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Identifying and Mapping the Key Challenges of Water in Sudan to Accelerate the Achievement of SDG6

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ABSTRACT

Sudan faces a complex nexus of water-related challenges that severely impede progress toward Sustainable Development Goal 6 (SDG 6) targets. Achieving Sustainable Development Goal 6 (SDG 6), which aims to ensure the availability and sustainable management of water and sanitation for all, remains a major challenge in Sudan due to persistent water scarcity, uneven distribution of resources, infrastructure degradation, climate variability, and socio-political instability. This study aimed to identify, classify, and spatially map the most serious water-related challenges across Sudan to support evidence-based decision-making and accelerate progress toward SDG 6. Despite possessing substantial potential water resources, Sudan's progress toward achieving SDG 6 by 2030 is severely hindered by a lack of integrated data on national water challenges and a failure to prioritize targeted, sustainable interventions. Data were collected from 300 stakeholders across 10 states in Sudan, supported by GPS-based mapping of water challenge locations and community validation. Data collection combined precipitation and LULC, water scarcity, stakeholder field surveys, and targeted point-source water salinity. These multi-tiered datasets were spatially integrated using ArcGIS overlay analysis and correlation tests to assess relationships among physical, institutional, and key water challenges.. The findings indicate that North Kordofan, Red Sea, White Nile, Kassala, and Gadarif experienced the highest levels of water scarcity. Additionally, elevated water salinity is most prevalent in the Red Sea, White Nile, Gedarif, and Gezira states. Positive correlations were observed between salinity and water scarcity ($r = 0.319$, $p < .001$), perceived intensive extraction of groundwater and water scarcity ($r = 0.198$, $p < 0.001$), and between perceived intensive extraction of groundwater and salinity ($r = 0.161$, $p < .005$). These results suggest that higher salinity and groundwater over extraction are linked to increased water scarcity. The findings provide spatially explicit evidence to guide policymakers in prioritizing sustainable water management interventions towards achieving SDG 6 and related SDGs.

Introduction

Access to a safe and adequate water supply is a fundamental human right that must be ensured for all people (Oliveira & Água, 2017; Scanlon et al., 2004). While Sustainable Development Goal 6 (SDG 6) aims to realize this mandate by 2030, achieving it remains a significant global challenge (Aman et al., 2024)—particularly where localized water vulnerabilities have not been systematically identified and mapped. True water security depends on addressing these baseline constraints to ensure sustainable access to safe, reliable water for all, while safeguarding resources to meet both present and future needs (Oliveira & Água, 2017; Scanlon et al., 2004).

SDG6 is alarmingly off-track, as highlighted in the recent status report on the SDGs published by UN-Water (Werner et al., 2025; Casale et al., 2025; Popescu, & Kemerink, 2025). Worldwide reports have shown too slow progress, and nations are not on track to achieve SDG 6 by 2030 (Leal Filho et al.,2025), with only four years remaining to meet this goal.

Some developing regions seem to be making progress toward achieving SDG 6; sub-Saharan Africa is lagging behind (Nkiaka, Bryant, Okumah, & Gomo, 2021). Sudan, like many regions, faces compounding pressures from water scarcity, pollution, climate change, and inadequate infrastructure (Salama, 2025). Sudan faces a range of water-related issues, including a lack of safe drinking water, inadequate sanitation, water pollution, and water scarcity (Elsheikh & Nasreldin, 2022). These challenges manifest unevenly across Sudan's regions, with significant disparities between rural and urban areas, as well as between Nile-dependent and non-Nile-dependent regions, highlighting the need for a spatially explicit understanding of water vulnerabilities.

While recent assessments have identified valuable generalized nationwide water resource challenges in Sudan, there remains a critical diagnostic gap regarding how these stressors vary spatially across sub-national administrative boundaries. To bridge this literature gap, this study introduces an integrated spatial-operational framework that moves beyond descriptive overviews. By harmonizing datasets encompassing remote-sensing LULC, precipitation boundaries, water scarcity, and stakeholder perception matrices across ten distinct states. This work provides a novel, empirical spatial classification.

Recent statistics indicate that more than 20% of the Sudanese population continues to drink from unimproved water sources, and 25% use poor-quality drinking water transported from unprotected sources (Haffirs) via donkey carts and tankers (El Sidieget al., 2022). The ongoing war in Sudan further exacerbates access to water (Aderinto & Olatunji, 2023). Water treatment plants, pumping stations, water pipes, and reservoirs have been damaged, either completely or partially, in the states of Gezira, Khartoum, North Kordofan, Sinnar, and Darfur. Workers at water stations have been displaced. The internally displaced people's and refugees' pressure on water demand has been observed in Kassala, River Nile, Northern State, and Red Sea, where water is already inadequate before the war. Additionally, data gaps and the absence of high-resolution spatial information on water challenges remain major obstacles to evidence-based planning, reinforcing the need for field-based mapping and geolocation of these challenges.

Most water challenges in Sudan have not been well identified (Simonin et al., 2023), and a greater percentage of the population remains without access to safe drinking water (Borgomeo et al., 2023). Published literature focused on activities that might best support global achievement of SDG 6, identifying potential barriers to achieve it (Idris et al., 2014),. However, published work on water supply and sanitation in Sudan is scattered and lacks focus on SDG 6.

There is a growing sense of urgency around the need to accelerate the SDG 6 (Aman, et al; 2024; Allen & Malekpour, 2023). To do so, the UN has designed and launched the “SDG 6 Global Acceleration Framework”, which includes five cross-cutting domains: finance, data and information, capacity development, innovation, and governance (Miao., et al; 2023). In this complex, identifying and mapping water challenges becomes a fundamental requirement. Chaet al (2021) mentioned the geographical heterogeneity of Sudan and the inequality of access to safe drinking water and sanitation. There is a significant gap in the spatial distribution of water challenges in Sudan, and previous research often examined water challenges in isolation. While previous studies have isolated either localized stakeholder perceptions or macro-scale environmental data, a significant gap remains in linking these domains. To fill this gap, this study provides a unique methodological contribution by integrating multi-sectoral stakeholder intelligence, GPS field validation points, and remote sensing datasets.

To address this gap, the main objective is to identify, classify, and map critical water challenges across 10 states in Sudan. Three core research questions guide this study:

1. How do water challenges vary across Sudan's 10 representative ecological-economic zones, and how are these challenges perceived across stakeholder groups?
2. To what extent do water quality degradation (salinity) and groundwater perceived intensive extraction spatially intersect to exacerbate water scarcity?
3. Where are the critical "hotspots" requiring urgent intervention to accelerate SDG 6?

This represents the first integration of stakeholder intelligence, GPS field validation, and remote sensing across 10 states. By mapping both "where" (spatial distribution) and "why" (causal mechanisms), this study aims to identify the most serious water challenges and pinpoint their locations to accelerate the achievement of SDG 6 in Sudan. This will determine where interventions can yield greater impact. This study will provide the necessary information for decisive policy action that is crucial for on-the-ground solutions (Evaristo, et al; 2023) and for triggering acceleration (Allen & Malekpour, 2023).

Methodology

Study area

This study was conducted from February 2019 to May 2020. The states involved and stakeholders' distribution were as follows: Gezira (36), Khartoum (34), North Kordofan (33), White Nile (31), Kassala (31), River Nile (29), Gadarif (28), Northern (27), Sinnar (26), and Red Sea (25) (Fig. 1). Table 1, shows the main characteristics of the states selected. We engaged 300 stakeholders, including water supply engineers, state water officials, community leaders, residents, youth, and private sector actors across ten states.

Table 1: The selected states main characteristics

State	Geographic location	Total land area (km2)	Predominant soil type	Primary income-generating activities	Long-term climatic regimes (rainfall, temp, wind velocity)	Key references
Khartoum	15°33' N, 32°32' E	~22,142	Soils: entisols, aridisols (alluvial clay & desert sands)	Industrial manufacturing, commercial trade, civil service, intensive riverine agriculture	Rainfall: 100–150 mm/yr Temp: 16°C (winter) – 45°C (summer) Wind: 3.5–5.1 m/s	Ahmed, et al, (2024).
North Kordofan	13°11' N, 30°12' E	~185,302	Soils: alfisols, entisols (*Goz* stabilized sand dunes)	Traditional rain-fed farming (millet, sesame, gum arabic), nomadic pastoralism (camels, sheep)	Rainfall: 150–350 mm/yr Temp: 14°C (winter) – 40°C (summer) Wind: 3.2–4.8 m/s	Elsiddig et al. (2021); Sharif & Daoud, (2022).
Sinnar	12°58' N, 33°59' E	~40,680	Soils: vertisols (deep, cracking dark alluvial clays)	Large-scale irrigated schemes (sugar, cotton), rain-fed mechanized farming, agropastoralism	Rainfall: 350–600 mm/yr Temp: 18°C (winter) – 42°C (summer) Wind: 2.8–4.2 m/s	Mohamoud, et al, (2019).
Kassala	15°27' N, 36°24' E	~42,282	Soils: aridisols, vertisols (silty deposits along Gash River)	Spate-irrigated horticulture (citrus, onions), mechanized rain-fed farming, transhumant pastoralism	Rainfall: 200–350 mm/yr Temp: 17°C (winter) – 43°C (summer) Wind: 3.0–4.6 m/s	Khalifa, et al, (2025).
Red Sea	19°37' N, 37°13' E	~212,800	Soils: lithic entisols, aridisols (skeletal gravels, saline coastal soils)	Shipping/port logistics, artisanal gold mining, nomadic pastoralism, seasonal spate wadi farming	Rainfall: 25–100 mm/yr (highly erratic winter rain) Temp: 20°C (winter) – 47°C (summer) Wind: 4.2–6.5 m/s	Elsawy, & Lakhouit, (2020)
Northern	19°05' N, 30°28' E	~348,765	Soils: aridisols (hyper-arid desert sands, narrow alluvial river strip)	Riverine terrace pump farming (dates, wheat, pulses), commercial gold mining, cross-border trade	Rainfall: < 25 mm/yr (negligible) Temp: 10°C (winter) – 46°C (summer) Wind: 3.8–5.5 m/s	Abdelwahab, et al, (2009).
Gedarif	14°02' N, 35°23' E	~71,628	Soils: deep vertisols (heavy, fertile basalt-derived dark clays)	Large-scale mechanized rain-fed crop production (sorghum, sesame), cross-border livestock trading	Rainfall: 500–800 mm/yr Temp: 19°C (winter) – 41°C (summer) Wind: 2.5–3.9 m/s	Taha, (2023).
Gezira	14°24' N, 33°31' E	~27,549	Soils: vertisols (highly uniform, swelling riverine clays)	Gravity-fed irrigated mega-agriculture (Gezira Scheme: wheat, cotton, sorghum, groundnuts)	Rainfall: 250–400 mm/yr Temp: 16°C (winter) – 43°C (summer) Wind: 3.1–4.4 m/s	Williams, et al, (2021).
White Nile	13°10' N, 32°20' E	~39,701	Soils: vertisols, entisols (alluvial floodplain clays and fringe sands)	Pump-irrigated agriculture (sugar cane, sorghum), freshwater fisheries, livestock rangelands	Rainfall: 300–450 mm/yr Temp: 17°C (winter) – 42°C (summer) Wind: 3.0–4.5 m/s	Salih, & Hamid, (2017).
River Nile	16°54' N, 33°44' E	~122,123	Soils: aridisols, entisols (desert sands flanking fertile alluvial banks)	Riverine center-pivot and pump agriculture (alfalfa, onions, fruits), cement manufacturing, gold mining	Rainfall: 25–100 mm/yr Temp: 12°C (winter) – 46°C (summer) Wind: 3.5–5.2 m/s	Elmobarak, & Mahgoub, (2014)

Data collection

In each state, the research team spent 7 to10 days conducting structured group discussions to identify the most serious water challenges. We asked stakeholders to identify and describe the challenges they perceived as most severe, providing the initial foundation for field verification. A structured group discussion approach was selected to achieve real-time data verification and build a robust consensus regarding macro-operational metrics. This methodology successfully filtered out point-source anomalies, providing a highly reliable and synthesized data aligned with the study's state-level spatial classification objectives. To capture the operational realities of water challenges across the 10 states, panels of experts in each state ranked the key water challenges, which directly informed the state-level spatial classification

Water quality is indicated by salinity levels using Total Dissolved Solids (TDS). This study focused specifically on a first-order indicator of physical-chemical suitability, rather than a holistic water safety. Saline water was used as a primary, readily accessible screening indicator of water quality, a fundamental prerequisite for community acceptance of water. The water scarcity was indicated by the deficit in water demand. In this study, water scarcity was operationalized strictly as a baseline deficit in water demand to serve as a contextual background for our analysis. A single sample was taken from North Kordofan, Gezira, Elgurashi, and the Red Sea, while two samples were taken from Kassala, Gadarif, Sinnar, Khartoum, and the White Nile. The samples were processed in each state water corporation's laboratories using a digital TDS/EC meter, with salinity measured in ppm

The overarching research design utilized a tri-focal integration matrix. By combining qualitative stakeholder intelligence with quantitative GPS ground-truthing and remote sensing indices, this framework overcame individual data limitations to provide a multi-dimensional characterization of regional water challenges

Data analysis:

Water is described as excellent if TDS <300ppm, good if TDS ranges from 300ppmto < 600ppm, fair when TDS ranges from 600ppm to < 900ppm, poor if TDS ranges from 900ppm to 1200ppm, and unacceptable if TDS ≤ 12000ppm.

The number of wells observed indicated that groundwater was being over-pumped for 24 hours. All the data were validated by the local community involved through focus group discussions and face-to-face questions

Because localized, quantitative hydrogeological datasets were unavailable for the studied areas, this study relied on stakeholder observations to characterize local operational pressures. To maintain technical distinction, reports of 24-hour continuous pumping were interpreted strictly as indicators of high-intensity operational behavior and perceived extraction pressure by the community, rather than verified physical aquifer overdraft.

Quantitative data from stakeholder discussions were entered and processed using SPSS version 20. Descriptive statistics was used to summarize the prevalence of identified water challenges across states, and correlation analysis was conducted to examine significant relationships among scarcity, salinity, and over-pumping. A significance level of $p < 0.05$ was adopted for all tests. To validate community data, water salinity was analyzed across the study areas. These states represent major hydrological and socio-economic zones with differing levels of water stress.

Geospatial analysis was undertaken by converting geospatial analysis which was undertaken by importing GPS-collected point coordinates into ArcGIS version 10.8 and converting them into point shape files. All GPS data were projected to the WGS 84 datum, UTM Zone 36N, to ensure spatial consistency with national geospatial datasets. The processed point layers were then quality-checked, overlaid with relevant spatial layers, and integrated into the national GIS database for subsequent spatial analysis to visualize the spatial distribution of water challenges, identify hotspot areas, and highlight states where interventions would generate the greatest impact (Hagr, et al; 2025).

The points were used as baseline ground-truth markers to anchor state hydrochemical parameters (TDS) within expected uniform-state aquifers.

The actual geospatial classification in ArcGIS involved a comprehensive spatial overlay analysis of multiple independent, continuous regional datasets mapped across the 10 states: State precipitation datasets were integrated to map regional climate zones, LULC spatial layers mapping, water scarcity, and georeferenced multi-sectoral stakeholder perception

We made the following correction:

The geospatial analysis of this study relied on a multi-criteria spatial overlay framework within ArcGIS, rather than simple point-source mapping. Spatial data layers were analyzed across Sudan's ten states: macro-climatic precipitation, LULC dynamic polygons, administrative state boundaries embedded with water scarcity, and stakeholder operational matrices.

We utilized the Google Earth Engine (GEE) cloud-computing platform for efficient geospatial data acquisition and processing (Gorelick., et al., 2017). Land Use/Land Cover (LULC) classification was derived from the ESA WorldCover v100 dataset at a 10 m spatial resolution (ESA, 2021), encompassing 11 discrete classes (e.g., cropland, forest, and bare land).

To analyze hydro-climatic conditions, long-term precipitation climatology (2000–2023) was computed using CHIRPS Daily data (Funk et al., 2015). The mean annual precipitation was calculated as follows:

$$\bar{P}_{2000-2023} = \frac{1}{24}\sum_{t=2000}^{2023} P_t$$

Where:

$\bar{P}_{2000-2023}$ is the long-term mean annual precipitation.

P_t represents the total annual rainfall for each year t.

Final spatial integration with field-based GPS observations, cartographic design, and multi-panel layout optimization were executed in QGIS 3.34 (QGIS Development Team, 2024), maintaining strict- georeferencing consistency within the WGS84/UTM Zone 36N projection.

These steps are presented conceptually in Fig. 2.

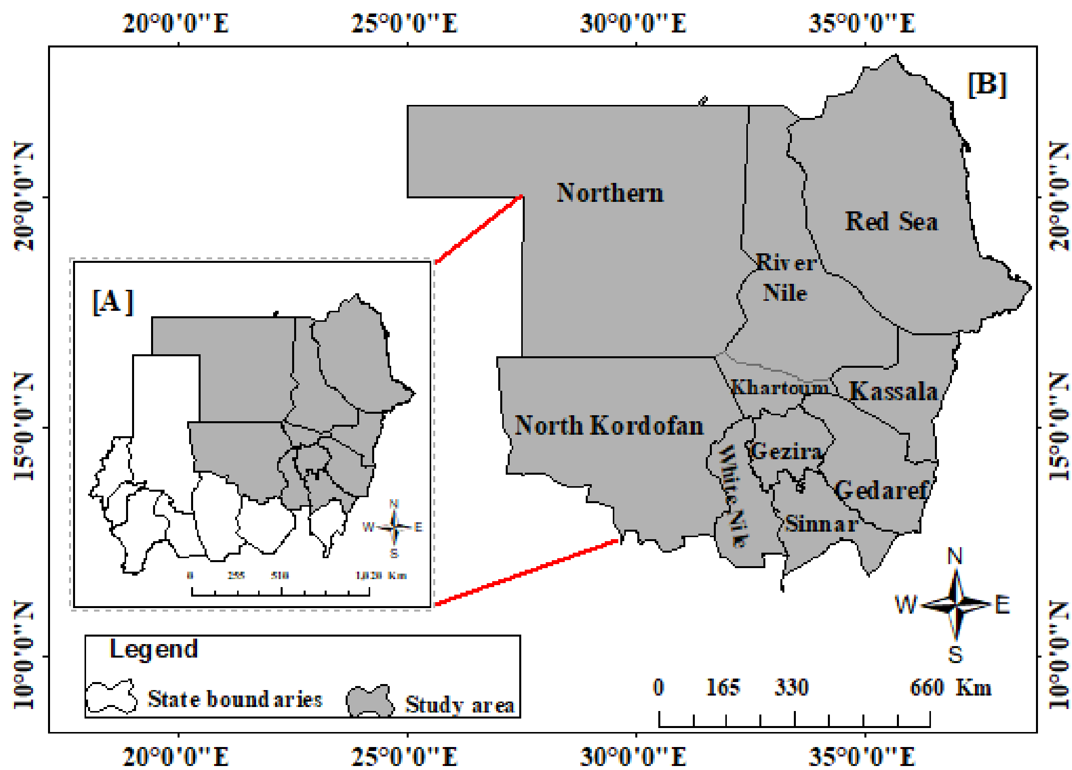

Fig 1. Maps of [A] location of the study area in Sudan, [B] study area

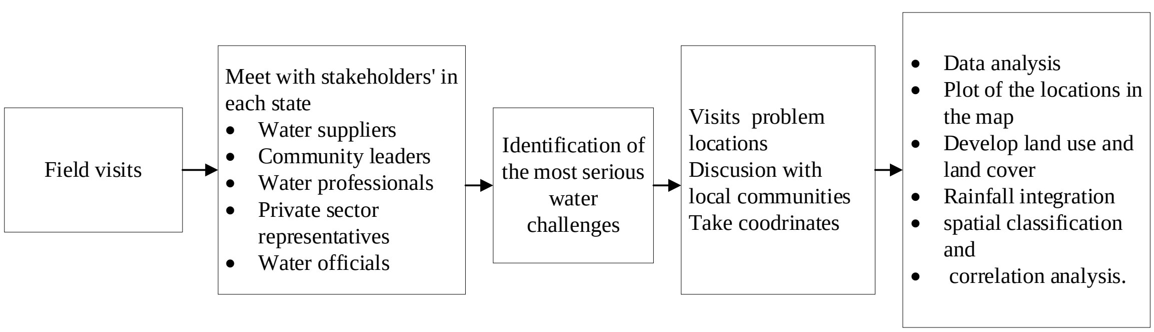

Fig 2. Graphical representation of the methodology steps

Results

The findings of this study show the spatial distribution of water challenges across the studied states. The data reveal a significant regional gap. This spatial disparity highlights that water vulnerability in Sudan is highly localized and strongly dictated by regional hydrogeological boundaries.

The water scarcity was indicated by the deficit in water demand and validated by the local community, who confirmed the presence of water scarcity in North Kordofan, White Nile, Gadarif, Kassala, and Red Sea states (Table 2, and Fig. 3A). The states of Sinnar, Gezira, and Khartoum were identified as water-rich states. The water deficit % represents quantitative secondary data retrieved directly from the state's Water Corporations. The stakeholder insights were used to validate these water scarcity issues.

Water quality in this study is indicated by salinity levels in water. Results have shown that the Red Sea, Kassala, North Kordofan, Gadarif, the White Nile, and Gezira are the states with very high salinity. Water salinity is described high in Khartoum, while in Sinnar, salinity levels are normal (Table 3) (Fig. 3B). Over pumping of groundwater was observed in some of the investigated states. Over-pumping of ground and shallow water indicates mismanagement and inefficient use of water resources. A greater percentage of stakeholders confirmed over-pumping of groundwater and shallow water in North Kordofan, Gadarif, Kassala, River Nile, and Northern state (Table 4) (Fig 3C).

The study has found out that North Kordofan, White Nile, Gedarif, Kassala, and Red Sea share the same water challenges, including very high salinity, water scarcity, and over-pumping of groundwater (Fig. 4).

Rainfall integration map (Fig 4) reveals distinct geographical and climatic divisions in Sudan's water landscape. A greater part of the study area (about 60%) of North Kordofan, Sinnar, Khartoum, Kassala, Red Sea and Northern states falls within the states receiving less than 432mm of annual rainfall. The land use and land cover (LULC) for the study area illustrates the transition from the arid Saharan in the north to the more fertile, semi-tropical savannah states in the south (Fig 6.).

Table 2: Water scarcity in the selected states

State	Water status	Water deficit %	Stakeholder confirmation (%)	Confirmation level
Sinnar	water-rich	21%	100%	universal
Gezira	water-rich	11%	100%	universal
Khartoum	water-rich	9%	100%	universal
North Kordofan	water-scarce	81%	100%	universal
Red Sea	water-scarce	46%	100%	universal
White Nile	water-scarce	20%	86.7%	high
Kassala	water-scarce	62%	83.3%	high
Gadarif	water-scarce	45%	73.3%	majority

Table 3: Salinity levels in different states

Salinity classification	States affected	TDS ppm	Description	Stakeholder confirmation
very high	Red Sea	≤ 17000	unacceptable	96.7%
	Kassala	1900-2600	unacceptable	53.3%
	North Kordofan	686.5	fair	50%
	Gedarif	2500 - 2730	unacceptable	66.7%
	White Nile	2900 - 3300	unacceptable	70%
	Gezira	7000	unacceptable	88.7%
high	Sinnar	503 - 721	fair	80%
normal	Khartoum	75–141	excellent	66.7%

Table 4 Overpumping of groundwater

State	Indicator	Stakeholder confirmation
North Kordofan	About 150 shallow wells, traditionally operated, produce about 900,000 m3 per day from Bara Basin	100%
Gedarif	About 200 shallow wells and deep wells pumped water for irrigating fruits	93.3%
Kassala	The drawdown in the Gash River aquifer reached 7 m in some places during the last 30 years	73.3%
Northern State	17 wells pumped about 156,672 m3 per day.	66.7%
River Nile	20 wells pumped about 156,000 m^3 per day	43.4%

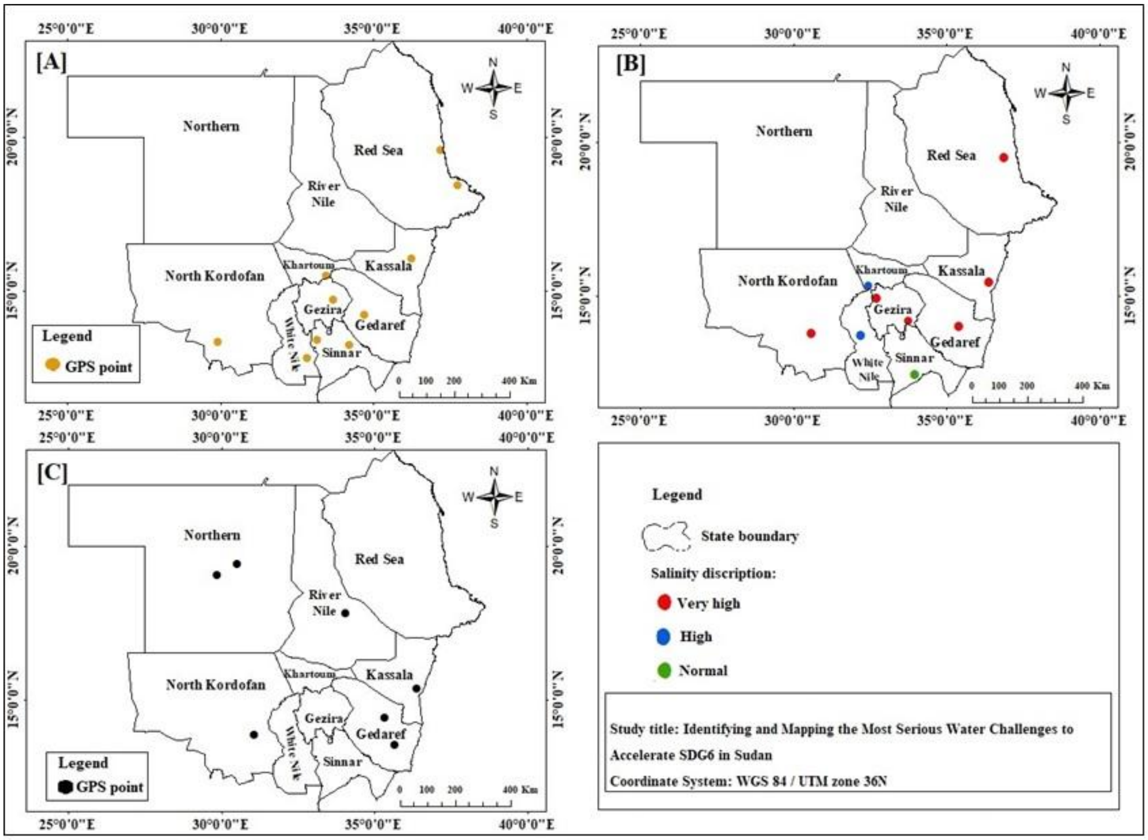

Fig 3: Maps of: [A] water scarcity, [B] salinity, and [C] over-exploitation of groundwater

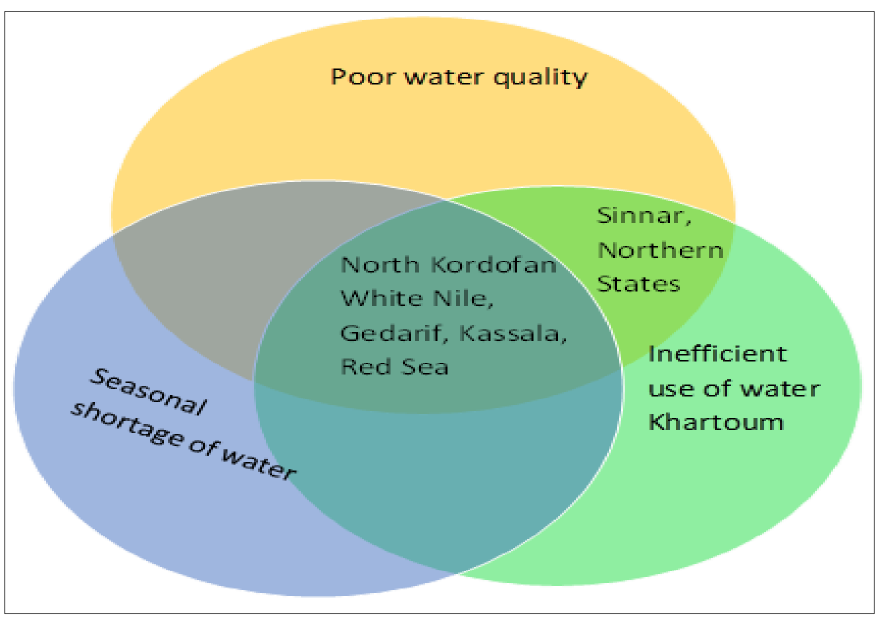

Fig 4. States with similar water challenges

The study investigated a positive correlation between poor water quality/ salinity and water scarcity (r .319, P < .001), between perceived intensive extraction of groundwater and water scarcity (r .198, p

< .001) and between perceived intensive extraction of groundwater and water salinity (r .161, p < .005) (Table 5). The results show that as salinity increases, water scarcity increases. Increased pumping is associated with greater water scarcity and also associated with higher water salinity, which may be due to saltwater intrusion from the Red Sea, as in the Red Sea Stat

Table 5: Correlation between perceived intensive extraction of groundwater and water scarcity

Relationship	coefficient (R)	P-value (P)
Salinity and water scarcity	0.319	< .001
Perceived intensive extraction of groundwater and water scarcity	0.198	< .001
Perceived intensive extraction of groundwater and salinity	0.161	< .005

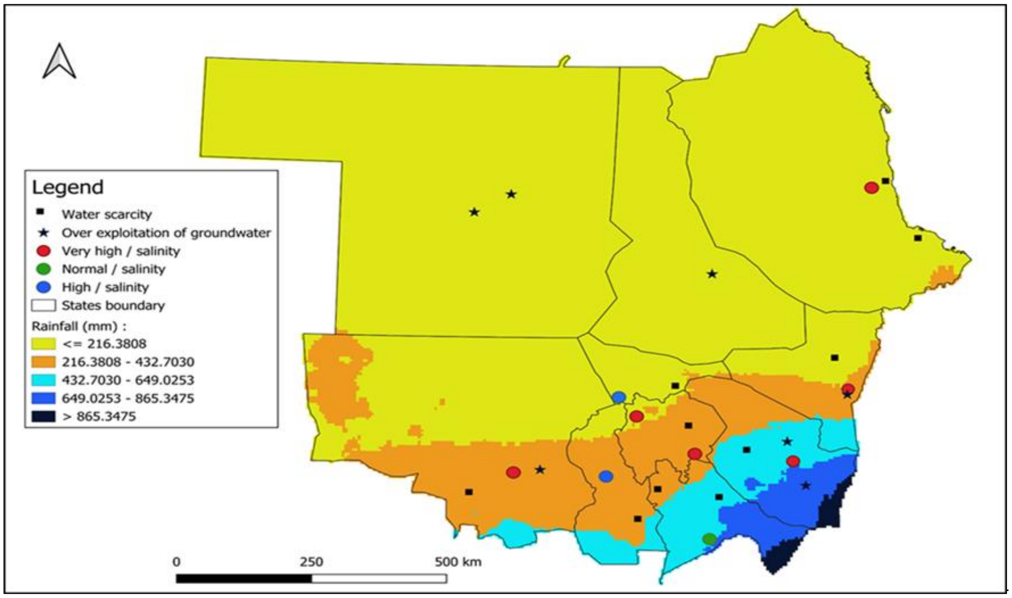

Fig 5: Integration of rainfall, water scarcity, water quality and water overuse

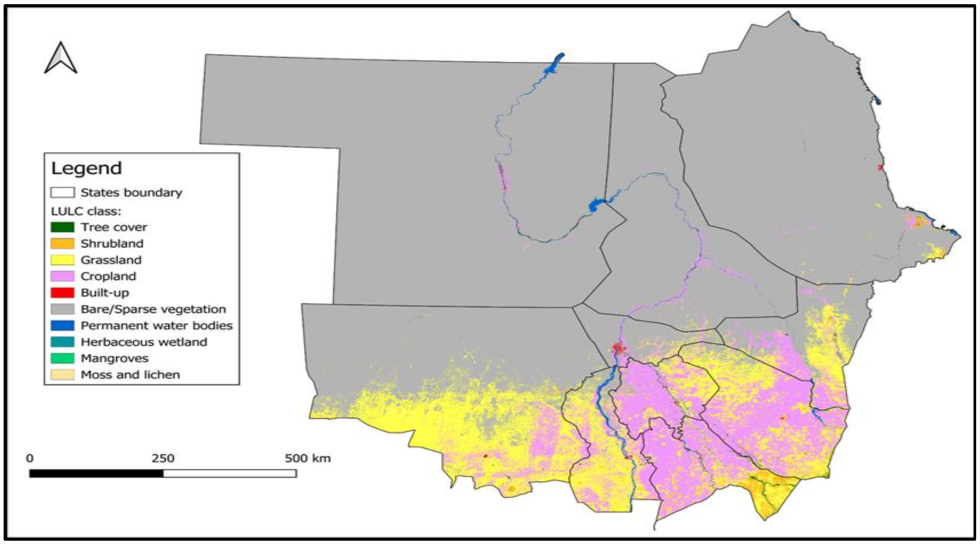

Fig 6: Land use and land cover 2023.

Discussion

Sudan's progress toward SDG 6 is severely affected by a nexus of water scarcity, deteriorating quality, specifically rising salinity, and the unsustainable over-extraction of groundwater. While erratic rainfall and climate-driven droughts diminish surface water availability, high salinity levels in central and eastern regions further degrade existing supplies, challenging national water security and long-term sustainability. In Sudan, despite the "relative" abundance of multi-sourced water quantities, yet the spatiotemporal variations adversely affect water availability and accessibility to the population majority in various arid and semiarid parts of the country (Adam, & Osman, 2024). Bare vegetation is dominant in the northern and northwestern states, including the Northern State, North Kordofan, the River Nile, Kassala, and Red Sea states. These states have little to no rainfall, resulting in bare vegetation. Cropland and grassland are sharply following the path of the Nile River moving north. These represent the vital irrigated agricultural schemes like the Gezira Scheme. In the south and southeast, there is extensive rain-fed farming, concentrated in Gezira, Sinnar and Gadarif.

Water scarcity

Water scarcity is widespread across Sudan. It is the single biggest water problem worldwide (Jury & Vaux Jr, 2005). In most cases, the scarcity is related to the specific state's geographical location. Water deficit hampers achieving socioeconomic development, especially in the concurrent climate change, large-scale transboundary river damming, conflicts over water resources, growing population, and economic contexts (Adam, & Osman, 2024). The ongoing conflict and the resulting influx of internal refugees introduce significant variables that may influence water demand patterns and resource pressures.

The results reveal distinct geographical and climatic divisions in Sudan's water landscape. We overlaid rainfall zones with specific water quality and quantity indicators. The results have identified hotspot zones that require immediate action to accelerate SDG6. A greater part of the study area (about 60%) of North Kordofan, Sinnar, Khartoum, Kassala, Red Sea and Northern states, receives less than 432mm of annual rainfall. This indicates a high reliance on non-renewable or transboundary water sources. The fact that 60% of the study area (North Kordofan, Sinnar, Khartoum, Kassala, the Red Sea, and Northern states) receives less than 432 mm of annual rainfall establishes a baseline of permanent meteoric water scarcity. In sub-Saharan hydro-climatology, the 400–450 mm isohyet represents a critical biophysical threshold. Rainfall increases significantly toward the southeast, exceeding 865mm. This region has higher potential for surface water and rainwater harvesting (RWH), yet faces different challenges like seasonal flooding. Water scarcity challenges are predominantly found in the central and western states, such as North Kordofan and Sinnar states. Scarcity here is likely a combination of low rainfall and lack of storage infrastructure.

North Kordofan is located in western Sudan, with a climate ranging from desert to semi-desert (Deafalla et al, 2014). Annual rainfall varies from 150 mm to 600 mm (Hinderson, 2004). The temperature ranges from 45 °C in summer to 11 ^{0}C in winter (Idris et al., 2014). Basement Rocks cover about 60% of the state area (Mohammed, 2017). Therefore, the state is experiencing acute water scarcity because of a lack of surface and groundwater. Water harvesting *(haffirs)* was traditionally designed to store unimproved water, and used by both humans and animals. The long-term climate change impact poses a challenge to predicting future water availability.

The results show that access to clean water is crucially low in North Kordofan State. The gap in water availability is 81% as confirmed by 100% of the state stakeholders. Funding gaps to establish new water sources further hinder the progress of SDG 6 (Aman, Hamidullah, Doost, Ziaul Haq, Hejran, Abdul Wali, Mehr, Ali Danandeh, Szczepanek, Robert, Gilja, 2024)

The White Nile State is dominated by the floodplain of the Nile Valley and the flat alluvial fan created by the seasonal *Khor Abu Habil (Said, 2013)*. The state is characterized by climate diversity between the rich and poor savannah (Abdelhalim, Finckh, Babiker, Oehl, & Science, 2014). Rains occur in July to September, ranging from 200 mm to 600 mm (Salih et al., 2017). The state lies on deep basement rocks. The only perennial surface water is the *Khor Abu Habil*, and numerous other subsidiary *khors* are filled during the rainy seasons. The flow just enters the western part of the state, reaching *Tendelti* and *Karmel*. The White Nile state is a water-scarce region. The gap in water needs is about 20% as confirmed by 86.7% of the respondents. So a greater percentage of the population remains without access to safe drinking water (Borgomeo et al., 2023). People travel a long distance of 6 km to bring water from shallow wells. There is no groundwater; however, the population depends on subsurface water harvesting under high evaporation challenges. The water harvesting lasts for less than 2 months and is used by both humans and animals.

In Gadarif, water shortage is a normal phenomenon (Abdo, 2022). The community is suffering from a shortage of water because of the basement rock. The gap in water availability is 45%. This fact was confirmed by 73.3% of the stakeholders. The community depends on rainfall and *Khor Abu Farga*. People buy water at prices ranging from 100 to 150 SDG per barrel (equivalent to 2 to 2.25 USD at the time). Recently, the government has been attempting to supply water from the *Setait* dam to Gadarif city, which may realize SDG 6 as on-the-ground solutions are essential (Evaristo et al, 2023).

The water deficit is 62% as 83.3% of the stakeholders confirmed water scarcity. In the northern part of Kassala, the villages of more than 20,000 people suffering from water shortage. The shortage of water lasts 6 months from December to June every year. Now people are digging individual shallow wells of 15-meter depth on the Gash-flow zone. Other residents buy water from other places at 35 SDG per barrel. Groundwater in arid and semi-arid regions like Kassala faces growing threats from over-extraction, limited recharge, and climate change (Almahi, Lü, & Zhu, 2025). Kassala is one of the states facing compounding pressures from water scarcity, pollution, climate change, and inadequate infrastructure (Salama, 2025) and therefore, Bashier & Abdelrahman (2025), suggested the establishment of a new water source and a reduction of groundwater extraction as sustainable solutions for water challenges in Kassala, east Sudan.

Water shortage in the Red Sea State represents 46%. All stakeholders (100%) supported this result. Rainfall in the Red Sea state is 50 mm to 300 mm during the wintertime (October to March).

Average temperature during summer reaches about 38°C and about 20°C during winter, and humidity ranges from 50% to 80%. Port-Sudan town and its surrounding areas depend mainly on surface water from the *Khor Arbaat* seasonal valley, which is located about 35 km north-west of the town. The Red Sea is the coastal state, particularly Port Sudan. Climate change is real, as indicated by the variability of the rainfall. The Port-Sudan area is considered one of the most vulnerable areas along the Red Sea coast of Sudan in terms of shortages in water supply (Elsheikh & Elsayed, 2015). Some households have no water at home.

Sinkat is located in the basement rock in a desert zone. No other sources of water except rainfall. No water harvesting efforts took place to improve water resources because landholders refused to establish any water infrastructure on their lands. In addition to salinity, most of the water challenges came from water pollution due to unprotected *hafirs* and dam siltation (Ahmed, 2024). In Sudan, water scarcity has resulted in increasing school dropout rates, especially among girls, who help their families in fetching water for both human and animal consumption, which, in the long run, affects the household economy by jeopardizing the rural household's human capital (Sabbil et al, 2022). Although there is an acute paucity in water quality data in most countries in SSA, evidence suggests that water quality is a critical and growing challenge to water security in the region (Nkiaka et al, 2021). However, water quality has historically received comparatively less attention despite its critical role in achieving sustainable water outcomes (Salama, 2025). Generally, as in many countries in SSA, ongoing conflict, political instability, and inadequate infrastructure severely affect implementation efforts of SDG6 in South Sudan (Duku, & Malek, 2024).

Saline water

The quality of water is considered one of the world's major challenges, particularly in low-income countries under the ongoing war. Poor-quality water remains a major public health risk in Sudan (Musa, Shears, Kafi, & Elsabag, 1999). Salinization is a global problem that degrades water quality, impairs the use of freshwater resources for human purposes, and threatens agricultural production and aquatic ecosystems (Flörke, Bärlund, van Vliet, Bouwman, & Wada, 2019). Approximately 32% of the population drinks unsafe water from unimproved sources (Yasin, 2024). Saline data serves as an entry point for identifying areas at risk of high mineralization, which can act as a stepping stone for targeted, full-spectrum SDG 6 monitoring pipelines.

Salinity is high and very high in the central, eastern, and northern states. This severely limits the usability of available water for both drinking and agriculture without expensive treatment. Salinity in the states of the Red Sea, Kassala, North Kordofan, Gadarif, the White Nile, and Gezira is very high and described as unacceptable, while salinity in Khartoum is high, and in Sinnar is normal.

In the White Nile State, high salinity of groundwater significantly ($P < .001$) causes water shortage. TDS in water ranges from 32900 ppm to 3300 ppm. More than 1000 people are suffering. Because of high salinity, 13 villages depend on shallow hand-dug wells, which are unsustainable under a changing climate. The water sources (shallow wells and *haffirs*) are 6 km from the village. Industrial waste is drained without treatment onto an empty land towards the White Nile. Waste water accumulated in open 6 ponds of 7600 m^2. The waste is near both agricultural land and the source of the waste. Unfortunately, the environmental law to manage the waste is not enforced.

The major water problem in Gadarif State is salty water because of the basalt zone, where wells were dried out and produced very salty water. Water is scarce during the summer time every year, and still people are using tankers and donkeys to bring water from far areas. Some of them use direct raw water from the Atbera River. Salinity in Gadarif significantly ($p < .001$) affects water scarcity. In Gadarif, total dissolved solids (TDS) vary from 250 to 2730 ppm. Salinities above 2000 ppm are encountered in the basalt aquifer and in some pockets within the sandstone aquifer (Hussein & Adam, 1995).

The Red Sea State is the most saline zone in Sudan (TDS $\leq$ 17000). Saline water in the state significantly affect water availability. Seawater intrusion into wells, causing high salinity, is the main water problem in Port Sudan city. Red Sea water mixes with groundwater at the base of alluvial sediments during pumping. This intrusion extends up to 7 km inland from the Red Sea coast. It causes high salinity in wells, and some wells have been closed because of high TDS. Poor water quality is widespread throughout the Red Sea State due to salts from the Red Sea and pollution from humans and animals. Still, open defecation and unhygienic practices constitute a major problem in the eastern part of Sudan. Sea water intrusion has affected the proper operation of hand pumps.

Over-pumping of shallow and groundwater

Over-exploitation of groundwater is concentrated in the northern and central states of the Northern, River Nile, North Kordufan, and Gezira states. This suggests that extraction rates for irrigation and domestic use exceed natural recharge, threatening long-term sustainability (SDG 6.4).

The unsustainable management of water resources in many regions has led to numerous environmental challenges related to water, some of which include water scarcity, increased pollution of water bodies, depletion of surface water and groundwater resources (Nkiaka et al., 2021). Intensive groundwater extraction practices are prevalent in various countries, which endangers local ecosystems (Monaco, 2024).

Sudan is dependent upon groundwater aquifers for its supply of water, both for human consumption and irrigation (Omer, 2002). However, problems such as overexploitation, the reduction of reliable yield, and the deterioration of quality have been observed (Abdo et al., 2012)

In North Kordofan State, the serious problem is excessive pumping of groundwater by farmers. The farming system is the only economic activity to generate income for the community besides animal grazing. The Farmers are pumping shallow water extensively to grow vegetables and fruits. There is no monitoring system for the groundwater and nobody knows what the extraction level is.

Drawdown of shallow wells caused by excessive pumping by farmers is the main water problem in Kassala state. Farmers grow water-consuming crops like oranges, grapefruit, bananas, onions, and alfalfa. Now, there are more than 4,000 small agricultural schemes in the state that use shallow wells for groundwater. The drawdown in the aquifer has reached 3m to 7m over the last 30 years. Decades of unsustainable exploitation of groundwater have led to acute degradation of groundwater quantity and quality, creating pressing challenges (Cooper & Hiscock, 2025)

The same excessive groundwater pumping in agriculture is happening in the Northern state. There are more than 20 agricultural schemes with a total area of 130,000 acres. The agricultural area consumes 156,672 m^3 per day. The state water corporation has recorded that the drawdown in groundwater level ranges from 3 m to 6 m in *Elgolid* town.

In the River Nile state, Investors grow a large area of 20,000 acers with groundwater to irrigate alfalfa and wheat crops. They were pumping 156,000 m3 per day without any control over the groundwater level. These inappropriate pumping rates influence water level in shallow wells, resulting in high drawdown and low well efficiency (Mohammed et al, 2023).

Over-pumping of groundwater indicates a problem of abstraction exceeding sustainable yield, likely leading to rapid water table decline and potential dry wells, causing acute water scarcity. Stakeholders confirm unsustainable abstraction of groundwater driven by the expansion of agricultural schemes without adequate monitoring. The problem may be exacerbated, particularly in the North Kordofan State, where there are no alternative water sources. Over-pumping has potential impacts on both the quantity and quality of water available for multiple uses.

Correlations between water challenges

The study investigated a positive correlation between poor water quality/ salinity and water scarcity and between perceived intensive extraction of groundwater and water salinity. This is because excess withdrawal of groundwater has resulted in depletion of the groundwater level (Pophare et al, 2014). Khorrami, M. and B.J.S.o.t. T.E. (Khorrami & Malekmohammadi, 2021) found that the declining trends of groundwater level have had a negative impact on the groundwater quality. They investigated that about 56% dug wells showed a positive correlation between depleting groundwater level and rising EC values. Salameh (2008) found that the present impacts on the groundwater itself are manifested in the drop in groundwater levels, saltwater intrusions, and deteriorating water quality. These relationships might be influenced by dynamic shifts in land cover, which may reduce ecosystem water yield.

While the correlation coefficients among baseline salinity, extraction patterns, and state-level water deficits are statistically significant, their mathematical magnitudes remain low to moderate. In broad, national hydro-geological and water governance frameworks, these low-magnitude correlations are standard and highly interpretive. They reflect the inherently non-linear, multifactorial nature of ambient water security, where physical geogenic signatures, structural supply infrastructure gaps, and local user behaviors interact simultaneously. The fact that these values are statistically significant confirms that a true, structural link exists across the studied states; however, their low absolute values demonstrate that no single indicator operates in isolation. This systemic complexity reinforces the necessity of adopting an integrated, multi-indicator diagnostic study

Policy implications

The identification and spatial mapping of Sudan's most serious water challenges offer a clear and compelling message: achieving SDG 6 will only be possible if interventions are targeted, evidence-based, and directed toward the places that need them the most. The maps reveal clusters of severe scarcity, rising salinity, and excessive groundwater extraction, showing that water insecurity does not affect all regions equally, but is concentrated in specific, high-risk areas. These insights have several important implications for policy and practice.

First, national water planning must move beyond broad, uniform strategies and adopt a more place-based approach. Hotspot regions such as North Kordofan, White Nile, Kassala, Gedarif, and the Red Sea states should be prioritized for investments in water infrastructure, groundwater recharge initiatives, salinity reduction measures, and climate-resilient supply systems. Directing limited resources to these critical zones can yield far greater impact than spreading them thinly across the country.

Second, the widespread presence of unsafe or poor-quality drinking water underscores the urgent need to strengthen water-quality monitoring. Establishing a national surveillance system, supported by reliable testing, reporting, and law enforcement, is essential. Clearer rules and stronger oversight, particularly concerning wastewater discharge and agricultural chemicals, would help reduce public-health risks that many communities currently face.

Third, the fact that multiple water challenges often occur in the same locations highlights the need for genuine integration across sectors. Implementing an effective Integrated Water Resources Management (IWRM) approach would enable water, agriculture, health, and environment authorities to coordinate their actions. Aligning national efforts with the SDG 6 Global Acceleration Framework, including its focus on data, governance, innovation, capacity, and financing, would help bring coherence to interventions and reduce duplication of effort.

Finally, the evidence produced by this study provides a practical foundation for more strategic decision-making. It can guide government agencies, NGOs, and development partners in directing resources where they are most urgently needed, designing context-appropriate solutions, and supporting vulnerable communities more effectively. By responding to these spatially identified challenges, Sudan can make meaningful progress toward SDG 6 and move closer to ensuring that every person has sustainable and equitable access to safe water for all.

Specifically, investments must shift from simply digging wells to providing water treatment technologies (desalination/filtration) in high-salinity zones. Agriculture in the central and northern belts must transition to efficient irrigation (drip/sprinkler) to halt the depletion of aquifers. Areas with <216mm rainfall are entirely dependent on the Nile or shared aquifers. This necessitates strong transboundary diplomacy and integrated management to prevent local conflicts over dwindling resources. In remote scarcity zones, centralized infrastructure is often absent. Progress relies on community-led Rainwater Harvesting (RWH) and local management committees.

The Southern states have the rainfall volume to support large-scale rainwater harvesting. Policy should focus on socioeconomic support and community participation to build resilient storage facilities that bridge the gap during the dry season.

Limitations

The ongoing conflict and the resulting influx of internal refugees introduce significant variables that may influence water demand patterns and resource pressures. These demographic shifts may affect the stability of the data and its long-term applicability. While the study prioritized actionable interventions, persistent financing challenges may hinder the immediate implementation of the proposed water solutions. With a sample size of 300 stakeholders, the findings may not be fully representative of the national landscape. While the data provides a robust local snapshot, the state-specific focus constrains the generalizability of these findings across Sudan's diverse national landscape. The inherent uncertainty in long-term climate change projections poses a challenge to predicting future water availability with absolute precision. The study acknowledges that rapid land-use changes alter evapotranspiration rates. These shifts in land cover may reduce ecosystem water yield, a variable that remains dynamic and may influence the observed relationship between water scarcity, salinity, and overuse of water.

While Total Dissolved Solids (TDS) serve as a valuable, high-feasibility proxy for gross mineralization and aesthetic palatability, it represents only one facet of water quality. A comprehensive assessment under the SDG 6 framework requires multi-parameter monitoring. TDS does not capture acute microbial contamination (e.g., E. coli), specific heavy metals or synthetic chemical pollutants, nor does it quantify water resource scarcity or volumetric sustainability. Consequently, the macro-scale data presented here should be interpreted strictly as a preliminary screening mechanism to flag salinity zones, highlighting areas where comprehensive, multi-indicator water quality testing is urgently required

Conclusion

This study provides a spatially explicit, evidence-based assessment of Sudan's most critical water challenges, offering new insights into how water scarcity, deteriorating water quality, particularly salinity, and unsustainable groundwater extraction interact across different regions of the country. By integrating stakeholder perceptions, GPS-based mapping, and statistical analysis, the study moves beyond generalized assessments to identify where water challenges are most severe and closely interconnected.

The findings demonstrate that water scarcity is the dominant national challenge, intensified by high salinity and uncontrolled extraction of groundwater and shallow water. North Kordofan, the White Nile, Kassala, Gadarif, and the Red Sea State emerge as key hotspots where multiple water stresses overlap, resulting in reduced access to safe drinking water, declining groundwater levels, and deteriorating water quality. In these areas, salinity limits domestic water use, while excessive pumping accelerates aquifer depletion and increases vulnerability to contamination and saline intrusion.

From a scientific perspective, the study confirms that water scarcity, salinity, and groundwater overexploitation are mutually reinforcing processes rather than independent problems. By clearly identifying priority regions and dominant water challenges, this research directly supports efforts to accelerate progress toward SDG 6. Decisions towards achieving SDG 6 should focus on the most serious challenges of water scarcity, quality, and overuse. Investing resources towards bridging identified water challenges will contribute to achieving all SDGs. The spatial evidence generated provides a practical foundation for targeting interventions, prioritizing investments, and promoting sustainable water management strategies that enhance water security and equitable access to safe water in Sudan. Spatially identified challenges of water in Sudan will support efforts to achieve SDG 6. Water challenge identification and mapping provide a practical foundation for more strategic decision-making. It will guide the efforts of stakeholders and partners on where to invest resources towards achieving the SDGs. The study confirms that Sudan's water challenges are not just about water scarcity but a geographic mismatch between quality, quantity, and demand. Accelerating SDG 6 requires a localized approach: treating salinity in the center and east, managing demand in the north, and harvesting the abundance in the southen part of the country.

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Competing Interests

The authors declared no conflict of interest

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