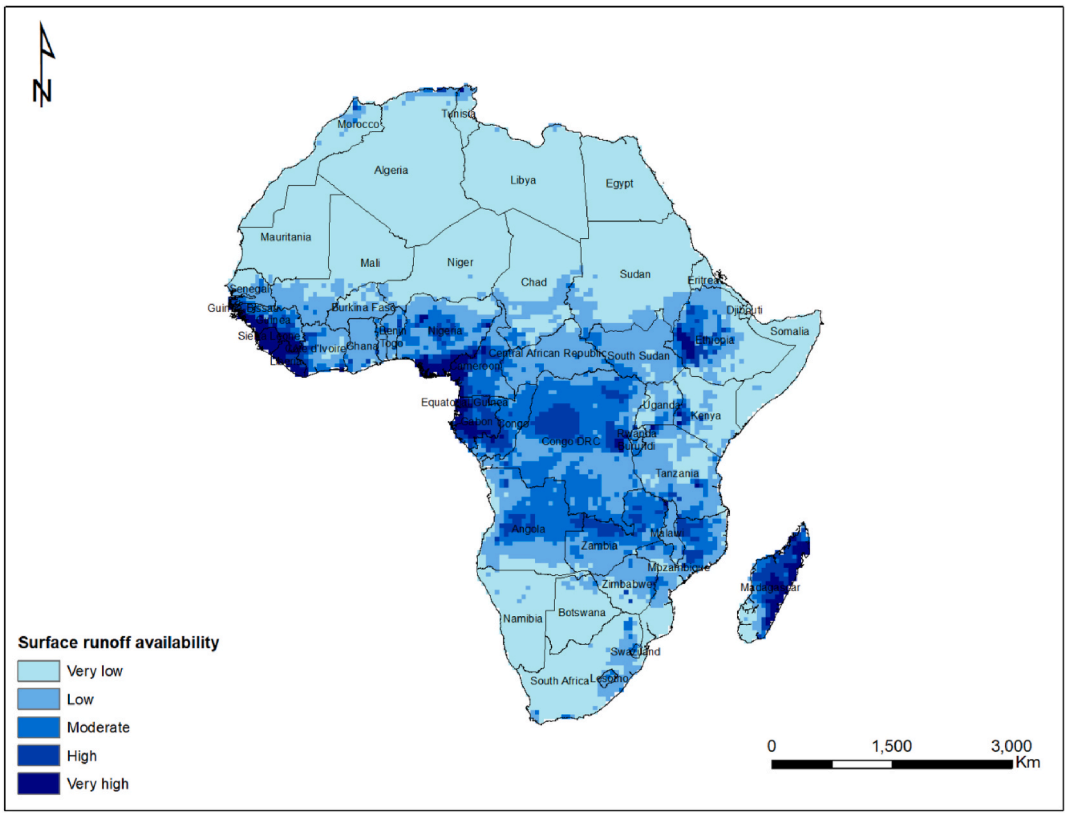


Fig. 4. Surface runoff water availability for MAR in Africa.

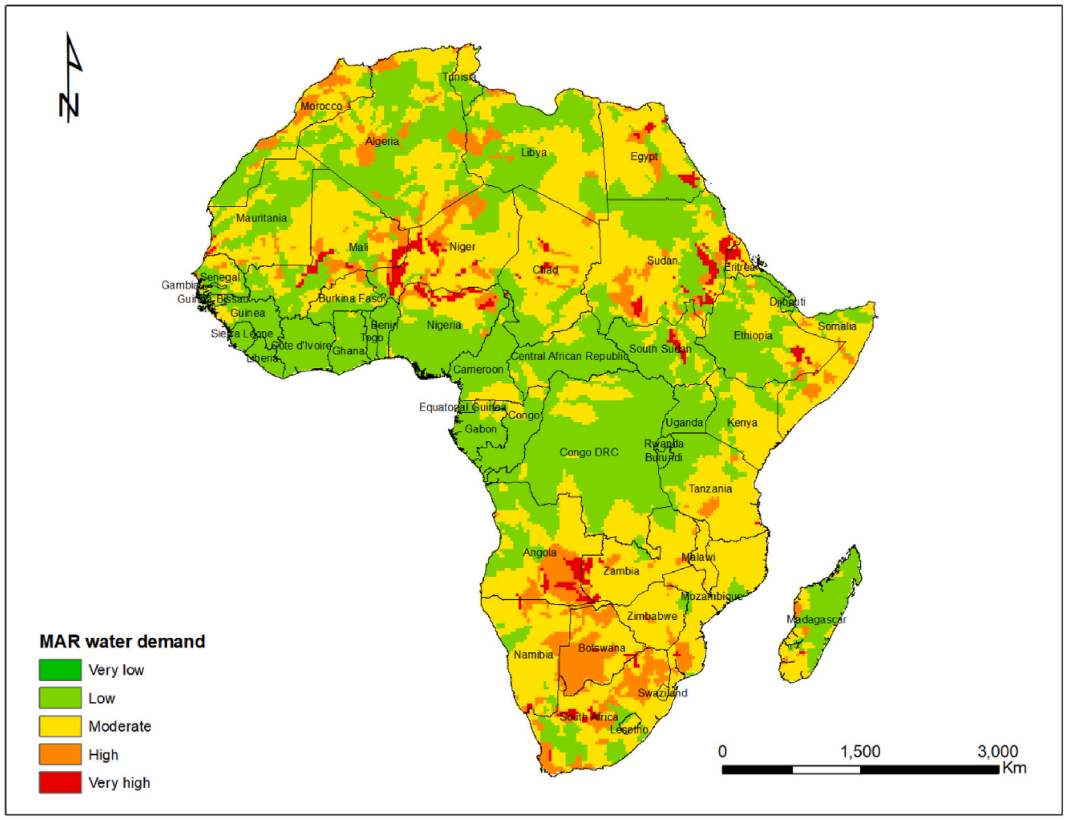


Fig. 5. MAR water demand classes in Africa.

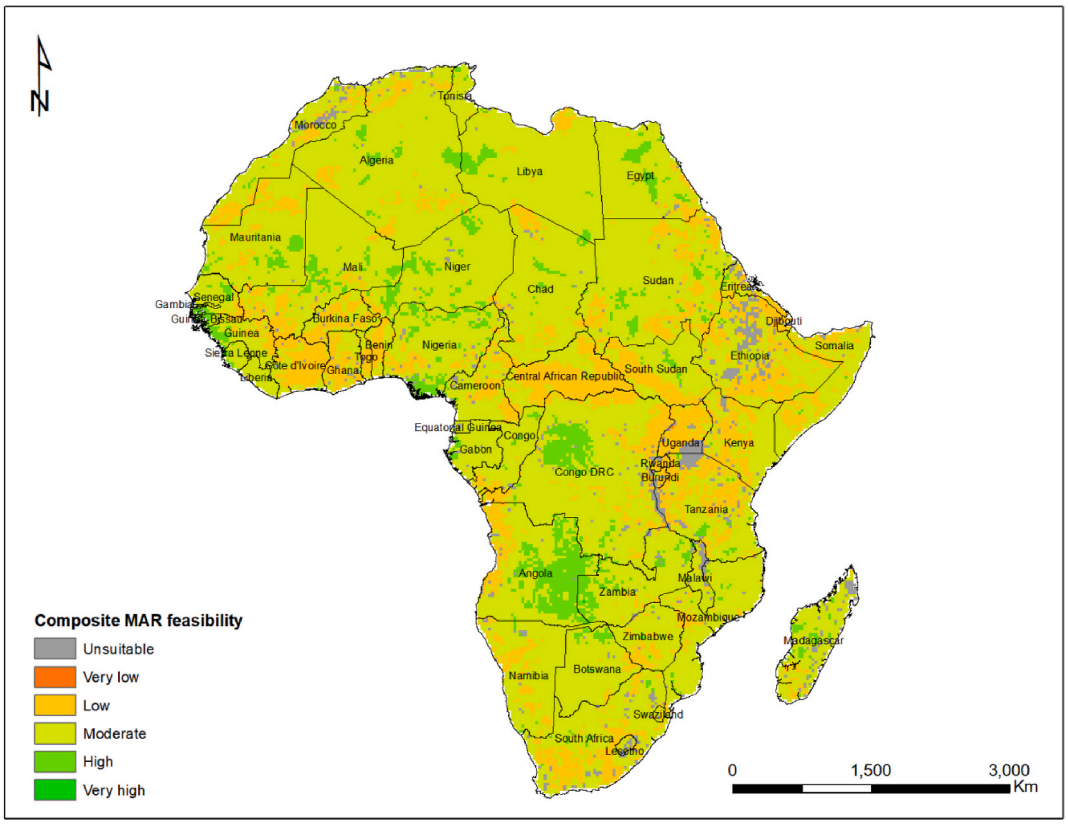


Fig. 6. Composite MAR feasibility map.

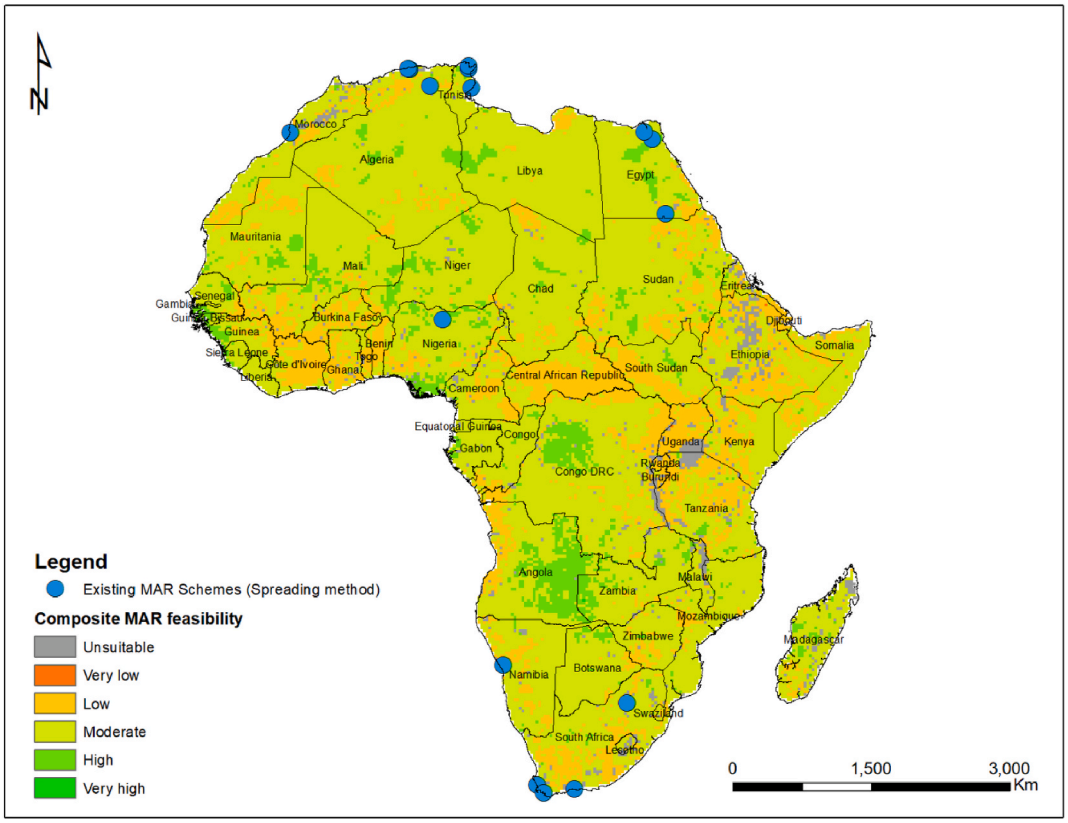


Fig. 7. Composite MAR feasibility map overlaid with 17 existing MAR spreading schemes in Africa from Ebrahim et al. (2020).

Table 7
Change in percentage of the continental area in each MAR feasibility class from the baseline.

Feasibility classes	Slope (+20%)	Slope (−20%)	Soil (+20%)	Soil (−20%)	Geology (+20%)	Geology (−20%)	Landuse (+20%)	Landuse (−20%)
Unsuitable	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0
Very low	0.2	0.2	0.2	0.2	0.2	0.2	0.2	0.2
Low	−1.4	2.3	0.2	0.2	3.9	−1.8	0.3	0.9
Moderate	1.2	−2.3	−0.8	−0.8	−4.1	2.2	0.1	−1.0
High	0.1	−0.2	0.4	0.4	−0.1	−0.6	−0.6	−0.1
Very high	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0

unexplored. This paper is the first to map MAR feasibility from this integrated perspective based on GIS-MCDA and, as such, is believed to offer the strongest guidance to date on the potential for MAR implementation on the continent. The GIS-MCDA MAR feasibility map for Africa reveals at least six key insights.

First, Africa has a substantial intrinsic aquifer potential for MAR application. North African countries such as Algeria, Egypt, Libya, and Sudan, along with Western African countries such as Chad, Nigeria, Mali, Mauritania, and Senegal, Central African countries such as the Republic of Congo and the Democratic Republic of Congo, and Southern Africa countries such as Botswana possess particularly high intrinsic aquifer potential. This is due to the sedimentary formations having good storage potential, favorable slope, and soil with high infiltration capacity. When we visually compared our intrinsic aquifer suitability map with the groundwater storage map for Africa by MacDonald et al. (2012), we found a high degree of consistency between the two.

Second, around 55% of the continent faces low surface runoff availability. Water availability is found to be the limiting factor for MAR application in the North African regions (e.g., Algeria, Egypt, Libya, Morocco, Sudan, and Tunisia), West African regions (e.g. Chad, Niger, Mali, and Mauritania), East Africa region (e.g., Somalia) and southern African regions (e.g. Botswana, Namibia, and South Africa). Hence, in areas where surface runoff potential is low, alternative water sources for MAR, such as the use of treated wastewater, need to be promoted, especially in arid urbanized areas where surface water resources are scanty (e.g., Namibia, South Africa, Tunisia) (Ebrahim et al., 2020).

Third, nearly 31% and 45% of Africa belong to low and moderate water demand classes, respectively. This is due to low water use for irrigated agriculture, industries, and municipal uses. Countries like Egypt, Morocco, and South Africa face severe water scarcity. This means they have a high water demand, but their available water resources are insufficient to meet those needs. Water demand will likely grow due to socio-economic development, an increase in population, and infrastructure investment (Cervigni et al., 2015; Lakmeeharan et al., 2020). Future water demand in coastal areas is expected to rise sharply, primarily driven by high population density and rapid urbanization. A worldwide water stress ranking by Hofste et al. (2019b) identified Eritrea, Botswana, and Morocco as the African nations experiencing the most severe baseline water stress. In regions already facing limited water due to baseline depletion (e.g., Angola, Egypt, Eritrea, Morocco, Somalia, South Africa, and Nigeria, etc.), groundwater depletion (e.g., Egypt, Sudan, Libya, and South Africa, etc.), and frequent droughts, high water demand creates a situation of extreme water scarcity. For further details, please refer to section S5 of the ESM.

Fourth, our analysis showed that a significant portion of Africa, roughly 73%, has moderate feasibility for MAR, while another 7% falls into the high feasibility category. In general, there is good potential for MAR in Africa, and the expansion of MAR in these regions can strengthen climate resilience. Most North African regions, including the Saharan Desert, appeared to be intrinsically very highly suitable for MAR application using the spreading method. However, due to the desert environment, water resource availability is limited, and population density is very low; hence, there is less demand. This is concordant with MacDonald et al. (2021), who described that most African countries (e.g., sedimentary aquifers in North Africa) have high storage potential but low rainfall and are water-stressed. Conversely, most African countries with small groundwater storage capacity (e.g., many crystalline basement aquifers) have high annual rainfall and are recharged regularly.

Fifth, while a substantial portion of Africa, approximately 58%, has high to very high intrinsic aquifer suitability for MAR, water availability is a significant constraint. Only 8% of the continent has high to very high water availability, and 17% faces high to very high water demand. As a result, only 7% of the area was classified as having high feasibility for MAR, and none was considered very high feasibility. Therefore, a MAR suitability evaluation that neglects factors beyond intrinsic aquifer suitability may be misleading. With the increasing population, climate change, and demand for agriculture, water demand will likely rise. According to Ebrahim et al. (2020), 21% of the studied cases utilized treated wastewater for MAR, particularly in countries with limited water resources like South Africa, Namibia, and Tunisia. Exploring alternative water sources, such as treated wastewater or water transfers, is essential to maximize MAR potential in Africa.

Sixth, a sensitivity analysis of the biophysical parameters' criteria weights showed that geology is the most significant factor influencing MAR feasibility, followed by slope and soil. Land use/land cover is less influential. While high-resolution (30 m) slope maps can be derived from public domain digital elevation models, geological maps often have lower resolution. Future local-scale investigations should consider supplementing geological data with geophysical surveys to minimize uncertainty in geological assessments.

Before concluding this discussion, it is essential to acknowledge the limitations of this study. First, criteria standardization in Multi-Criteria Decision Analysis (MCDA) is inherently subjective and uncertain. To reduce this uncertainty, we based our criteria standardization on a thorough literature review of similar studies. Second, a key challenge in MCDA is the inherent subjectivity in criteria weighting. To mitigate this, we used multiple criteria weighting methods and conducted a sensitivity analysis on criteria weights to assess the robustness of our results. Third, the present study considered only one type of water source. Considering alternative water sources like treated wastewater could increase the MAR potential. Fourth, the feasibility map developed in this study is designed to give a continent-wide view of MAR (i.e., 30 km x 30 km resolution) and is not intended to provide local-level MAR feasibility. GIS data with a finer resolution and a more detailed study are essential to reduce this uncertainty. Fifth, Ebrahim et al. (2020) noted that the 17 existing MAR cases used to validate the feasibility map may not be a complete list of MAR applications in Africa. Sixth, while intrinsic suitability is relatively constant over time, water availability and demand are temporally variable. Hence, the feasibility map must be updated as new data and information become available. Seventh, this study used long-term average annual runoff, but factors like the volume, frequency, and duration of available excess water are even more critical for successful MAR implementation. Eighth, available space for additional storage depends on the depth to groundwater at the time when recharging occurs, but this is not considered due to data limitations. Finally, this study did not consider water quality issues due to lack of data. However, for instance, fluoride is reported to be a major groundwater quality concern in regions along the East African Rift Valley (Malago et al., 2017). Future studies should, therefore, integrate spatial

data on depth to groundwater and water quality into their feasibility assessments.

5. Conclusions

There is potential for MAR to play a role in achieving water security in Africa. Given that MAR is not feasible everywhere, the role of this paper is to help focus MAR efforts on the most feasible areas. The feasibility map developed in this study offers a comprehensive assessment of MAR potential across the continent. The results of the MAR feasibility analysis indicate that approximately 18% of the continental area falls into the low feasibility class, 73% into the moderate feasibility class, 7% into the high feasibility class, and no areas were classified as very high feasibility class. In general, there is good potential for MAR in Africa, and the expansion of MAR in this region can strengthen climate resilience. The diversity in levels of feasibility provides a quantitative means to guide MAR application in Africa. It is hoped that this study will provide a regional view of MAR's feasibility in Africa and support the expansion of MAR in the region to address water security challenges in the changing climate.

The MAR feasibility map for Africa suggests significant potential for wider MAR implementation. However, local projects should be preceded by more detailed assessments considering technical aspects, social factors, and costs. This will ensure the success and sustainability of individual MAR initiatives. The map provides a visually appealing way to generate attention for MAR practices and increase awareness of MAR with the public and water professionals. It will help bring MAR to policymakers' attention so that they can prioritize MAR planning and investment. Similarly, funding organizations can use this information to identify investment areas to improve groundwater management through MAR. However, there is a need to strengthen MAR implementation capacity in Africa and document the impacts of successful MAR case studies so that the benefits of MAR can motivate additional roll-out of this approach. Furthermore, given MAR's potential to enhance resilience and water security in Africa, policymakers should ensure adequate resource allocation for its implementation.

CRediT authorship contribution statement

Girma Yimer Ebrahim: Writing – review & editing, Writing – original draft, Methodology, Investigation, Formal analysis, Data curation, Conceptualization. **Catalin Stefan:** Writing – review & editing, Methodology, Conceptualization. **Jana Sallwey:** Writing – review & editing, Methodology, Conceptualization. **Jonathan Lautze:** Writing – review & editing, Methodology, Conceptualization.

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.

Acknowledgments

We gratefully acknowledge the financial support from the TWAS-DFG cooperation visit Programme for scientists from sub-Saharan Africa, which enabled the lead author to conduct a two-month research visit (October 23 – December 23, 2017) at the INOWAS Junior Research Group at Technische Universität Dresden, Germany. We extend our sincere thanks to the CGIAR Initiative on NEXUS Gains (Working Package 2), a program funded by the CGIAR Trust Fund contributors www.cgiar.org/funders for thier financial support to finalize this study. We further extend our thanks to the Groundwater for Advancing Resilience in Africa (G4DR in Africa) project funded by the Global Environment Facility (GEF) for their additional financial support. The views expressed herein are solely those of the author(s) and do not reflect the opinions of the donor.

Appendix A. Supplementary data

Supplementary data to this article can be found online at https://doi.org/10.1016/j.gsd.2024.101374.

Data availability

Data will be made available on request.

References

Abascal, E., Gómez-Coma, L., Ortiz, I., Ortiz, A., 2022. Global diagnosis of nitrate pollution in groundwater and review of removal technologies. Science of the total environment 810, 152233.

Abdo, H.G., Vishwakarma, D.K., Alsafadi, K., Bindajam, A.A., Mallick, J., Mallick, S.K., Kumar, K.C.A., Albanai, J.A., Kuriqi, A., Hysa, A., 2024. GIS-based multi-criteria decision making for delineation of potential groundwater recharge zones for sustainable resource management in the Eastern Mediterranean: a case study. Appl. Water Sci. 14 (7), 160. https://doi.org/10.1007/s13201-024-02217-z.

Agarwal, E., Agarwal, R., Garg, R.D., Garg, P.K., 2013. Delineation of groundwater potential zone: an AHP/ANP approach. J. Earth Syst. Sci. 122, 887–898. https://doi.org/10.1007/s12040-013-0309-8.

Al-Ruzouq, R., Shanableh, A., Yilmaz, A.G., Idris, A., Mukherjee, S., Khalil, M.A., Gibril, M.B.A., 2019. Dam site suitability mapping and analysis using an integrated GIS and machine learning approach. Water 11 (9), 1880.

Aloui, D., Chekirbane, A., Stefan, C., Schlick, R., Msaddek, M.H., Mlayah, A., 2022. Use of a GIS-multi-criteria decision analysis and web-based decision support tools for mapping and sharing managed aquifer recharge feasibility in Enfidha plain, NE of Tunisia. Arabian J. Geosci. 15 (7), 658. https://doi.org/10.1007/s12517-022-09893-8.

Ayugi, B., Eresanya, E.O., Onyango, A.O., Ogou, F.K., Okoro, E.C., Okoye, C.O., Anoruo, C.M., Dike, V.N., Ashiru, O.R., Daramola, M.T., 2022. Review of meteorological drought in Africa: historical trends, impacts, mitigation measures, and prospects. Pure Appl. Geophys. 179 (4), 1365–1386.

Balek, J., 2011. Hydrology and Water Resources in Tropical Africa. Elsevier.

BGS, 2017. Geological map kindly provided by Brighid Ó Dochartaigh of the BGS [personal communication, on November 2017]. BGS derived the form a map released by USGS and described by Persits et al -. http://pubs.usgs.gov/of/1997/of r-97-470/OF97-470A/.

Bhuyan, M.J., Deka, N., 2022. Delineation of groundwater potential zones at micro-spatial units of Nagaon district in Assam, India, using GIS-based MCDA and AHP techniques. Environ. Sci. Pollut. Control Ser. https://doi.org/10.1007/s11356-022-24505-4.

Bhuyan, M.J., Deka, N., Saikia, A., 2024. Micro-spatial flood risk assessment in Nagaon district, Assam (India) using GIS-based multi-criteria decision analysis (MCDA) and analytical hierarchy process (AHP). Risk Anal. 44 (4), 817–832.

Bonilla Valverde, J.P., Blank, C., Roidt, M., Schneider, L., Stefan, C., 2016. Application of a GIS multi-criteria decision analysis for the identification of intrinsic suitable sites in Costa Rica for the application of managed aquifer recharge (MAR) through spreading methods. Water 8 (9), 391.

Bouri, S., Dhia, H.B., 2010. A thirty-year artificial recharge experiment in a coastal aquifer in an arid zone: the Teboulba aquifer system (Tunisian Sahel). Compt. Rendus Geosci. 342 (1), 60–74.

Braune, E., Xu, Y., 2010. The role of ground water in Sub-Saharan Africa. Groundwater 48 (2), 229–238.

Burke, E.R., Tront, J.M., Lyon, K.N., Rex, W., Castera Errea, M.I., Varughese, M.C., Newton, J.T., Becker, A.N., Vale, A.L., 2023. What the Future Has in Store: A New Paradigm for Water Storage-Overview for Policy Makers.

Carter, R.C., Parker, A., 2009. Climate change, population trends and groundwater in Africa. Hydrol. Sci. J. 54 (4), 676–689.

Cervigni, R., Liden, R., Neumann, J.E., Strzepek, K.M., 2015. Enhancing the Climate Resilience of Africa's Infrastructure: the Power and Water Sectors. World Bank Publications. http://hdl.handle.net/10986/21875.

Chaieb, H., 2014. Tunisian experience in artificial recharge using treated waste water. Regional Conference on Sustainable Integrated Wastewater Treatment and Reuse Sharm El Sheikh - Egypt, 1-2 December,, 2014.

Chen, Y., Yu, J., Khan, S., 2010. Spatial sensitivity analysis of multi-criteria weights in GIS-based land suitability evaluation. Environ. Model. Software 25 (12), 1582–1591. https://doi.org/10.1016/j.envsoft.2010.06.001.

Chirisa, I., 2008. A Population Growth and Rapid Urbanization in Africa: Implications for Sustainability.

Collier, P., Conway, G., Venables, T., 2008. Climate change and Africa. Oxf. Rev. Econ. Pol. 24 (2), 337–353. https://www.jstor.org/stable/23606648.

Connolly-Boutin, L., Smit, B., 2016. Climate change, food security, and livelihoods in sub-Saharan Africa. Reg. Environ. Change 16, 385–399.

Consbio, 2010. Conservation biology institute (consbio). https://www.arcgis.com/home/item.html?id=c891f64c13be4a2c96491e386bfed8c5. November 2021.

Daher, W., Pistre, S., Kneppers, A., Bakalowicz, M., Najem, W., 2011. Karst and artificial recharge: theoretical and practical problems: a preliminary approach to artificial

recharge assessment. J. Hydrol. 408 (3–4), 189–202. https://doi.org/10.1016/j.jhydrol.2011.07.017.
de Graaf, I.E.M., Gleeson, T., van Beek, L.P.H., Sutanudjaja, E.H., Bierkens, M.F.P., 2019. Environmental flow limits to global groundwater pumping. Nature 574 (7776), 90–94. https://doi.org/10.1038/s41586-019-1594-4.
Dillon, P., 2005. Future management of aquifer recharge. Hydrogeol. J. 13 (1), 313–316. https://doi.org/10.1007/s10040-004-0413-6.
Dillon, P., Pavelic, P., Page, D., Beringen, H., Ward, J., 2009. Managed Aquifer Recharge: an Introduction waterlines report series No. 13.
Dillon, P., Stuyfzand, P., Grischek, T., Lluria, M., Pyne, R., Jain, R., Bear, J., Schwarz, J., Wang, W., Fernandez, E., 2019. Sixty years of global progress in managed aquifer recharge. Hydrogeol. J. 27 (1), 1–30. https://doi.org/10.1007/s10040-018-1841-z.
Dillon, P.J., Pavelic, P., 1996. Guidelines on the quality of stormwater and treated wastewater for injection into aquifers for storage and reuse. In: Research Report No, 109. Urban Water Research Association of Australia, Melbourne.
Dodgson, J.S., Spackman, M., Pearman, A., Phillips, L.D., 2009. Multi-criteria Analysis: a Manual. Department for Communities and Local Government, London. http://eprints.lse.ac.uk/12761/1/Multi-criteria_Analysis.pdf. April 2022.
Doke, A.B., Zolekar, R.B., Patel, H., Das, S., 2021. Geospatial mapping of groundwater potential zones using multi-criteria decision-making AHP approach in a hardrock basaltic terrain in India. Ecol. Indicat. 127, 107685.
Ebrahim, G., Fathi, S., Lautze, J., Ansems, N., Villholth, K., Nijste, G., Magombeyi, M., Mndaweni, S., Kenabatho, P., Moehadu, M., 2017. Review of Managed Aquifer Recharge (MAR) Experience in Africa and MAR Suitability Mapping for Ramotswa Transboundary Aquifer Area. International Water Management Institute, Pretoria, South Africa.
Ebrahim, G.Y., Lautze, J.F., Villholth, K.G., 2020. Managed aquifer recharge in Africa: taking stock and looking forward. Water 12 (7), 1844. https://doi.org/10.3390/w12071844.
Ehsan, M., Shabbir, H., Al-Quraishi, A.M.F., Al-Ansari, N., Ahmad, Z., Abdelrahman, K., Sohail, M.T., Manzoor, Z., Shafi, A., Elbeltagi, A., 2024. Groundwater delineation for sustainable improvement and development aided by GIS, AHP, and MIF techniques. Appl. Water Sci. 14 (2), 23.
ESA, 2021. CCI land cover - S2 prototype land cover 20M map of africa 2016. http://2016africalandcover20m.esrin.esa.int/. November 2021.
Escalante, E.F., Sauto, J.S.S., Gil, R.C., 2019. Sites and indicators of MAR as a successful tool to mitigate climate change effects in Spain. Water 11 (9), 1943. https://doi.org/10.3390/w11091943.
FAO, 1979. Soil survey investigations for irrigation FAO soils. Bulletin 42.
Fathi, S., Hagen, J.S., Haidari, A.H., 2020. Synthesizing existing frameworks to identify the potential for Managed Aquifer Recharge in a karstic and semi-arid region using GIS Multi Criteria Decision Analysis. Groundwater for Sustainable Development 11, 100390. https://doi.org/10.1016/j.gsd.2020.100390.
Fekete, B., Vörösmarty, C., Grabs, W., 2002a. Global Composite Runoff Fields on Observed River Discharge and Simulated Water Balances/Water System Analysis Group, vol. 2002. University of New Hampshire, and Global Runoff Data Centre. Koblenz, Germany: Federal Institute of Hydrology (BfG).
Fekete, B.M., Vörösmarty, C.J., Grabs, W., 2002b. High-resolution fields of global runoff combining observed river discharge and simulated water balances. Global Biogeochem. Cycles 16 (3). https://doi.org/10.1029/1999GB001254, 15-1-15-10.
Gassert, F., Luck, M., Landis, M., Reig, P., Shiao, T., 2014. Aqueduct Global Maps 2.1: Constructing Decision-Relevant Global Water Risk Indicators. World Resources Institute.
Gaye, C.B., Tindimugaya, C., 2019. Challenges and opportunities for sustainable groundwater management in Africa. Hydrogeol. J. 27 (3), 1099–1110.
GEF, 2024. Global environment facility. https://www.thegef.org/what-we-do/topics/groundwater#:~:text=Today%20groundwater%20is%20estimated%20globally,24%25%20of%20direct%20industrial%20supply. (Accessed 4 September 2024).
Ghayoumian, J., Ghermezcheshme, B., Feiznia, S., Noroozi, A.A., 2005. Integrating GIS and DSS for identification of suitable areas for artificial recharge, case study Meimeh Basin, Isfahan, Iran. Environmental Geology 47, 493–500. https://doi.org/10.1007/s00254-004-1169-y.
Ghayoumian, J., Saravi, M.M., Feiznia, S., Nouri, B., Malekian, A., 2007. Application of GIS techniques to determine areas most suitable for artificial groundwater recharge in a coastal aquifer in southern Iran. J. Asian Earth Sci. 30 (2), 364–374. https://doi.org/10.1016/j.jseaes.2006.11.002.
Giordano, M., 2009. Global groundwater? Issues and solutions. Annu. Rev. Environ. Resour. 34 (1), 153–178.
Gizaw, M.S., Gan, T.Y., 2017. Impact of climate change and El Niño episodes on droughts in sub-Saharan Africa. Clim. Dynam. 49 (1), 665–682. https://doi.org/10.1007/s00382-016-3366-2.
Gleeson, T., VanderSteen, J., Sophocleous, M.A., Taniguchi, M., Alley, W.M., Allen, D.M., Zhou, Y., 2010. Groundwater sustainability strategies. Nat. Geosci. 3 (6), 378–379. https://doi.org/10.1038/ngeo881.
Goode, D.J., 2021. Managed Aquifer Recharge Suitability-Regional Screening and Case Studies in Jordan and Lebanon.
Gregory, P.J., Ingram, J.S., Brklacich, M., 2005. Climate change and food security. Phil. Trans. Biol. Sci. 360 (1463), 2139–2148.
Grinshpan, M., Furman, A., Dahlke, H.E., Raveh, E., Weisbrod, N., 2021. From managed aquifer recharge to soil aquifer treatment on agricultural soils: concepts and challenges. Agric. Water Manag. 255, 106991. https://doi.org/10.1016/j.agwat.2021.106991.
Hall, C., Dawson, T., Macdiarmid, J., Matthews, R., Smith, P., 2017. The impact of population growth and climate change on food security in Africa: looking ahead to 2050. Int. J. Agric. Sustain. 15 (2), 124–135.
Hofste, R.W., Kuzma, S., Walker, S., Sutanudjaja, E.H., Bierkens, M.F., Kuijper, M.J., Sanchez, M.F., Van Beek, R., Wada, Y., Rodríguez, S.G., 2019a. Aqueduct 3.0: Updated Decision-Relevant Global Water Risk Indicators. World Resources Institute, Washington, DC, USA.
Hofste, R.W., Reig, P., Schleifer, L., 2019b. 17 countries, home to one-quarter of the world's population, face extremely high water stress. https://www.wri.org/insights/17-countries-home-one-quarter-worlds-population-face-extremely-high-water-stress. March 2022.
Iglesias, A., Santillán, D., Garrote, L., 2018. On the barriers to adaption to less water under climate change: policy choices in Mediterranean countries. Water Resour. Manag. 32 (15), 4819–4832. https://doi.org/10.1007/s11269-018-2043-0.
ISRIC, 2018. ISRIC world soil information. https://data.isric.org/geonetwork/srv/eng/catalog.search#/home. July 2018.
Jafari, S., Zaredar, N., 2010. Land suitability analysis using multi AttributeDecision making approach. International journal of environmental science and development 1 (5), 441.
Jasechko, S., Perrone, D., 2021. Global groundwater wells at risk of running dry. Science 372 (6540), 418–421.
Koech, R., Langat, P., 2018. Improving irrigation water use efficiency: a review of advances, challenges and opportunities in the Australian context. Water 10 (12), 1771. https://doi.org/10.3390/w10121771.
Konikow, L.F., Kendy, E., 2005. Groundwater depletion: a global problem. Hydrogeol. J. 13, 317–320.
Kresic, N., 2006. Hydrogeology and Groundwater Modeling. CRC press.
Kuzma, S., Bierkens, M.F.P., Lakshman, S., Luo, T., Saccoccia, L., Sutanudjaja, E.H., R, V. B., 2023. Aqueduct 4.0: Updated Decision-Relevant Global Water Risk indicators." Technical Note. World Resources Institute, Washington, DC. https://doi.org/10.46830/writn.23.00061.
Lakmeeharan, K., Manji, Q., Nyairo, R., Poeltner, H., 2020. Solving Africa's infrastructure paradox. https://www.mckinsey.com/business-functions/operations/our-insights/solving-africas-infrastructure-paradox. April 2022.
MacDonald, A., Bonsor, H., Calow, R., Taylor, R., Lapworth, D., Maurice, L., Tucker, J., O Dochartaigh, B., 2011. Groundwater Resilience to Climate Change in Africa.
MacDonald, A., Davies, J., 2000. A Brief Review of Groundwater for Rural Water Supply in Sub-saharan Africa.
MacDonald, A., O Dochartaigh, B., Bonsor, H., Davies, J., Key, R., 2010. Developing Quantitative Aquifer Maps for Africa.
MacDonald, A.M., Bonsor, H.C., Dochartaigh, B.É.Ó., Taylor, R.G., 2012. Quantitative maps of groundwater resources in Africa. Environ. Res. Lett. 7 (2), 024009. https://doi.org/10.1088/1748-9326/7/2/024009.
MacDonald, A.M., Calow, R.C., MacDonald, D.M., Darling, W.G., Dochartaigh, B.E., 2009. What impact will climate change have on rural groundwater supplies in Africa? Hydrol. Sci. J. 54 (4), 690–703.
MacDonald, A.M., Lark, R.M., Taylor, R.G., Abiye, T., Fallas, H.C., Favreau, G., Goni, I.B., Kebede, S., Scanlon, B., Sorensen, J.P., 2021. Mapping groundwater recharge in Africa from ground observations and implications for water security. Environ. Res. Lett. 16 (3), 034012. https://doi.org/10.1088/1748-9326/abd661.
Magesh, N.S., Chandrasekar, N., Soundranayagam, J.P., 2012. Delineation of groundwater potential zones in Theni district, Tamil Nadu, using remote sensing, GIS and MIF techniques. Geosci. Front. 3 (2), 189–196. https://doi.org/10.1016/j.gsf.2011.10.007.
Mahé, G., Lienou, G., Descroix, L., Bamba, F., Paturel, J.-E., Laraque, A., Meddi, M., Habaieb, H., Adeaga, O., Dieulin, C., 2013. The rivers of Africa: witness of climate change and human impact on the environment. Hydrol. Process. 27 (15), 2105–2114.
Malago, J., Makoba, E., Muzuka, A., 2017. Fluoride levels in surface and groundwater in Africa: a review. American Journal of Water Science and Engineering 3 (1), 1–17.
Malczewski, J., 2004. GIS-based land-use suitability analysis: a critical overview. Prog. Plann. 62 (1), 3–65.
Martins, T.N., Leitão, T.E., Oliveira, M.M., Panagiotou, C.F., Stefan, C., Chkirbene, A., Portela, M.M., 2024. Proposal for a managed aquifer recharge feasibility index for southern Portugal using multi-criteria decision analysis. Groundwater for Sustainable Development 26, 101280.
Marwaha, N., Kourakos, G., Levintal, E., Dahlke, H.E., 2021. Identifying agricultural managed aquifer recharge locations to benefit drinking water supply in rural communities. Water Resour. Res. 57 (3), e2020WR028811.
Massmann, J., 2003. Implementation of infiltration ponds research. Research Report (No. WA-RD 578.1), Washington State Department of Transportation. https://rosap.ntl.bts.gov/view/dot/39535/dot_39535_DS1.pdf.
Miller, G.W., 2006. Integrated concepts in water reuse: managing global water needs. Desalination 187 (1–3), 65–75. https://doi.org/10.1016/j.desal.2005.04.068.
Murray, R., 2017. Managed Aquifer Recharge, an Introductory Guide for the SADC Groundwater Management Institute Including the Windhoek Case Study; Groundwater Africa. Cape Town, South Africa.
Murray, R., Tredoux, G., 1998. Artificial Recharge: A Technology for Sustainable Water Resource Development: Final Report to the Water Research Commission. WRC. South Africa.
Oiro, S., Comte, J.-C., Soulsby, C., MacDonald, A., Mwakamba, C., 2020. Depletion of groundwater resources under rapid urbanisation in Africa: recent and future trends in the Nairobi Aquifer System, Kenya. Hydrogeol. J. 28 (8), 2635–2656. https://doi.org/10.1007/s10040-020-02236-5.
Olivier, D.W., Xu, Y., 2019. Making effective use of groundwater to avoid another water supply crisis in Cape Town, South Africa. Hydrogeol. J. 27 (3), 823–826.
Ouedraogo, I., Defourny, P., Vanclooster, M., 2016. Mapping the groundwater vulnerability for pollution at the pan African scale. Sci. Total Environ. 544, 939–953.

Oyebande, L., 2001. Water problems in Africa—how can the sciences help? Hydrol. Sci. J. 46 (6), 947–962.
Panagiotou, C.F., Eisenreich, S., Barouta, O.T., Chekirbane, A., Martins, T., Neophytides, S., Khemiri, K., Stefan, C., 2024. Identification of feasible regions for managed aquifer recharge in the Republic of Cyprus using a co-participative multi-criteria decision analysis. Groundwater for Sustainable Development, 101323.
Podgorski, J., Berg, M., 2022. Global analysis and prediction of fluoride in groundwater. Nat. Commun. 13 (1), 4232.
Praveen, B., Sharma, P., 2019. A review of literature on climate change and its impacts on agriculture productivity. J. Publ. Aff. 19 (4), e1960. https://doi.org/10.1002/pa.1960.
Rahman, M.A., Rusteberg, B., Gogu, R., Ferreira, J.L., Sauter, M., 2012. A new spatial multi-criteria decision support tool for site selection for implementation of managed aquifer recharge. J. Environ. Manag. 99, 61–75. https://doi.org/10.1016/j.jenvman.2012.01.003.
Riad, P.H., Billib, M., Hassan, A.A., Salam, M.A., El Din, M.N., 2011. Application of the overlay weighted model and Boolean logic to determine the best locations for artificial recharge of groundwater. J. Urban Environ. Eng. 5 (2), 57–66. https://www.jstor.org/stable/26203357.
Roszkowska, E., 2013. Rank ordering criteria weighting methods–a comparative overview. Optimum. Studia Ekonomiczne 5 (65), 14–33. https://doi.org/10.15290/ose.2013.05.65.02.
Russo, T.A., Fisher, A.T., Lockwood, B.S., 2015. Assessment of managed aquifer recharge site suitability using a GIS and modeling. Groundwater 53 (3), 389–400. https://doi.org/10.1111/gwat.12213.
Saaty, T.L., 2004. Decision making—the analytic hierarchy and network processes (AHP/ANP). J. Syst. Sci. Syst. Eng. 13 (1), 1–35.
Saaty, T.L., 2008. Decision making with the analytic hierarchy process. Int. J. Serv. Sci. 1 (1), 83–98. https://doi.org/10.1504/IJSSCI.2008.017590.
Sallwey, J., Bonilla Valverde, J.P., Vásquez López, F., Junghanns, R., Stefan, C., 2019. Suitability maps for managed aquifer recharge: a review of multi-criteria decision analysis studies. Environ. Rev. 27 (2), 138–150. https://doi.org/10.1139/er-2018-0069.
Seidl, C., Wheeler, S.A., Page, D., 2024. Understanding the global success criteria for managed aquifer recharge schemes. J. Hydrol. 628, 130469.
Serdeczny, O., Adams, S., Baarsch, F., Coumou, D., Robinson, A., Hare, W., Schaeffer, M., Perrette, M., Reinhardt, J., 2017. Climate change impacts in Sub-Saharan Africa: from physical changes to their social repercussions. Reg. Environ. Change 17 (6), 1585–1600. https://doi.org/10.1007/s10113-015-0910-2.
Siebert, S., Burke, J., Faures, J.-M., Frenken, K., Hoogeveen, J., Döll, P., Portmann, F.T., 2010. Groundwater use for irrigation–a global inventory. Hydrol. Earth Syst. Sci. 14 (10), 1863–1880.
Stefan, C., Ansems, N., 2018. Web-based global inventory of managed aquifer recharge applications. Sustainable Water Resources Management 4 (2), 153–162. https://doi.org/10.1007/s40899-017-0212-6.
Steyl, G., Dennis, I., 2010. Review of coastal-area aquifers in Africa. Hydrogeol. J. 18 (1), 217–225. https://doi.org/10.1007/s10040-009-0545-9.
Titus, R., Beekman, H., Adams, S., Strachan, L., 2009. The basement aquifers of Southern Africa. Water Research Commission report no. In: TT, 428-09. South Africa.
Tredoux, G., Cain, J., 2010. The Atlantis Water Resource Management Scheme: 30 Years of Artificial Groundwater Recharge. Department of Water Affairs, Pretoria, South Africa. P RSA 000/00/11609/10 - Activity 17 (AR5.1).
Trisos, C., Adelekan, I., Totin, E., Ayanlade, A., Efitre, J., Gemeda, A., Kalaba, K., Lennard, C., Masao, C., Mgaya, Y., Ngaruiya, G., Olago, D., Simpson, N., Zakieldeen, R., Thorn, J., 2022. Africa. In: Climate Change 2022: Impacts, Adaptation and Vulnerability. Contribution of Working Group II to the Sixth Assessment Report of the Intergovernmental Panel on Climate Change. Cambridge University Press. https://doi.org/10.1017/9781009325844.011.
Tuinhof, A., Foster, S., van Steenbergen, F., Talbi, A., Wishart, M., 2011. Appropriate Groundwater Management Policy for Sub-saharan Africa: in Face of Demographic Pressure and Climatic Variability. World Bank.
UN, 2022. United Nations, the United Nations World Water Development Report 2022: Groundwater: Making the Invisible Visible. UNESCO, Paris.
USDA, 1986. Urban Hydrology for Small Watersheds, TR-55. Technical release 55, 2-6. Appendix A: Hydroloic Soil Groups.
Vaux, H., 2011. Groundwater under stress: the importance of management. Environ. Earth Sci. 62 (1), 19–23.
Wada, Y., Bierkens, M.F., 2014. Sustainability of global water use: past reconstruction and future projections. Environ. Res. Lett. 9 (10), 104003.
Wada, Y., Van Beek, L.P., Van Kempen, C.M., Reckman, J.W., Vasak, S., Bierkens, M.F., 2010. Global depletion of groundwater resources. Geophys. Res. Lett. 37 (20).
Wang, J.-J., Jing, Y.-Y., Zhang, C.-F., Zhao, J.-H., 2009. Review on multi-criteria decision analysis aid in sustainable energy decision-making. Renewable and sustainable energy reviews 13 (9), 2263–2278. https://doi.org/10.1016/j.rser.2009.06.021.
Water, U., 2018. 2018 UN World Water Development Report, Nature-Based Solutions for Water.
World Bank, 2018. Assessment of Groundwater Challenges and Opportunities in Support of Sustainable Development in Sub-saharan Africa. World Bank, Washington, DC, USA.
WRI, 2023. Technical Note: Aqueduct 4.0: Updated Decision-Relevant Global Water Risk Indicators by World Resources Institute (WRI).
Xu, G., Su, X., Zhang, Y., You, B., 2021. Identifying potential sites for artificial recharge in the plain area of the daqing river catchment using GIS-based multi-criteria analysis. Sustainability 13 (7), 3978. https://doi.org/10.3390/su13073978.
Yosef, Z.-M., Birhanu, B., Suryabhagavan, K.V., Tsegay, T., 2024. GIS-Based suitability mapping of managed aquifer recharge (MAR) in diredawa catchment, eastern Ethiopia. Int. J. River Basin Manag. 1–15.
Government of India, 2007. Manual on Artificial Recharge of Groundwater Central Ground Water Board. Ministry of Water Resources, Govt. of India, New Delhi. pp. 1-198 https://jsactr.mowr.gov.in/Public_Dash/download/Manual%20on%20Artificial%20Recharge%20of%20Ground%20Water.pdf [accessed 9, September, 2024).