WORKING PAPER

Water Data for Sudan’s Water, Food, and Environmental Systems

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Front cover photo: Front cover photo: Small water pond near a rural community in Gedaref State, Eastern Sudan (*photo*: Muhammad Khalifa)
Back cover photo: Agricultural landscapes in Gedaref State, Eastern Sudan (*photo:* Muhammad Khalifa).

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Context

In fragile and conflict-affected regions, one of the key challenges confronting humanitarian efforts is the ability to assess and address water availability. This challenge is compounded by limited data availability and restricted physical access, which hinder both immediate relief planning and design of long-term development interventions. In such a context, data derived from public-domain datasets (including remote sensing) that construct baseline information of biophysical variables and deviations for the landscape could be an effective solution. This issue brief reports on a data analysis conducted for Gedaref, Kassala, and White Nile: three major displaced persons-hosting states in Sudan. The main aim is to build and analyze public-domain datasets—including precipitation, evapotranspiration, land cover, vegetation productivity, drought patterns, and surface water extent—to enable researchers, humanitarian actors, and policymakers to identify priorities and entry points to improve water, food, and environmental security. The analysis aims to provide guidance for effectively responding to immediate crisis needs, and plan and foster long-term sustainable solutions. Elements of this approach can inform early assessments in other fragile and conflict-affected settings facing similar data limitations. This can build spatial and temporal understanding of biophysical conditions to guide humanitarian and development actors in more effectively targeting areas and interventions.

In addition to supporting immediate operational planning, this analysis contributes to anticipatory and risk-informed decision-making. By combining long-term historical climate records with near-real-time satellite observations, it enables both retrospective assessment as well as forward-looking screening of emerging hotspots. This is particularly relevant in displacement settings, where settlement patterns, water demand, and livelihood strategies may shift rapidly in response to climate or security dynamics. The structured use of harmonized, openly accessible datasets reduces dependency on intermittent field missions and allows for regular updating as new observations become available, strengthening adaptive planning capacity.

1. Background and Objectives

Sudan today faces compounding crises of fragility, climate change, conflict, and displacement. These have disrupted essential resource systems and livelihoods of millions of people (UNHCR 2025a). Across the country, the pressures of conflict, climate extremes (e.g., drought, floods) and environmental degradation intersect with growing humanitarian needs. In the eastern and central regions—particularly Gedaref, Kassala, and White Nile States (Figure 1)—Internally Displaced Persons (IDPs), refugees from neighboring countries, and local host communities live under threats of climate extremes, along with the pressure of poor services and limited resources to rely on (Saleh et al. 2024). Moreover, an additional challenge is the significant funding gap of nearly 72% (more than USD 300 million) of the estimated funds required to address the needs of the immediate crises (UNHCR 2025b).

This convergence of climatic stress and displacement has intensified competition over water, land, and ecosystem services, increasing pressure on already fragile natural resource systems. In many locations across the country, seasonal water shortages, declining vegetation productivity, and land degradation exacerbate social and economic vulnerabilities, reducing adaptive capacity among both displaced populations and host communities.

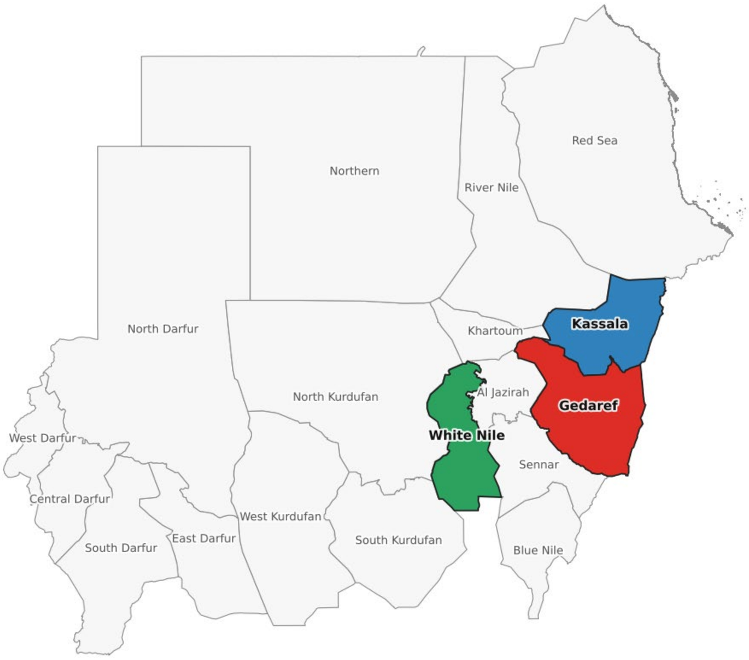


Figure 1. Map of Sudan's States, highlighting Gedaref, Kassala and White Nile States considered in this project. *Source:* Map produced by the authors using DIVA-GIS datasets.

Humanitarian actors usually respond to immediate needs, yet the scale and persistence of these challenges call for a deeper understanding of the underlying biophysical systems that sustain life and livelihoods. In this context, data-driven analysis becomes essential. However, in such fragile and conflict-affected areas, data scarcity, fragmented spatial coverage, and limited field access often hamper planning and coordinated actions. These conditions make it challenging to plan crisis relief and foster sustainable recovery efforts and long-term plans. Using public-domain datasets to develop a preliminary understanding of natural resource systems in displacement-affected regions is a useful and supportive approach which provides a foundation for more advanced modelling of natural systems. Outputs of analyzing these datasets help shape the effective response on the ground that can foster long-term resilience building and extend beyond immediate crises relief.

Against this backdrop, the International Water Management Institute (IWMI), in collaboration with the Alliance of Biodiversity International and the International Center for Tropical Agriculture (CIAT), are implementing a joint initiative under the CGIAR–UNHCR partnership in Sudan. The initiative seeks to identify practical entry points and create operational and sustainable solutions to strengthen water, food, energy, and environmental security amid ongoing fragility and conflict in Sudan, and to foster long-term resilience reaching beyond immediate crisis relief.

IWMI has extensive experience in addressing data gaps by leveraging digital innovation, including remote sensing, to support system analysis and evidence-based decision-making. Such interventions include assessment of the accuracy of remote sensing data (Mekonnen et al. 2023), hydrological modelling (Tarkegn et al. 2025), water accounting (Karimi et al. 2013; Mahapatra et al. 2024; Owusu et al. 2025), assessing climate extremes (Bergaoui et al. 2024; Obahoundje et al. 2024), assessing crop and land productivity (Hussain et al. 2003), and assessment and tools that help governments and humanitarian actors plan more effective and climate-informed interventions (Mekuria et al. 2024).

At the outset of this work, the use case for this project was codefined with UNHCR to support three specific applications: (i) identifying priority locations for improving water interventions around displacement sites across Gedaref, Kassala, and White Nile States; (ii) assessing land and vegetation conditions that influence food production, livelihoods and settlement planning;

and (iii) understanding exposure to climate risks that affect displaced persons and host communities. This brief presents results for three use cases, showing how these data layers can inform biophysical assessments and support both effective resource allocation and early recovery planning where ground access is limited.

The three selected states also represent distinct hydrological and agro-ecological systems within Sudan: Gedaref functions as a major rainfed production zone; Kassala is shaped by highly variable wadi systems and structural water deficits; and White Nile combines perennial riverine irrigation corridors with adjacent drylands. Analyzing these systems together allows for comparative insight into shared vulnerabilities—such as drought exposure—as well as state-specific intervention pathways. This strengthens the analytical value of the assessment for localized programming as well as broader national coordination.

By situating humanitarian planning within this broader environmental and hydrological context, the assessment supports a shift from reactive crisis response toward more strategic, risk-informed programming. Such an approach enhances the potential to align short-term relief efforts with longer-term resilience and recovery objectives.

2. Structure and Specification of the Data Inventory

2.1 Structure of the Inventory

The data inventory is organized around three interlinked thematic areas: water, food and agriculture and, environmental conditions. These themes draw on public-domain datasets that capture both biophysical and climatic dimensions of resilience, enabling a coherent spatial comparison across the three target states. The inventory combines variables that describe water availability and consumption conditions, vegetation productivity, land cover dynamics, and climatic stress. This facilitates the identification of zones where deficits and opportunities converge. Table 1 summarizes the data included in the current assessment and their main characteristics.

The selection of these parameters and data was informed by the need for core, easily interpretable indicators that directly support humanitarian and development programming. The selected public-domain datasets employed herein are widely used in research, development and humanitarian applications (Lang et al. 2020). They have demonstrated good performance in East Africa (see for example, Funk et al. 2015; Weerasinghe et al. 2020) and are available at spatial and temporal resolutions suitable for operational decision-making. While additional datasets—such as those available through IWMI’s DIWASA project (Velpuri et al. 2025)—could further enrich the analysis, the current assessment parameters serve as a practical example of how openly accessible spatial data can help overcome information gaps and generate actionable insights in fragile contexts.

Although remote sensing datasets contain inherent uncertainties—particularly in rainfall and evapotranspiration estimation and land cover classification—many have undergone extensive validation in different environments and are widely applied in operational settings. Their open accessibility enhances transparency, reproducibility, and coordination across agencies, allowing stakeholders to replicate or update the analysis as new data becomes available.

Main results and observations of the analysis are summarized in this brief. The detailed maps, graphs and other materials generated from the analysis are presented in a separate Annex (Link to Data slide deck), and layers of these datasets suitable for Geographic Information System (GIS) can be found here (Link to the data inventory).

Table 1. List of data included in the inventory and their characteristics.

Thematic domain	Key indicators and variables	Primary data sources	Spatial resolution	Analytical purpose	Source
Water	Precipitation (P)	(CHIRPS)	~5 km	Assess hydrological balance, water availability, and potential for water harvesting or recharge	Funk et al. (2015) Senay et al. (2013) FAO (2020)
	Actual Evapotranspiration (ETa)	SSEBop	~1 km		
	Water yield	Calculated from P and ETa	~5 km		
	Surface water bodies	WaPOR	100 m		
Food & Agriculture	Land cover dynamics	WaPOR	100 m	Evaluate agricultural potential, land degradation, and vegetation health	FAO (2020) FAO (2020) Didan (2015)
	Cropland extent and dominant agriculture systems	WaPOR	100 m		
	Vegetation productivity: Normalized Difference Vegetation Index (NDVI)	MODIS-MOD13Q1	500 m		
Environmental conditions	Drought indices – Standardized Precipitation Index (SPI)	CHIRPS	~5 km	Detect exposure to climate extremes	Funk et al. (2015)

2.2 Data Processing and Integration

The datasets were standardized and integrated within a single compatible mapping environment aligned with state and locality administrative boundaries. This ensured consistency and comparability across the three states. All datasets were first harmonized by reprojecting them to a standard coordinate system (WGS 84 / EPSG:4326). Precipitation (P) and Actual Evapotranspiration (ETa) were resampled to a spatial resolution of 5 km. Temporal aggregation was then applied to generate monthly and annual averages, capturing both the seasonal dynamics and inter-annual variability between 2000 and 2023. This processing means the data can be used directly to identify where water is scarce, where vegetation or cropland is declining, and where drought is intensifying at a spatial scale of 5 km. Water yield was estimated as P–ETa using CHIRPS rainfall and WaPOR evapotranspiration data. Here, water yield is a proxy for relative water surplus or deficit rather than actual runoff, as it does not account for storage changes, groundwater flows, or human water use. It is therefore used for comparative and spatial analysis rather than absolute water accounting. Drought intensity was assessed through the Standardized Precipitation Index (SPI) at 1-, 3-, 6-, 9-, and 12-month time scales, providing insight into both short-term fluctuations and prolonged dry conditions.

Short-term drought indicators (SPI-1 and SPI-3) were used to capture intra-seasonal rainfall interruptions that affect crop establishment and water access. Longer-term indices (SPI-9 and SPI-12) were applied to assess cumulative hydrological stress which influences groundwater recharge and reservoir sustainability. This multi-scale approach distinguishes between transient climatic shocks and structural water scarcity conditions.

Spatial and statistical analyses were performed at state and district levels to extract trends in rainfall, NDVI, water yield, and drought frequency. Finally, the various thematic layers were overlaid to pinpoint hotspots where multiple stressors, such as rainfall deficits, vegetation loss, and recurrent drought, coincide. This integrative approach enabled a coherent understanding of vulnerability and opportunity patterns, providing an analytical foundation for prioritizing action in fragile and displacement-affected settings.

Overlay analysis identifies districts where multiple stressors coincide, such as negative water balance, declining vegetation productivity, and recurrent drought. These compound-risk zones represent priority areas for intervention, particularly where displacement presence overlaps with environmental stress. While socio-economic vulnerability indicators were not directly included, the spatial linkage between biophysical stress patterns and displacement concentrations provides a first-order approximation of exposure.

In operational terms, this analysis supports key humanitarian decisions—such as identifying priority water intervention sites, selecting viable areas for settlements, targeting livelihood support where agricultural potential is higher, and highlighting zones where drought or resource scarcity may heighten protection risk. Specifically, rainfall and SPI layers help flag drought-prone and water-stressed zones; land-cover and NDVI indicators identify areas with higher agricultural productivity and recovery potential; and P–Eta-based water yield underscores relative water surplus or deficit conditions that are relevant for water access and irrigation feasibility. By mapping the overlap between needs (e.g., low rainfall, negative water yield, poor vegetation) and opportunities (e.g., higher NDVI, irrigated zones, water bodies), the analysis helps field teams focus limited resources for maximum impact in contexts where ground assessments are constrained.

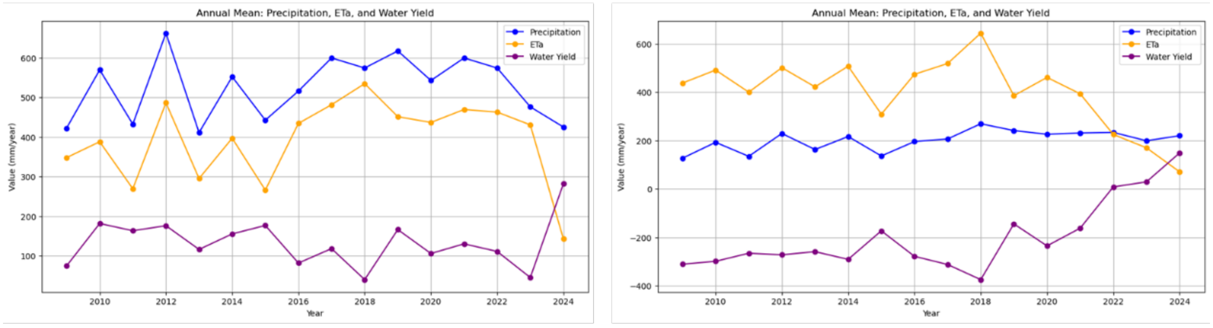
3. Key Observations

3.1 Precipitation, Evapotranspiration and Water Yield Patterns

The hydroclimatic regime across the three states is defined by short, intense wet seasons and long dry periods, shaping both agricultural potential and water stress. Average annual precipitation ranges between 200 mm in Kassala, 350–400 mm in White Nile, and up to 700–800 mm in Gedaref, with rains concentrated mainly from June to September (Figure 2). Despite this seasonal pattern, interannual variability is high; there are years that frequently fall below the long-term mean, especially where important displacement hotspots exist in Kassala and northern White Nile, such as Shagarab and Um Sangour refugee camps.

Evapotranspiration (ET) shows a consistently high-water consumption across Kassala and White Nile states. Annual ET averages 450–650 mm in Kassala, 500–700 mm in Gedaref and locally exceeds 800 mm in irrigated zones and over surface water bodies of White Nile.

Water yield (P-ET) reflects these delicate climatic balances. In Gedaref, positive yields occur mainly in some places within Doka, El Mogran, and Kassab, where annual surpluses reach up to 250 mm (peaking in August), enabling runoff generation and shallow groundwater recharge. Kassala, by contrast, exhibits persistently negative yields (–100 to –400 mm) across most districts which indicates the dominance of water losses and dependence on groundwater. In White Nile, spatial contrasts are pronounced: Southern districts such as Na Eima, Eg Gebelein, and Ez Zeleit experience near-neutral or slightly positive yields (up to +120 mm) especially in August, while northern areas remain in deficit due to high ET and sparse rainfall. Notably, many refugee camps are situated in the southern part of the White Nile state.



Gedaref

Kassala

White Nile

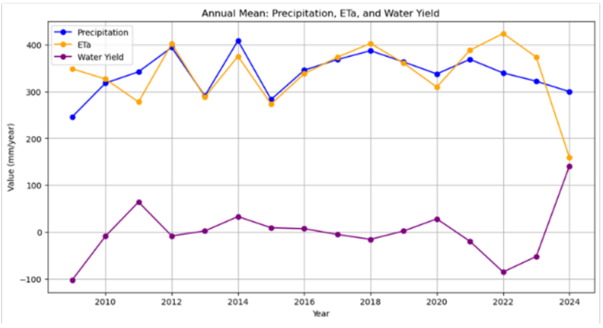


Figure 2. Time series (2009–2024) for precipitation, actual evapotranspiration and water yield in the three selected states. *Source:* Graphs produced by the authors using CHIRPS and SSEBop datasets.

Across the three states, about 80–90% of total rainfall falls between June and September. The peak monthly rainfall is observed in July–August of roughly 130–230 mm/month in Gedaref, 60–105 mm/month in Kassala, and 120–170 mm/month in White Nile (Figure 3), while rainfall drops to <5–10 mm/month during the dry season (January–March). Monthly ETa peaks in the same period at about 90–125 mm/month in Gedaref and Kassala and 80–105 mm/month in White Nile but remains 20–50 mm/month even during dry months. As a result, the monthly water yield becomes strongly positive only during July–August (up to +120–150 mm/month in Gedaref and +50–120 mm/month in southern White Nile), while remaining persistently negative for most of the year in Kassala (down to –80 to –100 mm/month). These seasonal contrasts highlight why monthly and seasonal estimates are essential for identifying planting windows, peak water availability, dry-season stress, and periods of heightened vulnerability for displaced populations.

These patterns indicate where water shortages are most likely to occur and where to focus the corresponding interventions. In Kassala and northern White Nile (where water yield is consistently negative), humanitarian actors should anticipate chronic gaps and prioritize options such as water trucking, borehole rehabilitation, and wadi-based harvesting. In contrast, parts of Gedaref (e.g., Doka, El Mogran, Kassab) and southern White Nile show seasonal surpluses (up to 200–250 mm/year or +120–150 mm/month), offering opportunities for small storage, rainwater harvesting, and seasonal water transfers to better support settlements and livelihoods. These spatial insights help avoid placing displaced communities in chronically water-deficit areas and guide more targeted, cost-effective interventions.

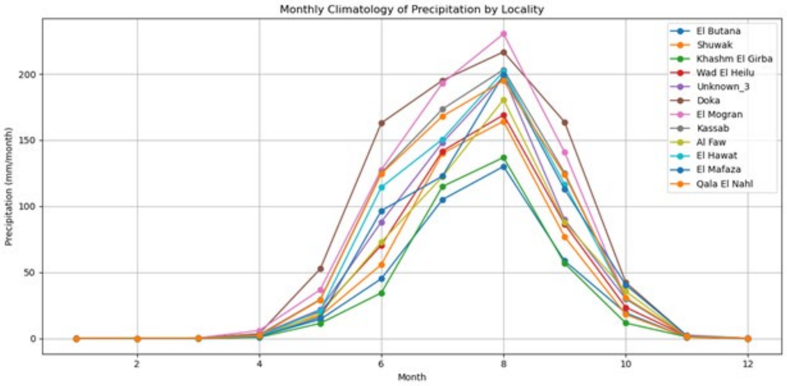


Figure 3. Time series of long-term (1981–2024) average of monthly precipitation over localities of Gedaref State. *Source:* Graphs produced by the authors using CHIRPS datasets.

3.2 Surface Water Bodies

Surface water resources in the three states are unevenly distributed. Data for 2022 reveals that permanent surface water bodies occupy only small fractions of around ~1% and 1.5% of the total areas of Kassala and Gedaref respectively, yet play a critical role in supporting irrigation, domestic use, and flood-recession agriculture. Surface water bodies in the White Nile State constitute around 34% of the total area.

In Gedaref, permanent water bodies are limited but locally significant. The Khashm El Girba and Wad El Heilui districts contain the largest reservoirs, covering about 12.7 km² and 54.8 km², respectively. These are associated with the Khashm El Girba Dam and downstream canals, which sustain the surrounding irrigated cropland and provide dry-season water storage. Most other districts, such as Kassab and Al Faw, show negligible surface water coverage, underscoring the heavy reliance on rainfall and seasonal runoff for agriculture.

Kassala State is notably water-scarce, with only some seasonal water bodies detected in 2022. Minor features appear in El Masana and New Halfa, each covering less than 3 km², corresponding to small reservoirs and structures. The state’s hydrology is dominated by the ephemeral wadi systems—particularly the Gash and Atbara—which flow only during intense seasonal storms, emphasizing the significance of floodwater harvesting and managed aquifer recharge to improve water security.

In contrast, White Nile State exhibits a much denser distribution of permanent surface water, concentrated along the White Nile River corridor. Districts such as Na Eima (106 km²), Eg Gebelein (72.9 km²), and En Naeim (18.3 km²) record the largest water bodies, and are supplemented by secondary reservoirs in Umm Remta and El Kereida. These continuous water sources underpin the state’s extensive irrigated agriculture and household supply systems. The spatial pattern indicates a clear hydrological divide—high water availability and irrigation infrastructure along the river, contrasted by dry lands with sparse surface storage for areas distant from the river corridor.

Overall, the surface water analysis highlights a sharp east–west gradient: White Nile benefits from perennial flows and irrigation networks, Gedaref relies on localized reservoirs and rainfall supply, while Kassala remains constrained by ephemeral flows and minimal storage. For humanitarian actions, these patterns showcase where reliable water sources exist as well as where major gaps remain. This helps ensure that the displaced communities are not embedded in areas with minimal surface-water availability.

3.3 Land Cover Distribution

Land cover analysis from 2009–2022, based on WaPOR datasets, shows that Sudan's total land area is dominated by bare/sparse vegetation (≈62%), grasslands (~18%), and shrublands (~10%), with smaller shares for irrigated and rainfed cropland and built-up settlements. In Gedaref, rainfed cropland occupies nearly 60% of the area, expanding gradually southward. Kassala is dominated by bare/sparse vegetation (~70%) and grasslands (~18%). Irrigated croplands concentrated along the Gash and Atbara wadis with limited areas of irrigated agriculture in the southern part of the state. White Nile is characterized by rainfed cropland (~35%), grassland (~35%), and bare/sparse vegetation (~18%). The states exhibit an increasing trend in irrigated croplands in tandem with reduction of rainfed croplands. Across the three states, land cover overtly appears stable but masks progressive ecological stress—notably, cropland expansion into marginal zones and loss of vegetative cover during drier years. These trends highlight the urgency of integrating sustainable land management and restoration into resilience planning for eastern and central Sudan.

3.4 Dominant Agriculture Systems

Agricultural systems across Sudan are spatially diverse, reflecting variations in rainfall, soil conditions, and access to irrigation. The national cropland statistics show that rainfed systems dominate, covering roughly 20–25% of the total land, while irrigated agriculture accounts for only 3–5%, concentrated mainly along the Nile and its tributaries.

In Gedaref, agriculture is overwhelmingly rainfed, with 85.4% of the state's area under rainfed cultivation and only 2.5% irrigated. This makes Gedaref Sudan's principal rainfed cropping zone (Elagib et al. 2019). District-level data show particularly high concentrations in Kassab (82.7%), Al Faw (75.2%), and Shuwak (72.7%), where semi-mechanized sorghum and sesame farming dominate the landscape. Smaller pockets of irrigation occur around Khashm El Girba (21%) and in Rahad, benefiting from the nearby reservoir and canal systems.

In contrast, Kassala State shows limited rainfed farming (Figure 4), with only 2.5% of its area cultivated under rainfed systems and 8.3% that is irrigated. Agriculture here is concentrated mainly along the Gash and Atbara River deltas, where wadi-based irrigation and flood-recession farming sustain crops during the short wet seasons. The Aroma and Kassala districts stand out with notable shares of irrigated cropland (20.2% and 6.3%, respectively), supported by surface water diversion from seasonal floods.

In White Nile State, agricultural systems are more diversified, combining both rainfed and irrigated components. Rainfed croplands occupy 29.1% of the state area, while irrigated lands account for 12.2%. Districts such as Eg Gebelein (55.2% rainfed; 9.0% irrigated) and En Naeim (12.5% rainfed; 7.3% irrigated) demonstrate strong mixed systems, while El Kereida and Rabak exhibit the highest irrigation intensities, ranging between 30% and 48%. These patterns align with the location of major irrigation schemes along the White Nile River and its canals, sustaining both cereal and horticultural crops.

Spatially, the three states represent distinct agricultural typologies: Gedaref as the rainfed production hub, Kassala as a wadi-fed system reliant on seasonal floods, and White Nile as an irrigation corridor. Together, they capture the structural diversity of Sudan's agro-ecological systems and underline the significance of tailoring interventions to the specific hydrological and climatic realities of each state.

These agricultural patterns show where livelihood support is viable and where communities are most exposed to climate shocks. In Gedaref, rainfed systems can sustain crop-based assistance but remain highly vulnerable to rainfall deficits. Kassala's reliance on groundwater and short-lived wadi flows leads to fragile livelihoods and necessitates drought-tolerant options and alternative water sources. In White Nile, stronger irrigation systems create opportunities for improved irrigation practices, more stabilized crop yield, and settlement planning near more reliable water and agricultural zones. Applying these strategies requires deeper contextual knowledge of the humanitarian situation undertaken in partnership with the targeted communities.

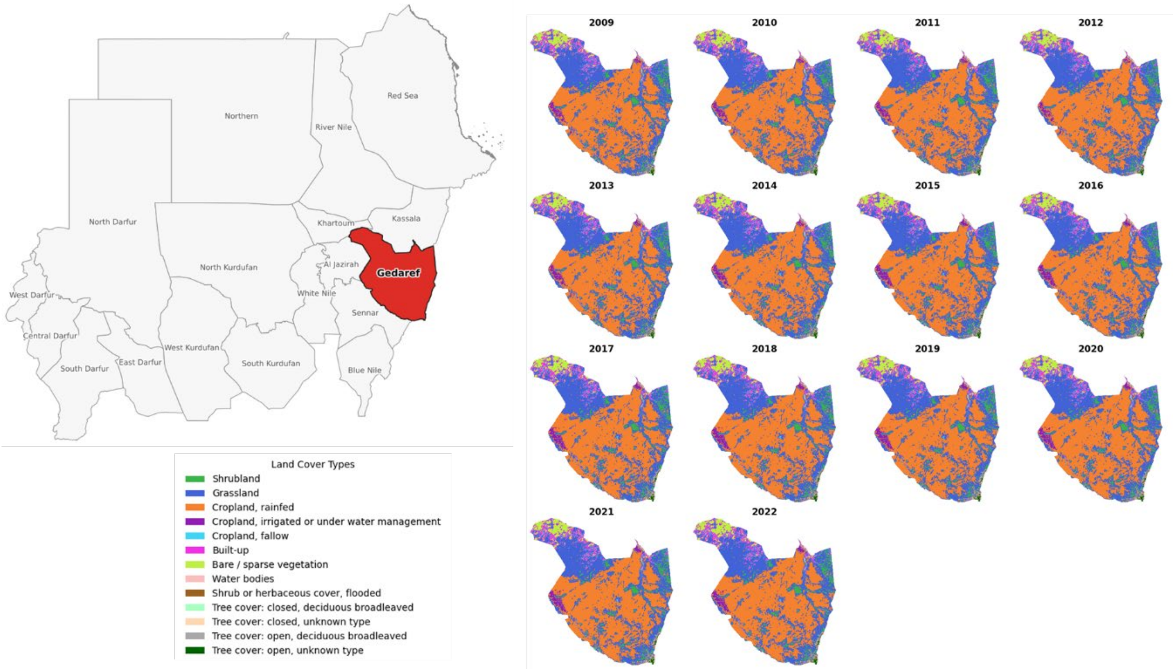


Figure 4. Maps of land cover types in the Gedaref States (2009–2022). *Source:* Map produced by the authors using WaPOR land cover dataset.

3.5 Vegetation Productivity

Vegetation productivity, represented by seasonal Integrated NDVI (iNDVI) over June–October, mirrors rainfall variability and water availability across the three states. Despite interannual fluctuations, all regions demonstrate a gradual improvement in NDVI since 2010, driven by episodic wet years and local irrigation expansion.

In Gedaref, iNDVI values are consistently higher when compared with other states, and average around 2.3, with peak greenness observed during 2016 and 2018–2024. Spatially, the most productive areas include Doka, corresponding to rainfed sorghum and sesame zones. However, deviations from the long-term mean reveal mainly alternating wet and dry cycles, underscoring the system's climatic sensitivity.

Kassala shows a weaker vegetation response, with mean iNDVI around 1.5, indicative of the limited and erratic rainfall regime. The Gash floodplain and New Halfa irrigation area appear as productivity hotspots, while surrounding districts show widespread declines during dry years (such as 2002, 2011, 2015, and 2017). The recovery after 2018 points to improved seasonal moisture and partial vegetation recovery.

In White Nile, iNDVI averages 1.8, with spatial concentration along the riverine corridor and irrigated zones near Kosti and Rabak. The 2004–2010 period shows a marked reduction, followed by gradual greening after 2015 which coincides with higher rainfall years.

Overall, NDVI trends confirm a strong coupling between rainfall anomalies and vegetation dynamics: short wet seasons drive rapid greening, while prolonged deficits cause sharp productivity losses. Sustaining vegetation cover in drier years thus requires interventions such as water harvesting, soil conservation, and drought-resilient cropping systems to stabilize productivity under increasing climate variability.

3.6 Drought Patterns

Drought analysis using the Standardized Precipitation Index (SPI) for the period 1981–2024 reveals pronounced interannual and intra-seasonal variability across all three states. Short-term (SPI-1 and SPI-3) fluctuations reflect erratic rainfall within the monsoon months; longer-term (SPI-9 and SPI-12) trends capture prolonged water stress linked to multi-seasonal deficits.

In Gedaref, drought events are frequent but generally moderate, corresponding to its higher rainfall base. The early 1980s and 1990s witnessed extended SPI-12 droughts, followed by recovery phases in the 2000s and 2020s (Figure 5). Seasonal SPI-1 and SPI-3 results show recurrent dry months, especially in December–February, that constrain rainfed planting activities.

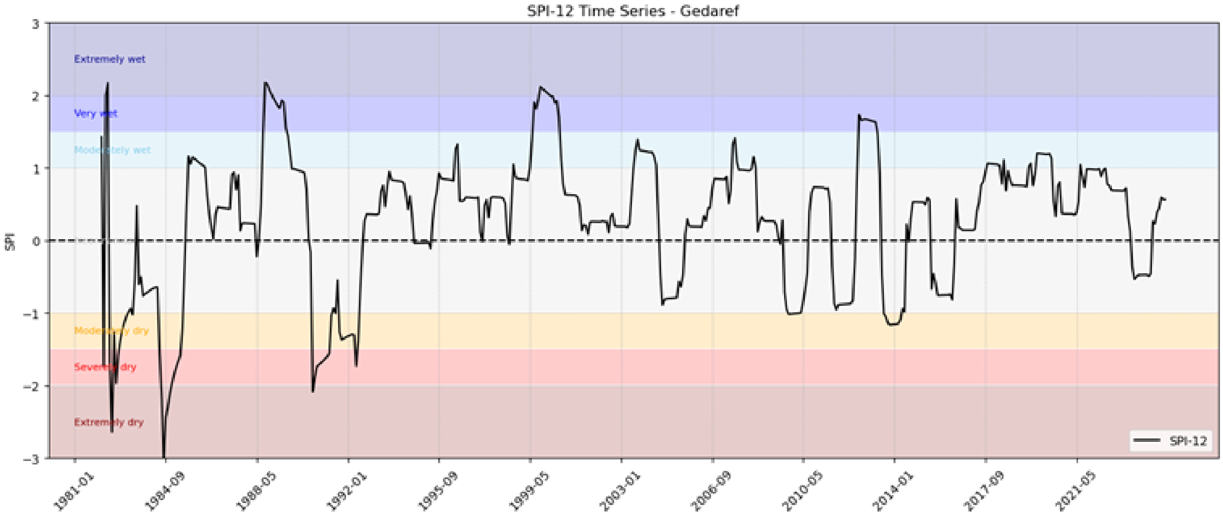


Figure 5. Time series of SPI intensity of prolonged dryness (SPI-12) in Gedaref State. *Source:* Graph produced by the authors using SPI data calculated based on CHIRPS precipitation dataset.

Kassala emerges as the most drought-prone of the three states. Similar to Gedaref, severe to extreme dry periods dominate the long-term SPI-12 record during the 1980 and 1990s. Despite the frequency of short wet spells within overall dry years, these short rainfall events are insufficient to offset prolonged water deficits. These patterns align with declining water yield and negative NDVI anomalies across much of the state.

In White Nile, drought cycles are less intense but more variable. Prolonged SPI-12 droughts occurred during the 1983–1985 and 2003–2005 periods, followed by wetter phases from 2013 onward. SPI-6 and SPI-9 records indicate that mid-season rainfall interruptions remain common, exposing rainfed agriculture to high production risk even in generally wet years.

These drought patterns highlight where climate shocks are most likely to disrupt water access and livelihoods. For instance, moderate but frequent dry spells in Gedaref signal risks for rainfed farming and underscore the importance of early warning and supporting strategies (such as adjusting sowing date and supplementary irrigation to avoid mid-season crop losses). More detailed studies are required to operationalize these strategies.

4. Cross-Cutting Synthesis of Findings

Across the three states, several overarching patterns emerge. First, hydroclimatic seasonality is highly concentrated, with most rainfall occurring within a short monsoon window. This creates brief periods of surplus that are followed by extended dry conditions, amplifying both opportunity and risk. Effective water harvesting and storage strategies therefore become essential to capture seasonal surpluses.

Second, spatial heterogeneity is pronounced. White Nile benefits from perennial river flows and irrigation infrastructure along the Nile corridor, while Kassala exhibits structural deficits driven by high evapotranspiration and limited storage. Of the three states, Gedaref occupies an intermediate position, with relatively favourable rainfall yet marked by high interannual variability.

Third, vegetation productivity trends indicate gradual greening since 2015 in several districts that is largely associated with episodic wet years and localized irrigation expansion. However, this recovery remains sensitive to rainfall variability, underscoring the need for soil moisture conservation and sustainable land management to stabilize gains.

Fourth, drought analysis confirms cyclical multi-year dry periods, particularly during the 1980s and early 2000s. This highlights the importance of preparedness systems that anticipate recurrence instead of treating drought as isolated events.

5. Key Entry Points for Enhanced Water, Food and Environmental Security

The analysis highlights several spatial and thematic entry points to strengthen water, food, and environmental security under fragile and displacement-affected conditions in the study area. Across the three states, climatic constraints and resource opportunities converge around a few actionable domains. In Gedaref, the combination of relatively higher rainfall and moderate water yield provides clear opportunities for utilizing rainwater harvesting, managed aquifer recharge, and small reservoirs. IWMI's WaterSTOP tool can help in identifying the potential for rainwater harvesting. Targeting productive zones (such as Doka and Kassab) can enhance soil moisture retention and improve the reliability of rainfed agriculture. Integrating nature-based solutions with soil and crop management would increase resilience against short dry spells while simultaneously sustaining vegetation and crop productivity.

In Kassala, persistent negative water balances and recurrent droughts point to the need for wadi system restoration, seasonal floodwater harvesting, and groundwater recharge schemes to stabilize the Gash and Atbara floodplains and provide protection from floods. These systems could be linked to small-scale irrigation and livelihood support for displaced and host communities. Expanding drought-resilient farming systems in conjunction with improving multi-use water-access would help offset the volatility of seasonal flows.

In White Nile, the integration of riverine irrigation management, off-river storage ponds, and efficient water use in existing schemes presents a major opportunity. The spatial contrast between irrigated corridors and drylands calls for scaling conjunctive surface and groundwater management and inclusive water allocation mechanisms that span agricultural as well as domestic needs.

By anchoring resilience actions in transparent, spatially grounded evidence for displacement landscapes, this approach provides a replicable model for science-informed decision-making that tethers humanitarian and development priorities to more sustainable and inclusive futures. Specifically, the generated datasets and indicators directly support the three use cases: (i) water interventions, by identifying drought-prone zones, water-deficit districts, and localized surplus areas suitable for harvesting and storage; (ii) settlement planning, by highlighting climatically viable and water-supported locations and avoiding chronically deficit zones; and (iii) livelihood recovery, by mapping agricultural potential, vegetation productivity, and seasonal water availability to target support where recovery prospects are the highest. Together, these applications demonstrate how integrated hydroclimatic and land-surface data can translate into practical, location-specific humanitarian and early recovery actions.

Embedding humanitarian planning within hydroclimatic evidence frameworks enhances both efficiency and sustainability. Instead of selecting intervention sites solely based on accessibility or short-term assessments, the integrated dataset enables the identification of structurally viable zones for water infrastructure, settlement planning, and livelihood recovery.

Districts combining moderate rainfall, seasonal positive water yield, and stable vegetation productivity represent higher-potential areas for agricultural recovery and community stabilization. Conversely, chronically deficit zones characterized by repeated drought and negative water balance indicate the need for sustained water supply interventions and alternative livelihood options.

By translating hydroclimatic signals into operational guidance, the approach bridges humanitarian and development planning. It supports immediate relief decisions—such as borehole targeting or water trucking—while informing longer-term investments within water harvesting, irrigation efficiency, and ecosystem restoration. This integration strengthens resilience-building efforts in displacement-affected landscapes where both urgency and sustainability must be addressed simultaneously

References

Didan, Kamel., 2015. MOD13Q1 MODIS/Terra Vegetation Indices 16-Day L3 Global 250 m SIN Grid V006. [Data set]. NASA Land Processes Distributed Active Archive Center. https://doi.org/10.5067/MODIS/MOD13Q1.006.

Elagib, Nadir Ahmed, Muhammad Khalifa, Abbas E. Rahma, Zryab Babker, and Suad Ibrahim Gamaledin. 2019. "Performance of major mechanized rainfed agricultural production in Sudan: Sorghum vulnerability and resilience to climate since 1970." *Agricultural and Forest Meteorology* 276–277, 107640, https://doi.org/10.1016/j.agrformet.2019.107640.

FAO (Food and Agriculture Organization of the United Nations). 2020. WaPOR, FAO's portal to monitor Water Productivity through Open-access Remotely sensed derived data. FAO. https://wapor.apps.fao.org.

Funk, Chris, Pete Peterson, Martin Landsfeld, Diego Pedreros, James Verdin, Shraddhanand Shukla, Gregory Husak, James Rowland, Laura Harrison, Andrew Hoell, and Joel Michaelsen. 2015. "The Climate Hazards Infrared Precipitation with Stations—A New Environmental Record for Monitoring Extremes." *Scientific Data* 2, 150066. https://doi.org/10.1038/sdata.2015.66.

Hussain, Intizar, R. Sakthivadivel, Upali Amarasinghe, Muhammad Mudasser, and David Molden. 2003. "Land and Water Productivity of Wheat in the Western Indo-gangetic Plains of India and Pakistan: A Comparative Analysis." IWMI Research Report 065. International Water Management Institute (IWMI). 57p. https://hdl.handle.net/10568/39852.

Bergaoui, Karim, Makram Belhaj Fraj, Stephen Fragaszy, Ali Ghanim, Omar Hamadin, Emad Al-Karablieh, Jawad Al-Bakri, Mona Fakih, Abbas Fayad, Fadi Comair, Mohamed Yessef, Hayat Ben Mansour, Haythem Belgrissi, Kristi Arsenault, Christa Peters-Lidard, Sujay Kumar, Abheera Hazra, Wanshu Nie, Michael Hayes, Mark Svoboda, and Rachael McDonnell. 2024. "Development of a Composite Drought Indicator for Operational Drought Monitoring in the MENA region." *Scientific Reports* 14, 5414. https://doi.org/10.1038/s41598-024-55626-0.

Karimi, Polad, Wim G. M. Bastiaanssen, and David Molden. 2013. "Water Accounting Plus (WA+) – a water accounting procedure for complex river basins based on satellite measurements." *Hydrology and Earth System Sciences* 17 (7): 2459–2472. https://doi.org/10.5194/hess-17-2459-2013.

Lang, Stefan, Petra Füreder, Barbara Riedler, Lorenz Wendt, Andreas Braun, Dirk Tiede, Elisabeth Schoepfer, Peter Zeil, Kristin Spröhnle, Kerstin Kulessa, Edith Rogenhofer, Magdalena Bäuerl, Alexander Öze, Gina Schwendemann, and Volker Hochschild. 2020. "Earth Observation Tools and Services to Increase the Effectiveness of Humanitarian Assistance." *European Journal of Remote Sensing* 53(Sup2): 67–85. https://doi.org/10.1080/22797254.2019.1684208.

Mahapatra, Smarnika, Naga Velpuri, Petra Schmitter, Shivam Pandey, and Alok Sikka. A. 2024. "Enhancing the Water Accounting Plus Framework to Evaluate Field-level Water Use and Availability in Rice-dominant Cropping System and Potential for Mapping GHG Emissions at Scale: A Case Study for the Eastern Gangetic Plains, Bihar, India." International Water Management Institute (IWMI). CGIAR Initiative on Excellence in Agronomy. 26p. https://hdl.handle.net/10568/173094.

Mekonnen, Kirubel Naga Manohar Velpuri, Mansoor Leh, Komlavi Akpoti, Afua Owusu, Primrose Tinonetsana, Tarek Hamouda, Benjamin Ghansah, Thilina Prabhath Paranamana, and Yolande Munzimi. 2023. "Accuracy of Satellite and Reanalysis Rainfall Estimates Over Africa: A Multi-scale Assessment of Eight Products for Continental Applications." *Journal of Hydrology: Regional Studies* 4, 101514. https://doi.org/10.1016/j.ejrh.2023.101514.

Mekuria, Wolde, Awdenegest Moges, Rediet Girma, Getahun Yakob, Tirusew Teshale, Alemseged Tamiru Haile, and Sandra Ruckstuhl. 2024. "Nature-based Solutions for Human and Environmental Resilience: The Case of Dolo Ado and Bokolmayo Districts, Somali Regional State, Ethiopia." International Water Management Institute (IWMI). CGIAR Initiative on Fragility, Conflict, and Migration. 40p. https://hdl.handle.net/10568/155265.

Obahoundje, Salomon, Seifu A. Tilahun, and Petra Schmitter. 2024. "Spatio-temporal Patterns of Dry and Wet Spells in Ghana's Savanna and Transitional Zones: A 40-year Analysis." Poster presented at the 8th edition of the conference "Climate and Impacts", Paris, France, 6-8 November 2024.

Owusu, Afua, Komlavi Akpoti, Mansoor Leh, Tharindu Perera, Lahiru Madushanka, Kirubel Mekonnen, Primrose Tinonetsana, Noosha Tayebi, Ana Cecilia Escalera-Rodriguez, Rafatou Fofana, and Naga Manohar Velpuri. 2025. "Bridging Scales and Borders on Water Availability and Use in the Transboundary Volta River Basin: A Water Accounting Approach." *Journal of Hydrology: Regional Studies* 59, 102377. https://doi.org/10.1016/j.ejrh.2025.102377.

Saleh, Ezzeldin, Khalid M. Dousa, Ahmed Babiker, Nour Elhouda At Alla Rahma, Hamad Abdel Hadi, Mustafa Elsayed, Suleima Ishag Elkhalifa, Sami Mahmoud Abdelkhair Momin, Ahmed Abubaker, Omer Mergani Nemery, Luai Mohmmed Bashir, Shahinaz Bedri, Nada Fadul, Yasir Hamad, and Zahir Osman Eltahir Babiker. 2024. "Health and Humanitarian Toll of Sudan's Forgotten War." *The Lancet* 404 (10461): 1383–1385. https://doi.org/10.1016/s0140-6736(24)01939-1.

Senay, Gabriel B., Stefanie Bohms, Ramesh K. Singh, Prasanna H. Gowda, Naga M. Velpuri, Henok Alemu, and James P. Verdin. 2013. “Operational Evapotranspiration Mapping Using Remote Sensing and Weather Datasets: A New Parameterization for the SSEB Approach.” *Journal of the American Water Resources Association* 49 (3): 577–591. https://doi.org/10.1111/jawr.12057.

Tarkegn, Temesgen Gashaw, Pieter R. van Oel, Abebe D. Chukalla, Ram Lakhan Ray, Gebrekidan Worku Tefera, Amare Haileslassie, Meron Teferi Taye, Abeyou W. Worqlul, Enyew Adgo, Amare Bantider, and Yihun T. Dile. 2025. “Modeling Integrated Impacts of Agro-hydrological Interventions on Blue and Green Water and Crop Yield in SWAT+.” *Journal of Hydrology: Regional Studies* 62, 102783. https://doi.org/10.1016/j.ejrh.2025.102783.

UNHCR (United Nations High Commissioner for Refugees). 2025a. Sudan Situation: UNHCR Monthly External Update #111. United Nations High Commissioner for Refugees (UNHCR). Accessed November 9, 2025. https://data.unhcr.org/en/documents/details/119415.

UNHCR (United Nations High Commissioner for Refugees). 2025b. Operational Data Portal. United Nations High Commissioner for Refugees (UNHCR). Accessed November 9, 2025. https://data.unhcr.org/en/country/sdn.

Velpuri, Naga Manohar, Abdulkarim H. Seid, Mansoor Leh, Kirubel Mekonnen, Alemseged T. Haile, Mariangel Garcia Andarcia, Afua Owusu, Komlavi Akpoti, Samuel Storr, Emma Greatrix, and Elizabeth Wamba. 2025. “Digital Solutions for Africa’s Water Management.” International Water Management Institute (IWMI). 12p. https://hdl.handle.net/10568/176180.

Weerasinghe, Imeshi, Wim Bastiaanssen, Marloes Mul, Li Jia, and Ann van Griensven. 2020. “Can We Trust Remote Sensing Evapotranspiration Products Over Africa?” *Hydrology and Earth System Sciences* 24 (3): 1565–1586. https://doi.org/10.5194/hess-24-1565-2020.

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