Societal Challenges and Suitability Mapping of Resilient Nature-Based Water Solutions: Evidence from Case Studies in White Nile, El Gedaref, and Kassala, Sudan

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Front cover photo: Rehabilitated degraded land using bench terrace in Ethiopia (*photo*: Wolde Mekuria/IWMI).
Back cover photo: The Genale Dawa River that supplies water for the refugees and host communities in the Somali Region, Ethiopia (*photo*: Wolde Mekuria/IWMI)

Contents

Acronyms and abbreviations

AFS	Agroforestry Systems
AGB	Aboveground Biomass
AVHRR	Advanced Very-High-Resolution Radiometer
CHIRPS	Climate Hazards Group Infrared Precipitation with Station
CMI	Christian Michelsen Institute
DEM	Digital Elevation Model
DRC	Danish Refugee Council
DTM	Displacement Tracking Matrix
EU	European Union
FAO	Food And Agriculture Organization
FNC	Forest National Corporation
GEE	Google Earth Engine
GIS	Geographic Information System
GPG	Good Practice Guidance
GSLRP	Gash Sustainable Livelihoods Regeneration Project
IDPs	Internally Displaced Persons
IFAD	International Fund for Agricultural Development
IOM	International Organization for Migration
IPCC	Intergovernmental Panel on Climate Change
ISRIC	International Soil Reference Information Centre
IUCN	International Union for Conservation of Nature
IWMI	International Water Management Institute
LC	Land Cover
LDN	Land Degradation Neutrality
LP	Land Productivity
LULC	Land Use and Land Cover
MoA	Ministry of Agriculture
MODIS	Moderate Resolution Imaging Spectroradiometer
NbS	Nature-Based Solutions
NDVI	Normalized Difference Vegetation Index
NGOs	Non-Governmental Organizations
NPs	Natural Products
OCHA	Office for the Coordination of Humanitarian Affairs
RNBWS	Resilient Nature-Based Water Solutions
ROAM	Restoration Opportunities Assessment Methodology
RWH	Rainwater Harvesting
SDG	Sustainable Development Goals
SEPAL	System For Earth Observation Data Access, Processing and Analysis for Land Monitoring
SOC	Soil Organic Carbon
SSA	Sub-Saharan Africa
SWC	Soil And Water Conservation
UN	United Nation
UNCCD	United Nations Convention to Combat Desertification
UNDP	United Nations Development Programme
UNHCR	United Nations High Commissioner for Refugees
UNICEF	United Nations Children's Fund
UNOPS	United Nations Office for Project Services
WFP	World Food Programme
WRI	World Resources Institute

Summary

In Sudan, the combined effects of environmental degradation, climate change, and human-induced conflict have driven widespread displacement. Migration — whether as an adaptation to environmental stressors such as droughts and floods, or as a response to violence, intensifies pressure on already fragile ecosystems and deepens a self-reinforcing cycle of vulnerability. In response to the intertwined challenges, resilient nature-based water solutions (RNBWS) offer a viable and cost-effective pathway by integrating biophysical, socio-economic, and governance dimensions, enhancing water security, restoring degraded ecosystems, strengthening livelihoods, and supporting inclusive, community-based natural resource management. However, to maximize these benefits, suitable options and areas for implementing RNBWS must be systematically identified and mapped for targeted, scalable actions.

This study focuses on three refugee-hosting areas in Sudan - Kassala, El Gedaref, and White Nile – with a threefold aim: (i) to assess key societal and environmental challenges in each state; (ii) to identify RNBWS appropriate to the local socio-ecological conditions; and (iii) to map areas most suitable for implementing these solutions to enhance environmental sustainability and livelihood resilience.

The study combined an extensive review of published and grey literature (to understand societal challenges and potential solutions) with multi-temporal satellite imagery and geographic information system (GIS) - based techniques (to profile biophysical conditions, such as land-use and land-cover change, land-degradation neutrality, and site characteristics such as slope and soil type). Spatial analysis techniques, guided by international best practices, including the International Union for Conservation of Nature (IUCN) Global Standards for Nature-based Solutions, and the Restoration Opportunities Assessment Methodology (ROAM), were then used to pinpoint and prioritize optimal sites for the identified RNBWS.

Results show that across the three states, economic hardship, conflict, weak governance, natural disasters, and climate change are the main contributors to displacement and migration. The influx of refugees and internally displaced people (IDPs) could put intense pressure on host communities, overstraining public services and intensifying competition for natural resources, which often contributes to further environmental degradation. While economic challenges cut across all three states, environmental challenges are most acute in Kassala and El Gedaref, and social challenges are most pronounced in White Nile, which might be attributed to the refugee influx and service constraints.

Over the last two decades, the study detected substantial land degradation and landscape transformation in the three states. Forestlands, shrublands, grasslands, and water bodies have declined markedly, while agricultural land, settlements, and degraded areas have expanded. Land degradation neutrality (LDN) assessments show an increasing proportion of land categorized as degraded and a declining share of stable and improving lands, highlighting growing ecosystem vulnerability.

At the same time, socio-economic analysis reveals structural constraints that shape both vulnerability and the feasibility of interventions, including limited formal land tenure, high dependence on rainfed agriculture and natural resources, food insecurity, and increasing competition over land, water, grazing, and fuelwood between displaced and host communities. These pressures are compounded by rising living costs and limited livelihood diversification opportunities. Governance-related findings further indicate gaps in institutional capacity, coordination challenges among humanitarian and government actors, and ambiguities in land and resource rights, all of which can exacerbate conflict and constrain effective planning and implementation of RNBWS. On the positive note, the spatial analysis indicated

extensive potential areas suitable for various RNBWS, including tree-based solutions (e.g., agroforestry, reforestation), rainwater harvesting (RWH) structures, soil and water conservation (SWC) measures, and ecological restoration practices. Many locations were found to be potentially suitable for multiple solutions simultaneously, indicating opportunities for integrated solutions that provide compounding environmental and livelihood benefits.

These findings underscore the importance of integrating RNBWS into humanitarian development and state-level planning in Sudan's fragile, conflict-affected, displacement-hosting landscape. They highlight the need for adaptive, landscape-scale planning that not only respond to biophysical challenges but also explicitly incorporates socio-economic realities and governance constraints, supported by targeted investments to jointly address sustainable resource management, livelihoods, and water security. Spatially explicit evidence could inform this integrated approach, guiding development planning, humanitarian programming, and climate adaptation strategies. Crucially, these findings have broader relevance across dryland, refugee-hosting regions in the Horn of Africa and the Sahel, where RNBWS offer a cost-effective, context-appropriate pathway that aligns environmental restoration with livelihood resilience.

For the research to translate into real-world improvements, a clear impact pathway is envisaged. The study's outputs are tailored for uptake by humanitarian organizations (e.g. United Nation (UN) agencies like United Nations High Commissioner for Refugees (UNHCR), International Organization for Migration (IOM) and World Food Programme (WFP), and international/national Non-Governmental Organizations (NGOs) focusing on refugees, water, and food security), government bodies at state and national levels (e.g. ministries or departments of water resources, agriculture and forestry, environment, and refugee affairs), and civil society or community-based organizations engaged in environmental management and livelihood support. In addition, the evidence generated is highly relevant for bilateral donors, climate finance mechanisms (e.g., Green Climate Fund, Adaptation Fund), and multilateral development banks, providing a robust analytical basis to inform investment priorities and develop bankable project pipelines for RNBWS. These stakeholders can use the maps and recommendations to plan, target, and scale up RNBWS interventions on the ground (for instance, prioritizing sites for water harvesting or reforestation in refugee-hosting areas), as well as to inform policies and investment strategies (for example, incorporating nature-based solutions into state development plans, or aligning humanitarian relief with sustainable resource management initiatives). By guiding such operational programs and policy decisions, the research aims to direct investments to the most suitable interventions and locations, ultimately helping to combat food and water insecurity and environmental degradation while building the resilience of refugees, IDPs, host communities, and the ecosystems they depend on.

1. Introduction

Global displacement nearly doubled during the last decade (UNHCR, 2025), and crises have become a persistent humanitarian challenge owing to their complex social, economic, and environmental consequences (Spiegel and Mhlanga, 2022). In particular, low- and middle-income countries, which host the majority of the world's refugees (~71%), face significant social, economic, and environmental challenges (UNHCR, 2025), often compounded by increased pressure on already stretched public services and limited institutional capacity for effective planning and regulatory enforcement. Social and economic challenges manifest in many ways, including increased competition for scarce resources and essential services such as water, healthcare, education, and land for cultivation (Yasmin et al., 2022; Coniglio et al., 2023). The key environmental pressures in refugee-host community settings stem from sudden, concentrated population increases, which place immense demands on local natural resources, particularly for energy, shelter, and agriculture (OCHA, 2025). These pressures often manifest as deforestation and forest degradation (Dampha et al., 2025; Karmakar et al., 2025), land and soil degradation (Bernard et al., 2020), water scarcity and contamination (Yasmin et al., 2022), biodiversity loss (Awono et al., 2022), pollution and waste management challenges (Islam, 2020), and climate change vulnerability (Fransen et al., 2024; Dampha et al., 2025). These challenges pose a serious threat to livelihood systems, reduce ecosystem resilience, and intensify competition over shrinking resources (Naik et al., 2025), elevating the potential for social stress and, in some cases, tensions or even conflict between refugees and host communities (Ali and Ocha, 2018).

Survival remains the primary concern for refugees, and host nations often face the urgent task of responding to refugee crises quickly, without sufficient time for planning. As a result, environmental issues often remain unaddressed until both refugees and the host population face the adverse effects of environmental degradation (Dutta, 2023). The impact of environmental degradation is even more severe in Sub-Saharan Africa (SSA), where it is driven by socio-cultural norms, economic hardship, weak policy enforcement, and limited knowledge of sustainable practices (Kyomuhendo et al., 2025), leading to deforestation, air pollution, soil degradation, biodiversity loss, and negative effects on livelihoods.

Like other SSA countries, Sudan faces significant challenges that affect people's well-being, the environment, and the economy, driven by prolonged conflict, climate change, and degradation of natural resources (Al-Sharif, 2024). Since the recent conflict began on April 15, 2023, Sudan has descended into one of the world's most severe humanitarian and displacement crises. Nearly 13 million people have been forcibly displaced, 8.9 million internally and 3.7 million to neighboring countries, placing an immense burden on Sudan's collapsing infrastructure, public services, and the limited capacities of host nations (Hussien and Ahmed, 2025). In addition, such displacement could contribute to further environmental degradation, which often manifests as poor sanitation, flooding, deforestation, soil erosion, poor waste management, and pollution (Osman and Yasin, 2024). Khairalseed (2015) highlighted desertification as one of the primary environmental challenges, affecting approximately 5 × 105 km^2 of land and more than half of Sudan's population. These pressures are exacerbated by the recent conflict and by increasing rainfall variability and recurrent droughts, which are strongly linked to climate change and, in many instances, have forced communities to migrate due to security and water scarcity (Musa, 2024).

In the past, widespread tree cutting for household energy, charcoal production, and agricultural expansion reduced vegetation cover and worsened soil erosion (Elsheikh and Babikir, 2022; UNHCR, 2023). In some locations, for example, in Darfur, this, further exacerbated by climate change, has resulted in widespread environmental migration, with people forced to leave their homes due to environmental factors such as droughts, famine, floods, and other extreme weather events (Gomez, 2023). The interconnection among climate change, conflict, and displacement remains a critical area of debate, as these factors form a vicious cycle affecting millions in Sudan (Basheer and Elagib, 2024). Migration, whether as an adaptation strategy to climate change or a response to conflict, places additional strain on fragile ecosystems, as is the case in Sudan, which cannot absorb large influxes of people (Basheer and Elagib, 2024).

Because the specific factors causing displacement are difficult to disentangle, it is important to adopt a holistic approach to address the complex social, economic, and environmental consequences of displacement (Basheer and Elagib, 2024). This complexity calls for a holistic, system-based approach that recognizes displacement not only as a short-term humanitarian crisis but also as a long-term development and environmental challenge. In this context, reconciling life-saving humanitarian responses with life-changing, resilience-oriented interventions is particularly critical, especially during the establishment and management of refugee camps. While emergency assistance is essential to protect lives in the short term, it must be complemented by longer-term solutions that promote shared resource use and governance, environmental stewardship, reduce pressure on natural resources, prevent environmental degradation in the landscapes where camps are located, and support sustainable livelihoods for both refugees and host communities (Thalheimer et al., 2022). By aligning immediate humanitarian assistance with nature-based and resource-efficient interventions, humanitarian programs can contribute to enhanced long-term resilience, reduced conflict over scarce resources, and more dignified, self-reliant living conditions for displaced populations and their hosts (Mendum et al., 2024).

In such contexts, Resilient Nature-based Water Solutions (RNBWS)[1], co-developed with displaced and host communities, offer innovative approaches to restore ecosystems, improve livelihoods, and enhance climate adaptation for both groups (Quintero-Angel et al., 2023). RNBWS includes integrated interventions that deliberately combine ecosystem restoration with water and livelihood-oriented practices, such as tree-based systems (e.g., reforestation, afforestation, and agroforestry practices) linked to crop and livestock production, sustainable watershed management coupled with soil and water conservation for agriculture, water harvesting structures that support both domestic and productive uses, and wetland restoration integrated with fisheries or other income-generating activities. Beyond their biophysical components, RNBWS also incorporates social, institutional, and market considerations to ensure inclusive participation, local ownership, and economic viability. When implemented through locally grounded, participatory approaches, these measures can reduce vulnerability, strengthen food and water security, and foster social cohesion in displacement-affected areas (Debela et al., 2023; Juster et al., 2025). Mendum et al. (2024) argue that by leveraging readily available ecosystem resources to provide water, food, energy, and other essential services, RNBWS align with and reinforce displaced communities' own adaptive strategies to improve living conditions while supporting broader sustainability goals. Furthermore, integrating RNBWS builds on existing local knowledge and capacities, positioning displaced and host communities as co-creators of more sustainable and resilient solutions (Mendum et al., 2024).

[1] "RNBWS are spatially integrated combinations of nature-based solutions for water and agricultural water management. They encompass innovative agroecological and ecological water management techniques, coupled with social and market mechanisms that support long-term sustainability. In essence, RNBWS involve people working with their local natural environment to sustain water and ecosystems while improving livelihoods" (Fraj et al., 2025, p. 1).

In arid and semi-arid regions (such as the study area) that host displaced populations, evidence on RNBWS highlights a promising approach leveraging natural processes to enhance biodiversity, water security, and climate resilience (Gebrael et al., 2024; Gorain et al., 2025). This evidence is directly relevant to humanitarian agencies (e.g., UNHCR, IOM, WFP, and international/national Non-Governmental Organizations (NGOs) focusing on refugees, water and food security), government bodies at state and national levels (ministries of water resources, agriculture and forestry, environment, and refugee affairs), and community-based organizations engaged in environmental management and livelihood support, as well as to bilateral donors, climate finance mechanisms (e.g., Green Climate Fund, Adaptation Fund), and multilateral development banks, guiding their planning, programming, investment, and implementation decisions in these contexts. By improving water storage, purification, and regulation, RNBWS protects communities from climate impacts such as droughts and floods (Bagwan, 2024). These solutions provide cost-effective, locally adaptable methods for addressing environmental migration and supporting both displaced and host communities (Kiribou et al., 2025). Integrating RNBWS evidence into humanitarian and development programs can also foster long-term economic resilience by reducing climate change impacts, diversifying livelihoods, and creating jobs in ecosystem restoration (Nyambo et al., 2025). Despite challenges like funding constraints, population movement, weak governance, and land tenure insecurity, these nature-based solutions offer humanitarian, governmental, and local partners powerful means to restore drylands, combat degradation, and strengthen local community resilience.

Considering these interconnected challenges in fragile and conflict-affected areas and the potential contributions of RNBWS to addressing them, this study – focusing on Kassala, El Gedaref, and White Nile states of Sudan – aims to: (i) assess societal and environmental challenges in selected refugee-hosting communities; (ii) identify potential RNBWS that can address these challenges; and (iii) map potential or suitable areas for implementing the identified RNBWS. This study builds on IWMI's ongoing work on RNBWS in the MENA region, particularly the Al Murunah and Wiqaya projects, by extending their integrated, resilience-focused approaches to a new fragile and displacement-affected context[2]. This study is grounded in the understanding that effective solutions for fragile and conflict-affected areas must be tailored to local realities, both physical and social. Addressing these interconnected challenges requires identifying the societal needs and biophysical characteristics unique to each setting – a task reinforced by the fact that the targeted study areas represent diverse socio-ecological systems where competition over scarce resources has intensified due to displacement dynamics. By combining literature review, socioeconomic analysis, and geospatial mapping, this study seeks to generate actionable insights that align humanitarian priorities with environmental sustainability.

[2] See almurunah.iwmi.org/ and https://www.iwmi.org/projects/wiqaya/ for more information on these projects.

2. Materials and methods

2.1. Study area

The study was conducted in Kassala, El Gedaref, and White Nile states of Sudan, located in eastern and southeastern Sudan (Figure 1). Kassala State, covering about 48,802 km² and sharing a border with Eritrea, has a population of over 2.5 million people. It features semi-arid to dry sub-humid conditions with an average annual rainfall of between 400 and 700 mm (CMI, 2020; Etifor and Hamerkop, 2022). El Gedaref, which borders Ethiopia and the south and southwestern parts of Kassala, spans approximately 59,762 km² and receives an average annual rainfall of 700–900 mm. The climate in El Gedaref is relatively warm, with daily maximum temperatures ranging from 25°C to 40°C. The presence of fertile clay soils and adequate rainfall makes El Gedaref a highly suitable region for rainfed crop cultivation in Sudan. White Nile State, covering 38,461 km² and home to approximately 2.5 million people, is situated along the White Nile River, where irrigation projects and riverine farming are essential for supporting livelihoods (Abd El-Hamid et al., 2021).

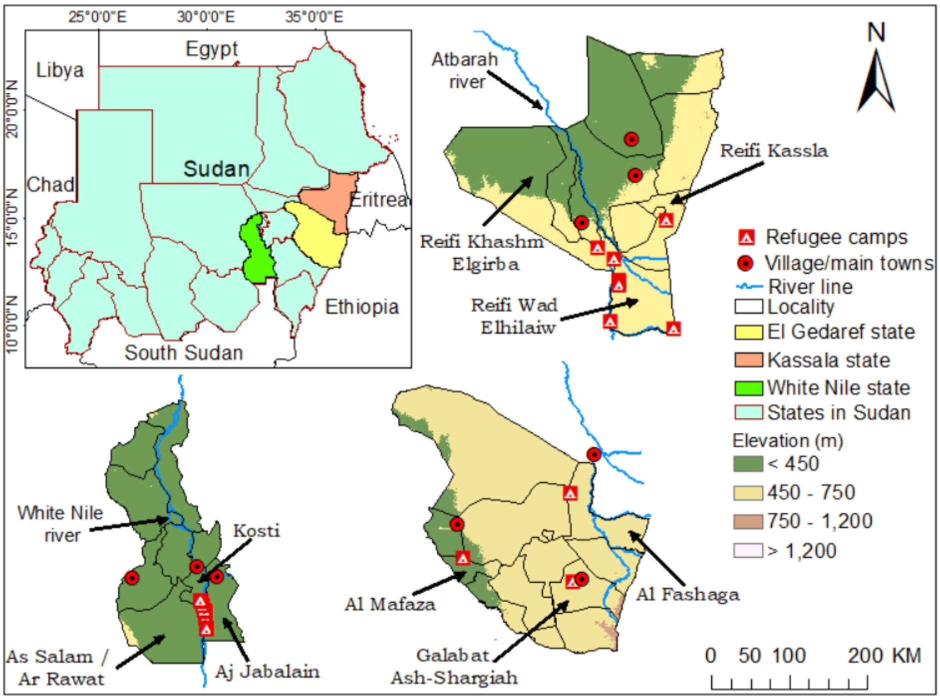

Figure 1. Location map of the study areas with the spatial distribution of refugee camps within each state. (Source: authors using data from OCHA (https://data.humdata.org/dataset/sudan-administrative-boundaries-2) and UNHCR (https://data.humdata.org/dataset/unhcr-refugee-camps))

Sudan has long hosted millions of refugees fleeing from neighboring countries, and a significant number of them have settled in the White Nile, El Gedaref, and Kassala states. Estimates as of April 30, 2026, indicated that 410,538 refugees were in nine refugee camps in White Nile, 109,394 refugees in seven refugee camps of Kassala, and 61480 refugees in three refugee camps of El Gedaref (Figure 2). Nearly all refugee camps in the three states are found along the White Nile and Atbara rivers, where most host communities reside (Figure 2). Apart from refugees, internally displaced persons (IDPs) pose a significant challenge in Sudan. Recently, fighting in Sudan has sharply increased the number of IDPs across the country. As of 30 April 2026, over 8,936,175 people have been displaced within Sudan. Of these, about 6.7% (598,426) of the IDPs live in the three states.

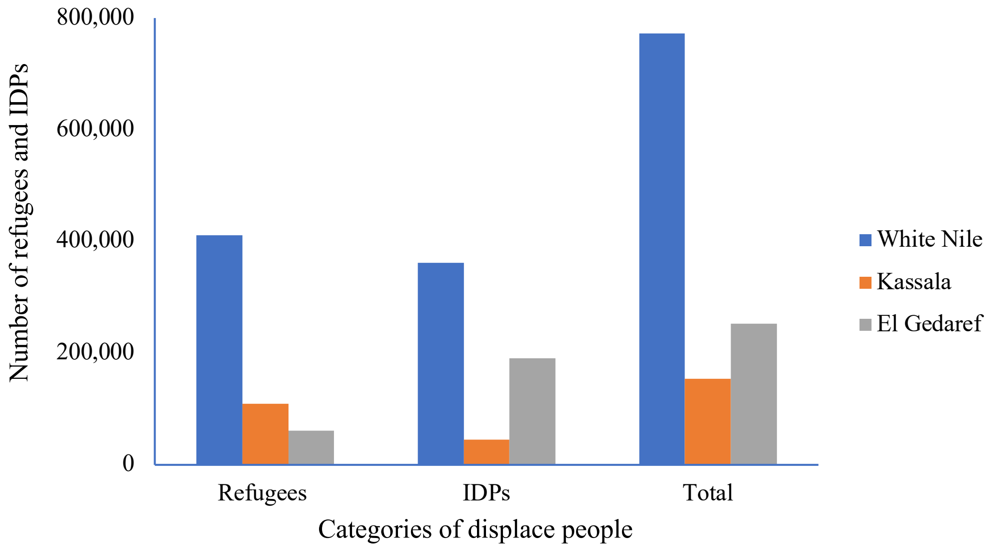

Figure 2. Refugee and IDP population as of 30 April 2026 (Source: Author's creation based on the information available at: https://data.unhcr.org/en/country/sdn)

2.2. Data collection and analysis

This study primarily employed literature reviews to assess societal challenges in the three states of Sudan and identify RNBWS that can address these challenges (see section 2.2.1). Additionally, spatial analyses were used to develop biophysical profiles of these states (see section 2.2.2) and to map suitable areas for implementing the identified RNBWS (see section 2.2.3).

2.2.1. Literature review

An extensive literature review was conducted to identify and synthesize existing research on societal challenges faced by refugee and host communities in the Kassala, El Gedaref, and White Nile states of Sudan, as well as the use of RNBWS. Evidence was collected from the literature regarding key success and failure factors for implementing and scaling RNBWS. Sources included peer-reviewed journal articles, policy reports, and publications from international organizations accessed through academic databases such as Scopus, Web of Science, and Google Scholar, as well as the grey literature from UNHCR, FAO, and IWMI repositories. The search employed a combination of keywords and Boolean operators, including “Sudan refugees,” “host communities,” “societal challenges,” “deforestation,” “water insecurity,” “land degradation,” “drought,” “flood,” “nature-based solutions,” and “resilient water management.” The inclusion criteria focused on studies published in English within the last 15 years that addressed the environmental and social dimensions of displacement and water-related resilience. Relevant data were extracted, categorized into thematic areas, and synthesized using a deductive, manual coding approach to inform the assessment.

2.2.2. Biophysical characterization

The biophysical characterization of the three states included profiling soil characteristics, topographic features, agroecological zones, long-term annual rainfall, land use and land cover (LULC) dynamics, and assessing land degradation neutrality (LDN).

Data sources

Spatial datasets collected from various open-source geographic information system (GIS) and remote sensing platforms were used for biophysical characterization. Soil characteristics were retrieved from the FAO Harmonized World Soil Database version 2.0 (https://gaez.fao.org/pages/hwsd) and the SoilGrids raster layer at 250 m spatial resolution, developed by the International Soil Reference Information Centre (ISRIC) (https://soilgrids.org).

Long-term mean annual rainfall data were retrieved from the Climate Hazards Group InfraRed Precipitation with Station (CHIRPS) data, available at https://data.chc.ucsb.edu/products/CHIRPS-2.0/global_annual/tifs/. Topographic information was derived from 12.5m Digital Elevation Models (DEM) acquired from the Alaska Satellite Facility (https://search.asf.alaska.edu/#/). Agroecological zones defined in terms of climate, landform and soil, and/or land cover were retrieved from the Regional Center for Mapping of Resources for Development (https://gmesgeoportal.rcmrd.org/datasets/rcmrd::agro-ecological-zones-dataset/about).

Landsat 4-5 Thematic Mapper, Landsat 7 Enhanced Thematic Mapper Plus, and Landsat 8 Operational Land Imager / Thermal Infrared Sensor images with 30 m resolution were used for mapping the LULC for the years 2005, 2015, and 2025 and assessing the LULC dynamics during the last two decades. A Sentinel-2 image with 10 m resolution was used for mapping the current (2026) LULC and potential areas suitable for the identified RNBWS. These distinctions were made to ensure the mapping of potential suitable areas is based on high-resolution current LULC conditions. Landsat and Sentinel-2 images were collected from the System for Earth Observation Data Access, Processing and Analysis for Land Monitoring (SEPAL) portal (https://sepal.io) and the Google Earth Engine (GEE) platform. A time series of the Normalized Difference Vegetation Index (NDVI) dataset was derived from the Advanced Very-High-Resolution Radiometer (AVHRR) provided by the Global Inventory Modeling and Mapping Studies (GIMMS) and the Terra Moderate Resolution Imaging Spectroradiometer (MODIS) Vegetation Indices (MOD13Q1, Version 6) (Mekuria and Girma, 2025) for LDN analysis.

Land use and land cover analysis

Satellite image pre-processing, hybrid classification (combining unsupervised and supervised classification), accuracy assessment, and change detection were conducted in ArcGIS 10.8 and ERDAS IMAGINE 16 (Gorelick et al., 2017; Patel et al., 2024). The classification accuracy was evaluated using a confusion matrix and standard accuracy metrics, including the overall accuracy, producer’s accuracy, user’s accuracy, and Kappa coefficient (Girma et al., 2022). Post-classification comparison was applied to detect, quantify, and map LULC changes over different time periods.

Land degradation neutrality assessment

LDN was assessed following the Good Practice Guidance (GPG) by integrating three sub-indicators: land productivity (LP), land cover (LC), and soil organic carbon (SOC) (Sims et al., 2021). LP changes were determined from time-series NDVI datasets, and the Water Use Efficiency (WUE) correlation method was applied to minimize the influence of climate and seasonal variability in Trends.Earth (Schillaci et al., 2023; Moges et al., 2023). LC changes were assessed using custom LULC data, analyzing land cover transitions to identify stable and changing pixels and generating degradation typologies, and combined in Trends.Earth to compute the land degradation status. SOC changes were estimated using the IPCC/UNCCD land-use conversion coefficients, with areas losing or gaining more than 10% SOC classified as degraded or improved, respectively (Yuan et al., 2022; Sims et al., 2021). Finally, the sub-indicators were integrated using the “One-Out, All-Out” (1OAO) principle to determine the overall extent of degraded land (Sims et al., 2021; Schillaci et al., 2023; Zhao et al., 2023).

2.2.3. *Identification and mapping of resilient nature-based water solutions*

Identification of solutions

We used multiple methods to identify and verify potential RNBWS. First, we used literature reviews (see section 2.2.1) to compile RNBWS suitable for the study sites that can address societal challenges. Second, we used the criteria outlined by Albert et al. (2021) and two frameworks: the International Union for Conservation of Nature (IUCN) Global Standard for Nature-based Solutions (IUCN, 2020) and the Restoration Opportunities Assessment Methodology (ROAM) to identify, verify, and design RNBWS (IUCN and WRI, 2014). The Global Standard provides a framework of eight criteria (Table 1) and associated indicators for identifying, designing, and verifying nature-based solutions. The IUCN standards can be applied to both large- and small-scale interventions across diverse settings, from protected areas to productive landscapes to urban areas, across different regions, and in modified or intact ecosystems (IUCN, 2020).

We applied an adaptive version of the ROAM framework (Moges et al., 2023), cognizant that conflict-related access constraints prevented the full participatory elements and formal socio-economic assessment that ROAM typically entails. In the absence of extensive on-ground stakeholder engagement, we relied on a combination of secondary data sources (including national datasets, prior field studies, and project reports), expert knowledge, and intensive spatial analysis to identify and prioritize tree-based RNBWS for restoration. To partially compensate for limited field access, we conducted multiple virtual consultations via online platforms with humanitarian and development organizations actively operating in the study areas, as well as national experts familiar with local conditions. These engagements provided critical context-specific insights and served as an important proxy for local knowledge, allowing us to triangulate and validate spatial and literature-based findings. While connectivity, security, and logistical constraints limited broader remote engagement (e.g., with community-led stakeholders), the combination of these data sources and iterative expert validation provided a sufficiently robust basis for decision-making. These adaptations allowed us to adhere to ROAM's core principles of context-specific, cost-effective planning, even though the stakeholder engagement and socio-economic assessments were necessarily limited. Figure 3 summarizes the ROAM workflow (i.e., the five main steps) for identifying and prioritizing tree-based RNBWS. Table 2 summarizes the overall processes and key steps followed during the identification of potential RNBWS.

Table 1. The IUCN Global Standard for Nature-based Solutions and its Eight Criteria and the relationship with the ROAM activities or procedures. (Source: IUCN and WRI, 2014; IUCN, 2020)

Criteria	Description
Criterion 1 - Identifying the societal challenge- Step 1 in the ROAM approach	Includes climate change (adaptation and mitigation), disaster risk reduction, ecosystem degradation and biodiversity loss, food security, human health, social and economic development, and water security.
Criterion 2 - Design of the solution responding to the scale of the issue- step 2 in ROAM	Scale refers to geographic scale across land and sea, as well as the economic, ecological, and societal aspects of the land/seascape.
Criteria 3, 4, and 5 - Correspond to the three pillars of sustainable development: environmentally sustainable, socially equitable, and economically viable- Steps 3 and 4 in ROAM.	For each Criterion, some understanding of the current resources and context, in the form of a baseline, and sustainable actions going forward, is required for implementation of a strong nature-based solutions (NbS).

Criterion 6 - The balancing of trade-offs; selecting solutions having both short and long-term gains- Step 4	This refers to meeting communities' short-term interests and long-term environmental goals.
Criterion 7 - Adaptive management	Facilitates continuous learning about system-wide processes and adapting the NbS according to systemic changes.
Criterion 8 - Ensuring sustainability- Step 5	This is linked with identifying success and failure factors and designing appropriate interventions

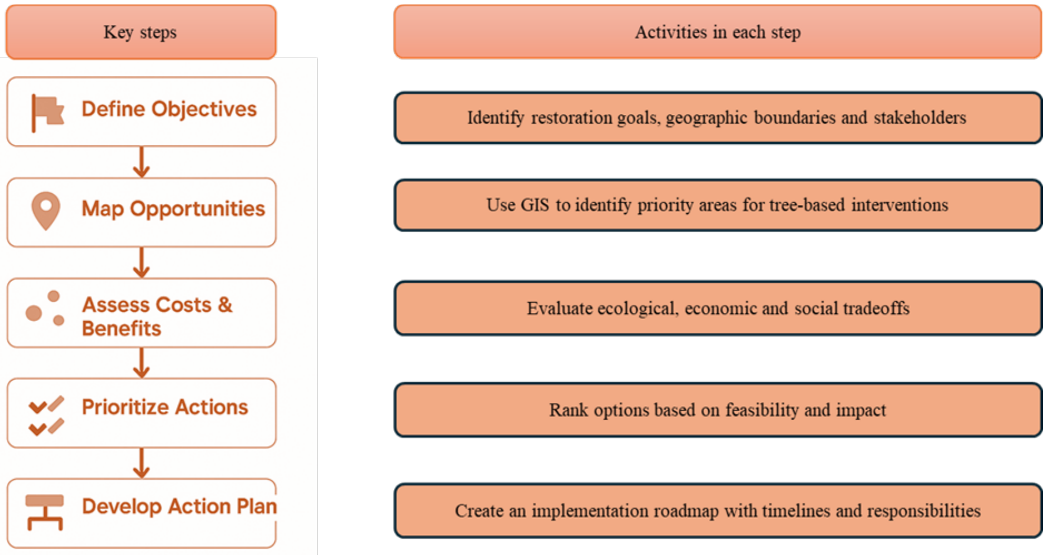

Figure 3. The five steps in restoration planning using the ROAM approach. (Source: IUCN and WRI, 2014)

Table 2. Steps followed to identify resilient nature-based water solutions (Source: Authors)

Steps	Purpose	Activities/examples	Tools/criteria
Step -1: Baseline assessment	Understand the ecological, social, and economic context of the study areas.	Collect data on LULC and biophysical characteristics, water resources, and community needs.	Biophysical profiling using GIS and remote sensing, literature review.
Step – 2: Problem and opportunity analysis	Identify the main environmental challenges (e.g., soil erosion, water scarcity) and opportunities for restoration.	Map degradation hotspots or LDN status.	LDN assessment using sustainable development goals (SDG) indicators
Step 3: Identification of RNBWS	Select interventions that address challenges while delivering co-benefits.	Using the criteria outlined by Albert et al. (2021), and IUCN and ROAM frameworks, RNBWS categorization as tree-based, watershed management, water harvesting, wetland restoration, riparian buffer restoration, etc.	Matching the challenges with the benefits of RNBWS.
Step 4: Mapping potential areas	Estimate suitable or potential areas for implementing the identified RNBWS.	Spatial mapping of potential areas.	Ecological suitability, inclusion and exclusion criteria, overlay analysis, etc.

Mapping potential areas for the identified resilient nature-based water solutions

To map potential areas for RNBWS, the process begins by establishing clear inclusion and exclusion criteria that reflect both the biophysical and socio-economic characteristics (such as land size, land tenure, agriculture, livestock, and livelihood mechanisms) of the sites. These criteria are informed by the specific requirements of the proposed solution, including hydrological conditions, soil properties, land use patterns, and ecological integrity, as well as lessons learned from experience and best practices. Equally important is the identification of key limiting factors, such as water availability, land tenure constraints, infrastructure limitations, and community acceptance, which could hinder successful implementation. By systematically integrating these considerations, the mapping exercise ensures that the selected areas not only meet the technical and ecological prerequisites but also offer favorable conditions for long-term sustainability and resilience. This approach provides a robust framework for prioritizing sites where nature-based solutions can empower refugees and host communities to address shared challenges and build resilient livelihoods.

Using the inclusion and exclusion criteria and advanced spatial analysis tools in ArcGIS, the potential areas suitable for each identified RNBWS were delineated. The process involved multiple techniques adapted from Shabir et al. (2019), including buffer analysis, overlay analysis, attribute-based selection, and Boolean logic operators. Buffer analysis was applied to define zones of influence around critical landscape features, such as water bodies, riparian corridors, and transportation networks. Overlay analysis was used to identify locations meeting multiple suitability criteria, such as land use, soil type, slope, and hydrological conditions. Attribute-based selection was employed to extract specific sites that met predefined inclusion or exclusion conditions for each RNBWS option. Boolean logic operators (e.g., AND, OR) were used to combine individual suitability layers into composite maps, highlighting priority areas for intervention.

2.2.4. Assessment of environmental benefits

The potential contributions of the identified RNBWS to environmental benefits, particularly biodiversity conservation and ecosystem integrity, were evaluated. In addition, a complementary analysis of above-ground biomass was conducted to characterize its contribution to the agricultural and pastoral-based livelihood benefits. This involved analyzing both short-term and long-term benefits, as well as potential trade-offs, using information from literature, reports, and documented experiences. The expected environmental benefits were quantitatively estimated based on carbon stock accumulation (Liu et al., 2023). The aboveground biomass (AGB) was estimated using a biomass function that considered NDVI as an independent variable using Equation 1 (Fantahun et al., 2022).

$$\log_{10} AGB = 0.812 + 1.762(NDVI) \ldots\ldots\ldots\ldots\ldots\ldots\ldots\ldots\ldots\ldots\ldots (\text{Eq. } 1)$$

Where NDVI is the Normalized Difference Vegetation Index calculated as

$$NDVI = \frac{NIR - R}{NIR + R} \ldots\ldots\ldots\ldots\ldots\ldots\ldots\ldots\ldots\ldots\ldots\ldots\ldots\ldots\ldots\ldots\ldots\ldots\ldots\ldots. (\text{Eq. } 2)$$

Where NIR and R represent the Near Infrared and Red bands.

Following the estimation of above-ground biomass, above-ground carbon was estimated using Equation 3 (Eggleston et al., 2006).

$$Carbon\ Content\ (t\ C\ ha^{-1})\ =\ 0.5\ \times\ AGB\ (t) \ldots\ldots\ldots\ldots\ldots\ldots (\mathrm{Eq.}\ 3)$$

Where *t C ha*$^{-1}$ is tons of carbon per hectare, *AGB* is aboveground biomass.

Carbon stocks are traded as CO_2 units (Höhne et al., 2003); therefore, the CO_2 equivalent (t CO_2 ha^{-1}) was estimated by multiplying the carbon stock (t C ha^{-1}) by the molar conversion factor of 3.67 (Olschewski and Benitez, 2005) as shown in Equation 4.

$$CO_2(t\ CO_2eq\ ha^{-1}) = Carbon\ content\ (t\ C\ ha^{-1}) * 3.67 \ldots\ldots\ldots (Eq. 4)$$

3. Results and Discussion

3.1. Biophysical characteristics

The biophysical characteristics of Kassala, El Gedaref, and White Nile states exhibit considerable spatial variation in elevation, slope, rainfall, and soil type (Figure 4), reflecting differences in biophysical characteristics among the three states. Elevation ranges from 337 m to 1,516 m in Kassala, 406 to 1,229 m in El Gedaref, and 353 to 660 m in White Nile state, showing a decreasing gradient from east to west (Figure 4a-c). Most areas (81% in El Gedaref, 69% in Kassala, and 77% in White Nile) are characterized by very gentle or flat slopes (i.e., having 0–5% slope), while 18%, 29%, and 23%, of the area of the three states respectively, fall under gentle slopes (5–15%) (Figure 4d-f). The long-term mean annual rainfall shows a clear north-to-south gradient (Figure 4g-i), ranging from 86 to 575 mm in Kassala, 186 to 1,000 mm in El Gedaref, and 114 to 495 mm in White Nile state. We identified eight major soil types in Kassala, and six in El Gedaref and White Nile, each (Appendix Table 1). Vertisols dominate in El Gedaref (77.8%) and White Nile (56.5%), while Kassala shows relatively diverse soil composition, primarily Cambisols (36.6%), Vertisols (22.9%), and Luvisols (19.6%).

The observed variability in elevation, slope, rainfall, and soil types across Kassala, El Gedaref, and White Nile states has important implications for identifying and mapping RNBWS. The east–west and north–south gradients, respectively in topography and rainfall, imply that hydrological processes, runoff generation, and water retention potential differ substantially across the landscape. While the predominance of flat to gently sloping terrain suggests broad suitability for landscape-scale interventions, differences in elevation and rainfall regimes require context-specific design and placement to ensure effectiveness and long-term resilience.

Similarly, spatial heterogeneity in soil types strongly conditions RNBWS' performance and sustainability. The dominance of Vertisols in El Gedaref and White Nile highlights opportunities for high productivity, water-retentive systems, but also underscores the need to address risks of waterlogging, impeded groundwater recharge, and seasonal cracking through appropriate drainage-sensitive RNBWS options. In contrast, the more diverse soil mosaic in Kassala, including Cambisols, Luvisols, and Arenosols, points to variable infiltration, fertility, and moisture storage conditions, necessitating differentiated RNBWS portfolios rather than uniform interventions. Taken together, these biophysical variabilities reinforce the importance of spatially explicit, multi-criteria mapping approaches that integrate topography, climate, and soils to identify RNBWS that are not only suitable, but also resilient under contrasting environmental conditions.

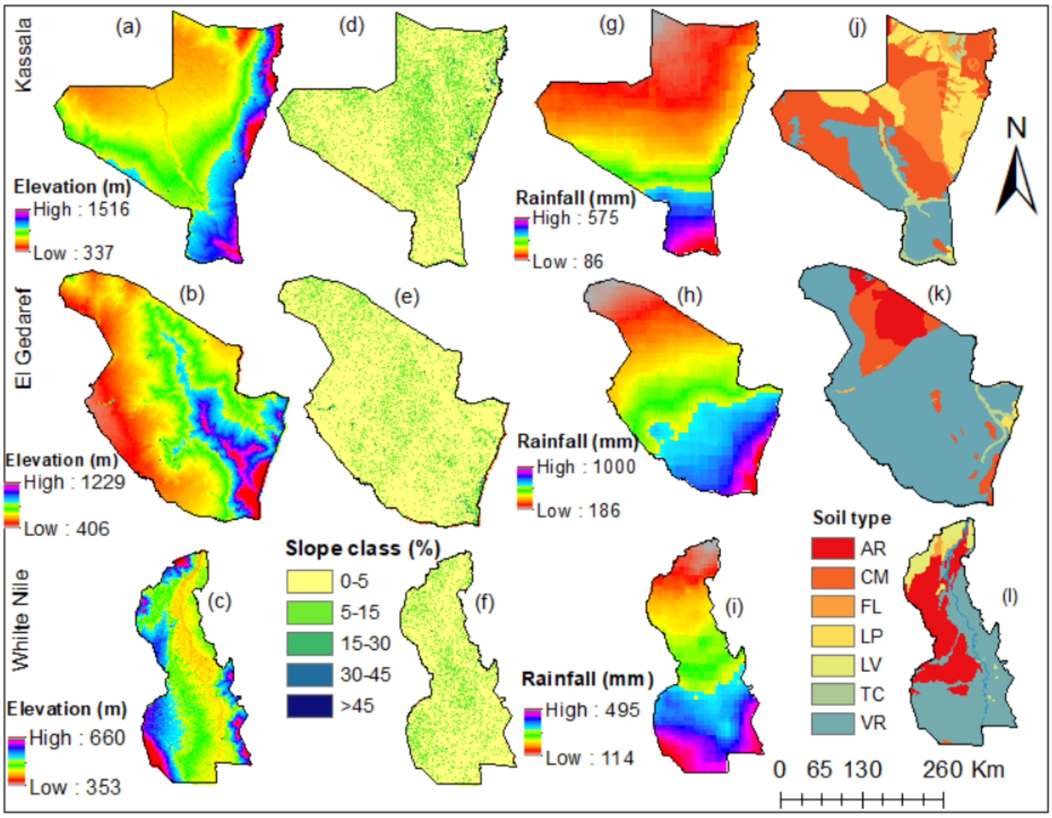

Figure 4. Biophysical characteristics of Kassala, El Gedaref, and White Nile: Elevation (a-c), Slope class (d-f), mean annual rainfall (g-i), and major soil type (j-l). AR refers to Arenosols, CM-Cambisols, Fl-Fluvisols, LP-Leptosols, LV-Luvisols, TC-Technosols, and VR - Vertisols. (Source: author's creation)

3.2. Land use and land cover dynamics in the three states

Analysis of LULC changes over the 21 years (2005–2025) reveals significant landscape transformations driven mainly by agricultural expansion, deforestation, settlement growth, and vegetation degradation. Forestlands declined by 68% in Kassala, 80% in El Gedaref, and 35% in White Nile, indicating extensive deforestation and pressure on natural vegetation. Grasslands decreased by 20% in Kassala, 61% in El Gedaref, and 64% in White Nile. On the other hand, farmland increased by 46%, 27%, and 5% in El Gedaref, White Nile, and Kassala, respectively. Settlement areas increased across all three states, with the highest expansion (214%) over the 21 years recorded in Kassala (Table 3). This may be attributed to the existence of old settlement areas in the state. Bare land increased in Kassala (33%) and White Nile (6%), while it declined in El Gedaref (19%). In 2015, the observed increase in waterbodies in Kassala and El Gedaref was associated with the construction and impoundment of the Upper Atbara and Setit Dam Complex (Shuka et al., 2022). Figure 5 shows the LULC for 2005, 2015, and 2025.

The observed dynamics over the past 21 years indicate intensified human pressure on natural ecosystems, and the need for restoration through the implementation of RNBWS, including tree-based nature-based solutions, such as afforestation, exclosures, and agroforestry practice, rangeland restoration, water harvesting, and diverse watershed management practices to enhance ecosystem resilience and sustain agricultural productivity in the studied states. Settlement growth across all three states suggests the importance of designing RNBWS that are suitable for urban and peri-urban areas.

Table 3. Land-use and land-cover dynamics (Area in hectares) (Source: authors' analysis)

State name	Year	Waterbodies	Forestlands	Farmlands	Bare land	Settlement areas	Grasslands	Shrublands
Kassala	2005	31825	382027	1063385	1783181	129825	479267	1010715
	2015	77716	294643	1031485	2081219	247327	425049	722785
	2025	13837	122314	1117206	2371587	407063	382321	465896
	Δ (2025-2005)	-17988	-259713	53821	588406	277238	-96946	-544819
El Gedaref	2005	47484	698937	2304288	1051675	216933	809829	847102
	2015	75759	456395	2589415	970018	439367	623959	821335
	2025	22570	138738	3372616	855193	648963	313271	624897
	Δ (2025-2005)	-24914	-560199	1068328	-196482	432030	-496558	-222205
White Nile	2005	171563	174370	1372548	1135046	116014	279265	595269
	2015	151812	158542	1469879	1271289	197117	142808	452618
	2025	105480	113916	1743385	1206453	276826	101659	296336
	Δ (2025-2005)	-66083	-60454	370837	71407	160812	-177606	-298933

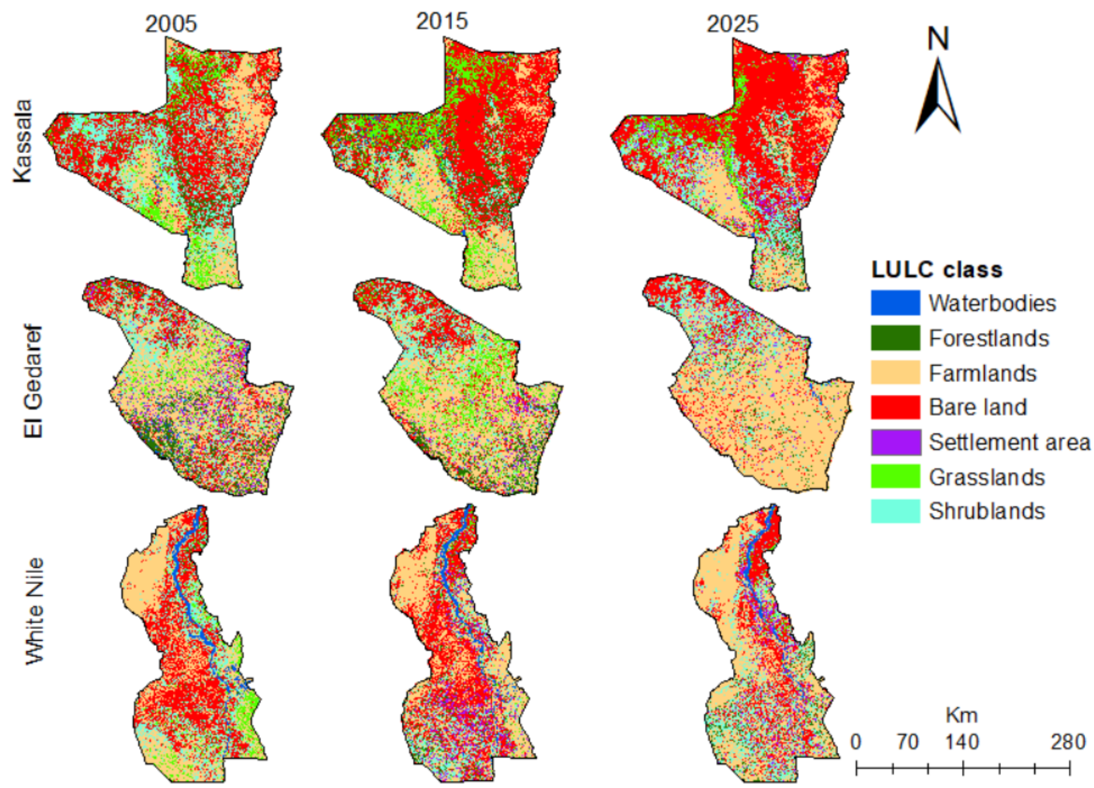

Figure 5. Land-use and land-cover classes for the years 2005, 2015, and 2025 (Source: Authors' creation)

3.3. Land degradation neutrality of the three states

The LDN assessment over the 21 years (2005–2025) indicates a consistent shift toward land degradation in the three states (Table 4, Figure 6). Areas showing degraded status increased from

29.1% to 37.1% in Kassala, 42.1% to 56.1% in El Gedaref, and 33.6% to 38% in White Nile. On the other hand, areas displaying improved status declined from 29.2% to 12.2%, 33.5% to 11.8%, and 33.8% to 13.9% in Kassala, El Gedaref, and White Nile state, respectively. The LDN trend highlights the vulnerability of the states to environmental stress.

Table 4. Land degradation indicators based on SDG 15.3.1 (Source: authors' analysis)

LDN status	Kassala state				El Gedaref state				White Nile state			
	2005-2015		2015-2025		2005-2015		2015-2025		2005-2015		2015-2025	
	ha	%	ha	%	ha	%	ha	%	ha	%	ha	%
No data	20732.6	0.4	20732.6	0.4	13546.2	0.2	13545.7	0.2	131960.6	3.4	131958.4	3.4
Degraded	1418917.0	29.1	1809470.0	37.1	2515221.6	42.1	3351961.7	56.1	1293228.4	33.6	1460077.3	38.0
Stable	2016437.0	41.3	2456286.3	50.3	1446774.1	24.2	1904036.4	31.9	1122067.3	29.2	1719409.5	44.7
Improved	1424140.2	29.2	593738.0	12.2	2000706.3	33.5	706704.4	11.8	1298818.5	33.8	534629.5	13.9
Total	**4880227**	**100**	**4880227**	**100**	**5976248**	**100**	**5976248**	**100**	**3846075**	**100**	**3846075**	**100**

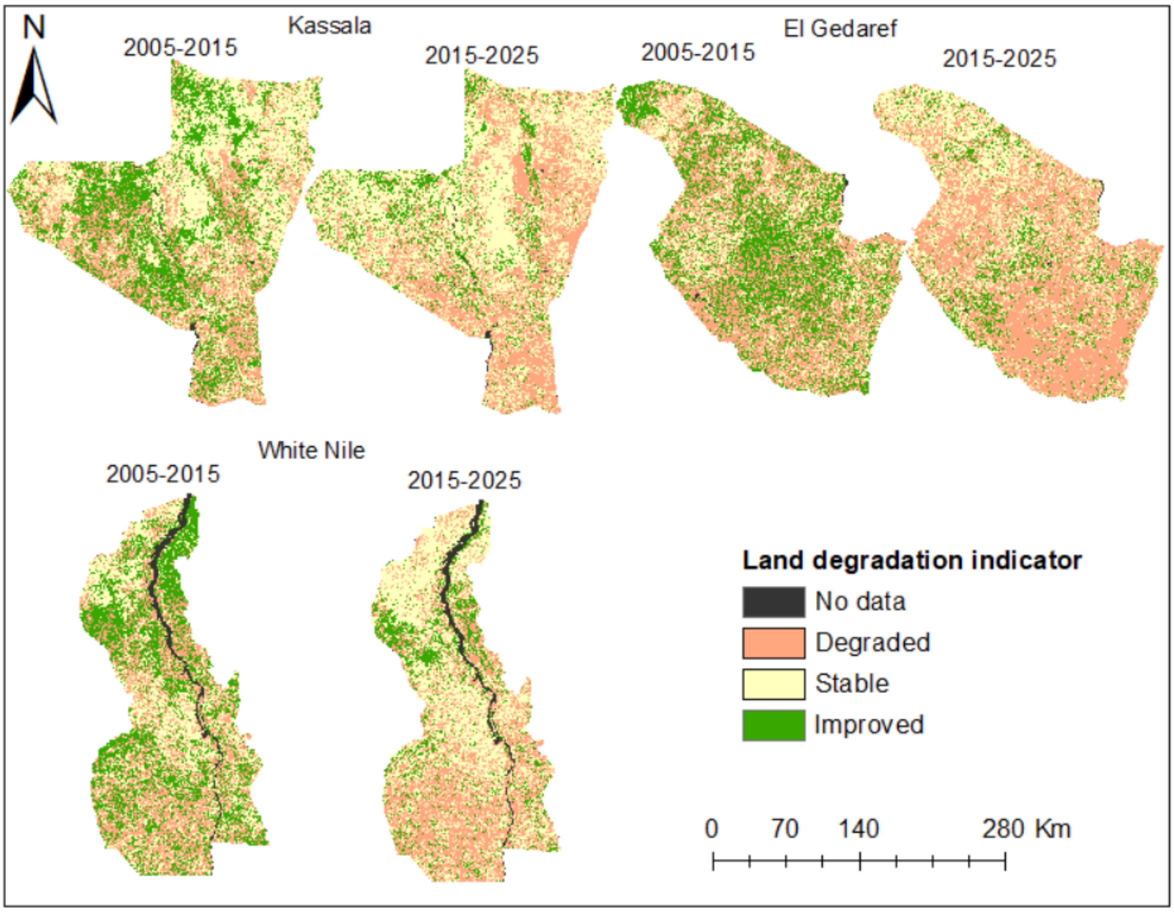

Figure 6. Land degradation indicator map for Kassala, El Gedaref, and White Nile state (Source: authors' creation)

3.4. Socio-economic characteristics

3.4.1. Land size, land tenure, and agriculture

The total land size of Sudan is over 1.7 million square kilometers, and the size of the three states is comparable, ranging from 0.04 to 0.06 million square kilometers. Based on the 2020 land cover, the Agricultural land in Sudan accounts for 18% of the total land area of the country (33 million ha), with 95% share of the rainfed agriculture (Kumar et al., 2023).

In Sudan, the land tenure system is complex. Less than 10% of the land is registered, and according to the formal law, all unregistered land in the country is owned by the government. (Rahma et al., 2024).

Cultivated lands in El Gedaref are nearly twice as much as White Nile and four times than Kassala (Table 5). Like other states of Sudan that receive sufficient rains (e.g., Blue Nile), rainfed agriculture is dominant and contributes a greater share to food production in the three studied states (Kumar et al., 2023). Irrigated agriculture is higher in Kassala than in the other two states. This, perhaps, might be due to the drier climate and availability of water from the Atbara and Gash Rivers.

Table 5. Agricultural lands under rainfed and irrigated systems in the three states (Kirui et al., 2024)

State	Population	Total area	Rainfed agriculture		Irrigated agriculture		Total	
		ha	ha	%	ha	%	ha	%
White Nile	2,493,880	3,846,080	2,128,100	6.8%	35,900	2.2%	2,164,000	6.6%
El Gedaref	2,208,385	5,976,248	4,031,000	12.8%	39,500	2.5%	4,070,500	12.3%
Kassala	2,519,071	4,880,224	849,600	2.7%	189,300	11.8%	1,038,900	3.1%
Total for Sudan	**52,032,122**	**176,504,800**	**31,400,000**		**1,600,000**		**33,000,000**	

Note: percent values of rainfed and irrigated agricultural lands are calculated in reference to the total rainfed and irrigated agricultural lands in Sudan

3.4.2. Livestock

One of the major livelihood activities in the study regions is livestock keeping, where camels, goats, sheep, and cattle are found in different proportions (Figure 7). From 2009 to 2020, all livestock showed about 3% change. The dominant livestock is shoats (both goats and sheep), with a share of over 68% in 2009 and slightly decreasing to over 66% in 2020.

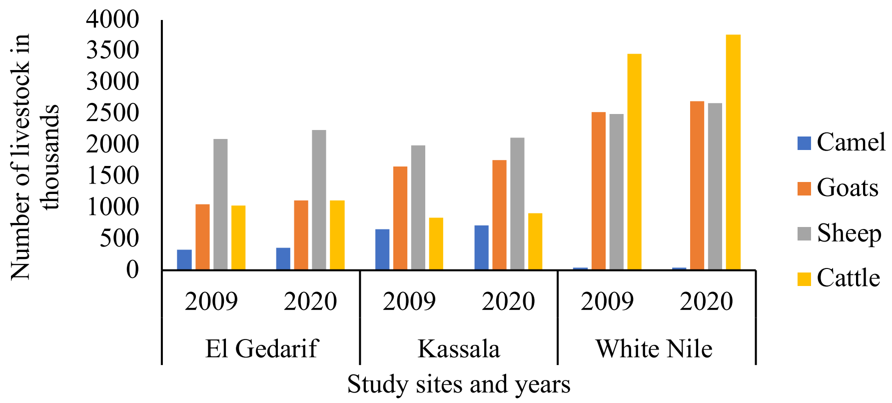

Figure 7. Livestock type and number in the study areas in 2009 and 2020 (adapted from Alfadul et al., 2024).

3.4.3. Livelihood mechanisms

According to the Sudan Livelihoods Roadmap (2023-2025) (UNHCR, 2024), the host communities and refugees across White Nile, Kassala, and El Gedaref states rely on diverse and complementary livelihood strategies shaped by local resources and economic opportunities. Table 6 summarizes the main livelihood strategies of refugees and host communities, the nature of refugee-host community interactions, and the key characteristics and challenges shaping the livelihood outcomes across White Nile, El Gedaref, and Kassala states. While livelihood activities vary according to local resources and economic opportunities, agriculture remains the primary source of income for both groups.

Studies (e.g., Moreda, 2025) indicated that refugee workers in White Nile, El Gedaref, and Kassala operate under constrained and often inequitable conditions. Although Sudan's Asylum Regulation Act (2014) formally grants the right to work, in practice, refugees face restricted access to permits, forcing many into informal employment where they are exposed to low wages, delayed payments, and exploitation. Access to productive assets is also limited: land ownership is generally prohibited, rental arrangements are costly and mediated through host communities, and access to irrigation and equipment is minimal. While markets exist, movement restrictions frequently limit participation in more profitable opportunities. These structural barriers, combined with recurring resource tensions, highlight that existing livelihood systems are not fully fair or enabling, and therefore should not be promoted without careful consideration of these inequities.

Table 6: Livelihood mechanisms of refugees and host communities and their interactions

State	Refugee livelihoods	Host community livelihoods	Refugee–host linkages	Key characteristics / challenges
White Nile	Seasonal farm labor (especially sorghum and sesame harvesting), informal employment, limited non-farm activities, and aid-supported livelihoods	Smallholder crop production, livestock rearing, fishing, fuelwood sales, land rental to refugees, and employment of refugee labor	Refugees provide agricultural labor; hosts provide land and employment opportunities	Strong dependence on agriculture; highly seasonal livelihoods; vulnerable to climate and market shocks
El Gedaref	Informal/semi-formal labor in crop production (planting and harvesting of sorghum and sesame), limited petty trade	Rain-fed cereal and oilseed farming, livestock keeping	Refugees meet seasonal labor demand; hosts provide land access and employment	Agriculture is the dominant livelihood source; limited livelihood diversification opportunities
Kassala	Farm labor, land-rental and sharecropping arrangements, produce-sharing, petty trade, small businesses, informal services	Mixed farming, agro-pastoralism, livestock rearing, and limited market trading	Land-sharing, sharecropping, and labor arrangements create strong economic interdependence	More diversified livelihoods than other states; constrained by limited assets, insecure land tenure, and weak market access
Common features across states	Agriculture-based livelihoods supplemented by informal work, petty trade, and aid assistance	Agriculture, livestock, and natural resource-based activities	Strong economic interdependence through labor, land access, and production arrangements	Heavy reliance on agriculture and natural resources, limited diversification, exposure to environmental and market risks

3.5. Societal challenges

Across Sudan, economic hardship, conflict, persecution, natural disasters, and climate change are the major drivers of displacement and migration, leading to both internal displacement and cross-border movements (Hussien and Ahmed, 2025; Agyemang et al., 2026). In the three focus states of White Nile, Kassala, and El Gedaref, decades of protracted crises have created complex displacement dynamics. For example, White Nile hosts Sudan's largest refugee population, mainly South Sudanese, with roughly 47% of refugees as of April 2026 (Figure 2). Kassala, likewise, held over 109,000 long-term refugees (primarily from Eritrea and Ethiopia) as of 30 April 2026 (Figure 2), the third-highest caseload nationally.

Across White Nile, Kassala, and El Gedaref, IDPs have moved to population centers in search of better prospects (Babekir and Aalen, 2024). Over 73% of IDPs in Kassala reside in urban areas, primarily in Kassala town and New Halfa, while about 79% of those in El Gedaref live within host communities in towns rather than formal camps (IOM, 2024). White Nile is similarly affected: refugee camps and transit centres are severely overcrowded, with roughly 64% of IDPs sheltering with host communities and only 17% housed in formal camps (IOM, 2024). This influx of refugees and IDPs has significantly expanded local populations: in White Nile, new arrivals have nearly doubled the populations in some areas, whereas in El Gedaref, IDPs increased the population by an estimated 44% in 2023–2024, placing extreme pressure on housing, water, and social services (OCHA, 2023b; UNICEF, 2023; Babekir and Aalen, 2024). For example, in Kassala town, rents have reportedly risen to US$600–1,000 per month, far beyond the reach of most displaced families (IOM, 2024).

Conflict-related income losses—stemming from disrupted livelihoods and the suspension of civil servant salaries due to ongoing insecurity—have further weakened public service delivery, leading to the closure or minimal operation of schools and clinics (Babekir and Aalen, 2024). Across the three states, displacement can intensify existing pressures on already stressed ecosystems, particularly where governance, energy access, and land management systems are weak. Particularly, in Kassala, heavy dependence on firewood for cooking by refugees and host households has accelerated deforestation and bushland degradation around refugee-hosting areas (UNHCR, 2022a; Babekir and Aalen, 2024). In El Gedaref and White Nile, increased demand for water and grazing land has contributed to soil degradation, pasture depletion, and localized farmer–herder conflicts, as shared resources become increasingly scarce (Babekir and Aalen, 2024). These pressures underscore how displacement can amplify environmental stress in already vulnerable ecosystems, with degradation of forests, soils, and water resources emerging as persistent challenges in refugee-hosting landscapes of eastern Sudan.

Table 7 summarizes key challenges documented in humanitarian and donor agency reports (e.g., UNHCR, OCHA, FAO, DTM, DRC) for Kassala, El Gedaref, and White Nile states. These reported stresses encompass environmental degradation (notably deforestation and soil erosion), climate and hydrological risks (droughts and flood hazards), natural resource pressure (overgrazing, competition over land and fuelwood), and socio-economic constraints limiting services and livelihoods (water scarcity, food insecurity, healthcare strain, and conflict). We emphasize that the challenges listed in Table 7 originate from secondary sources (agency assessments) rather than our own field measurements. However, selected environmental issues, particularly deforestation and LULC transformation, were cross-validated through our independent biophysical analyses (satellite-based LULC change detection and LDN indicators), which confirmed that the agencies' reported stresses align with observed biophysical changes.

Table 7. Challenges of displaced people and host communities (Adapted from sources indicated in the Table).

Challenge categories	Key challenges	Reference
	Kassala state	
Social	Water scarcity during dry months	FAO, 2023; UNHCR, 2024; Ethar Relief, 2024
Environmental	Drought and flood risk along the river lines	
Environmental/social	Pressure on farmland and grazing areas	
Environmental	Soil degradation	
Environmental	Deforestation	
Environmental	Limited water resources	
Environmental	Flood risk along Khors	Raut, 2020; UNHCR, 2024; Saeed Ali, 2014
Environmental	Grassland degradation due to livestock pressure	
Environmental	Vegetation loss	
Environmental	Disappearance of pasture species (Grassland degradation)	
Environmental	Overgrazing	
Social	Water shortage, Limited access to clean water	
Environmental	Environmental degradation	
Social	Fuelwood depletion due to long-term refugee settlement	
Social	High population pressure	
Social	Conflicts between the refugees and the hosts	
Social/economic	Limited livelihood opportunity	
Environmental	Waste management issues	
Environmental	Flooding during heavy rains	DTM, 2024; OCHA, 2024
Social	Disease spread (waterborne diseases)	
Environmental	Deforestation	
	El Gedaref State	
Economic/social	Resource competition	UNHCR, 2023
Environmental	Climatic risk and frequent droughts	
Economic/social	Food security gaps	
Social	Loss of pasturelands	
Social	Water scarcity	
Environmental	Deforestation	
Environmental	Soil erosion and land degradation	
Social	Conflicts with host communities	
Environmental	Over-grazing land	
Social	Scarcity of fuelwood	
Economic/Social	Limited livelihood options	
Environmental	Flood risks in rainy seasons	OCHA, 2023b
Social	Limited water access in the dry season	

Social	High pressure on grazing areas shared with pastoralists	
Environmental	Deforestation for settlement expansion and firewood,	
Social/Economic	Conflict over access to fertile farmland	
Environmental	Occasional flooding	DRC, 2023
Environmental	Soil degradation due to intensive cultivation	
Environmental	Overgrazing and declining vegetation cover	
Social	Firewood scarcity	
Social	Competition over farmland with local communities	
	White Nile	
Social/Economic	Food insecurity	UNHCR, 2022b
Environmental	Flooding risks disrupting agricultural production	
Social/Economic	Resource pressure due to refugee influx	
Economic/Social	High dependence on firewood (deforestation)	
Social	Limited reliable water sources	
Social	Nutrition and healthcare access constraints	
Social/Economic	Resources pressure/ competition due to the influx	
Social	Sanitation/latrine coverage constraints	OCHA, 2025; UNHCR, 2025; UNHCR, 2024; UNHCR, 2023
Social	Malnutrition and WASH challenges;	
Social/Economic	Shelter, health service strain	
Social/Economic	Competition over grazing land with host pastoralists	
Environmental	Environmental pressure from fuelwood collection	
Environmental	Risk of over-exploitation of wood and pasture	
Social	Malnutrition hotspots	DRC, 2023
Environmental	Shortage of fuel wood, clearing all biomass and wood	

3.6. Experience in using resilient nature-based water solutions to address challenges

Experience with RNBWS in Sudan's White Nile, El Gedaref, and Kassala states includes applications for flood management, water resource management, and sustainable agriculture. Specifically, projects have involved water spreading and rainwater harvesting (RWH) in El Gedaref and Kassala, community-led forest and wetland restoration in White Nile, and water purification efforts in both flood-prone states. These solutions are often implemented through collaborations among local communities, government agencies, and international organizations. Overall, the existing experiences in using RNBWS to address the challenges or stressors summarized in Table 7 in the three states of Sudan can be categorized as: tree-based RNBWS, water harvesting, and soil and water conservation (SWC) measures.

3.6.1. Tree-based resilient nature-based water solutions

Diverse types of tree-based RNBWS have been implemented in the three states of Sudan to address complex and interlinked challenges. These solutions include multiple agroforestry practices, measures used to stabilize riverbanks using native vegetation, and afforestation activities.

Agroforestry practices

The key aspects of experience with agroforestry in White Nile, El Gedaref, and Kassala states include:

(i) Project-based implementation: Projects, such as the Sudan Sustainable Natural Resources Management Project (SSNRMP) (2014-2023), have directly supported agroforestry, particularly in states like Kassala and White Nile, by focusing on community-based management and income-generating activities through natural products (NPs) from agroforestry systems (AFS).

(ii) Market and value chain development: Initiatives have identified the potential of AFS, recognizing the importance of dryland NPs like Gum Arabic, and have focused on strengthening local capacity to trade these products.

(iii) Integration with traditional practices: Agroforestry is being integrated with traditional agriculture, particularly in semi-mechanized rain-fed systems common in states like Kassala and El Gedaref. This includes integrating fodder trees and shrubs to provide dry-season animal feed, complementing crop production.

Notably, many agroforestry interventions (e.g., under projects like the SSNRMP) are implemented in refugee-hosting areas of White Nile, El Gedaref, and Kassala, and are explicitly designed for joint participation by displaced populations (refugees and IDPs) alongside local host communities. These activities aim to alleviate pressures on natural resources exacerbated by refugee influxes, such as unsustainable fuelwood extraction and overgrazing, while providing shared livelihood and income opportunities (e.g., via gum Arabic value chains) for both groups. By engaging refugees and hosts in community-based management, such interventions also foster social cohesion and contribute to the restoration of settlement-affected environments (Juster et al., 2025; Turyamureba et al., 2026).

The primary agroforestry practices in the White Nile, El Gedaref, and Kassala states of Sudan are agroforestry parklands (scattered trees on farmlands) and gum Arabic cultivation within a bush fallow system, also known as the Taungya system in reserve forests. Other practices include home gardens, boundary planting, and protective windbreaks/shelterbelts. While these practices are prevalent across the central clay plains of Sudan, they manifest slightly differently in each state (Table 8). Key tree species found in these AFS that contribute to soil fertility (especially nitrogen fixation) and provide various products (food, fodder, gum Arabic, wood) include: (i) Acacia senegal, (ii) Acacia seyal, (iii) Balanites aegyptiaca, (iv) Ziziphus spina-christi, (v) Mangifera indica (Mango), (vi) Citrus sinensis (Orange), and (vii) Azadirachta indica (Neem).

Table 8. Major agroforestry practices and their mode of implementation in the three states of Sudan (Source: Authors' creation)

Agroforestry practices	Modes of implementation	White Nile	El Gedaref	Kassala
Acacia Senegal plantation (Gum Arabic cultivation)	Individuals and groups, often in collaboration with the Forest National Corporation (FNC), as part of the "Revitalizing the Sudan Gum Arabic Production and Marketing Project".	✓		
Village woodlots	Small-scale community and village woodlots are established and managed by local user groups.	✓		
Shelterbelts and windbreaks	Protective Plantings are established to control sand encroachment and protect agricultural lands.	✓	✓	✓
Agroforestry Parkland Systems	Crops are commonly grown under a patchy cover of naturally regenerated and scattered trees, such as Acacia mellifera and Balanites aegyptica.		✓	
Taungya Systems	This is a key practice in forest reserves in El Gedaref and Kassala, like Rawashda and Wadkabou, Gash and Tokar deltas, where farmers are allocated land to cultivate annual crops (e.g., groundnut, sesame, sorghum) in the initial years while tending to be planted tree seedlings, often Acacia senegal and Acacia seyal.		✓	✓
Integrated Agricultural Systems	Agroforestry is practiced in irrigated areas and on floodplains, integrating crops like bananas with recommended shade and protective trees such as Acacia tortilis, Acacia nilotica, and Eucalyptus camaldulensis.			✓
Rehabilitation of Rangelands	Efforts focus on community-based rangeland rehabilitation through revegetation and sustainable grazing practices, which form a silvopastoral component of agroforestry.			✓
Fruit tree planting and Homegarden	Fruit trees are an ideal option along the Nile and Angereb rivers through irrigation. Home gardens are a good intervention in small scale farmers found around the refugee catchment area.	✓	✓	✓
Alley cropping	Mainly in areas producing maize and sorghum.	✓	✓	✓

These agroforestry practices are not ad hoc interventions but are well established within Sudan's national forestry and land-use systems. Most are implemented under the guidance and regulatory oversight of the Sudan FNC, which is mandated to manage forest reserves, support tree-based production systems, and promote sustainable land management across different agro-ecological zones. Practices such as gum Arabic plantations, taungya systems, shelterbelts, village woodlots, and rangeland rehabilitation are routinely implemented through community–state partnerships and have been strengthened over time by donor- and government-supported projects, including gum Arabic revitalization, afforestation, rangeland management, and climate-resilience programmes. These projects provide technical support, planting material, tenure arrangements, and capacity building, thereby embedding agroforestry within existing institutional structures and linking livelihood objectives with forest restoration, land rehabilitation, and environmental governance in White Nile, El Gedaref, and Kassala states. However, despite the breadth and longevity of these efforts, there is limited evidence of systematic, independent impact evaluation to assess their effectiveness, scalability, and sustainability. Addressing this gap through rigorous monitoring, evaluation, learning, and impact assessment (MELIA) would be critical for informing future investments and scaling.

Riparian buffer restoration (riverbank stabilization with native vegetation)

Sudan faces recurrent flooding along rivers, exacerbated by deforestation and degraded riverbanks. In response, riparian buffer restoration – stabilizing riverbanks with native trees, shrubs, and grasses – has been adopted in parts of White Nile, El Gedaref, and Kassala states. The nature-based interventions, often implemented through projects by the UN agencies and government partners, aim to reduce flood severity while providing co-benefits like improved livelihoods and ecosystem services (Table 9). Projects often integrate planting trees, shrubs, and ground cover along riverbanks to create a natural buffer zone.

Table 9. Major riparian buffer restoration initiatives in the three states of Sudan (adapted from project documents indicated in the table and footnote)

State	Initiatives	Activities	Purpose	Implementers	Beneficiaries
White Nile	Refugee-host community reforestation initiative; launched in 2017	Large-scale planting of native trees	To combat both land degradation and flood risk	UNHCR, in partnership with Sudan's FNC.	By 2020, over 250,000 South Sudanese refugees and the local host population (~1.7 million) were indirect beneficiaries[3]
Kassala	Gash Sustainable Livelihoods Regeneration Project (GSLRP) (2004 – 2011)	Planting of riverbank shelter belts (using native acacia and mesquite species)	Spate irrigation rehabilitation and erosion control	International Fund for Agricultural Development (IFAD) and the Government	Approximately 350,000 to 480,000 people in the Gash area benefited from this project[4]
	Rehabilitation of flood protection spurs and embankments (launched in 2021)	Planting vetiver grass and indigenous shrubs on the re-shaped riverbanks	Flood protection	UNDP and partners	protecting an estimated 400,000 residents in greater Kassala[5]
El Gedaref	Adapting to Climate Change in East Sudan project (2015–2017)	Villagers planted over 10,000 native neem and acacia trees as well as grass species.	Sustain agriculture, restore ecosystems, and slow rain runoff	German Red Cross and Sudanese Red Crescent	An estimated 4,400 people directly benefited (51% of them women) through increased food security and income[6]

[3] https://africarenewal.un.org/en/magazine/restoring-sudans-forest-cover-one-tree-time

[4] https://reliefweb.int/report/sudan/sudan-ifad-funds-food-and-water-project-eastern-kassala-state

[5] https://www.undp.org/sudan/news/investing-flood-prevention-infrastructure-kassala-city

[6] https://redcross.eu/projects/adapting-to-a-changing-climate-in-east-sudan

According to the project report, early outcomes of the Refugee-host Community Reforestation Initiative in White Nile (Table 9, UNHCR 2020) include reduced firewood shortages (by creating nearby woodlots) and a safer source of cooking fuel for refugees (particularly women, who previously trekked long distances for wood). Socio-economically, the project created paid nursery jobs for local women and refugees, built skills in agroforestry, and improved community relations (by engaging both refugees and Sudanese in tree planting).

While the primary aim of the GSLRP was food security and land tenure, an important outcome was improved flood control: rehabilitated river channels and vegetated buffers now divert seasonal floodwaters more safely onto fields, reducing damage to downstream villages. IFAD noted socio-economic benefits such as higher incomes for smallholders (from improved crop yields) and protection of housing and community assets from flood destruction. Although no formal cost–benefit valuations were released, the catastrophic 2003 flood in Kassala (which submerged about half the town and caused damages in the millions of US dollars) illustrates the magnitude of losses that such flood-prevention projects are designed to avert.

In addition to flood protection, the UNDP's Rehabilitation of Flood Protection Spurs and Embankments Initiative is key in safeguarding the large Al-Gash agricultural scheme (21,000 hectares), which is vital to the state's economy. Kassala has also benefited from long-running reforestation programs in its refugee-hosting areas. Since 1985, UNHCR and FNC have planted over 19 million trees across eastern Kassala (Shagarab and other camp areas) to restore denuded land. This created 28,400 hectares of community forests and green belts. Although initiated for refugee energy needs, this massive effort has clear hydrological benefits: the forests curb the advance of desert sands, stabilize wadi banks, and reduce flash runoff into the Gash and its tributaries (UNHCR press release 2020). An evaluation indicated the program directly benefits about 15,000 people (9,000 refugees and 6,000 locals) through agro-forestry livelihoods.

According to the project report, the impact of the El Gedaref Climate Change Initiative (Table 9, and see the link in the footnote) on livelihoods was significant: training in organic fertilizer production and soil conservation, combined with the improved water retention from tree planting, led to higher and more reliable crop yields in demonstration plots (farmers reported lower input costs by eliminating expensive chemical fertilizers). Importantly, planting trees in degraded areas has started to revive local water cycles – residents observed rising water tables and improved well water availability after two years, as tree roots helped more rain infiltrate rather than run off. Economic analysis from this project (Table 9) noted that these nature-based measures are cost-effective for climate adaptation: farmers saved money (and avoided health risks) by using home-made compost, and the community trees yield long-term benefits (fuelwood, fruit, and shade) essentially for free after the initial planting investment.

Afforestation

Afforestation practices in Sudan's White Nile, El Gedaref, and Kassala states primarily involve community-based initiatives and project partnerships to combat desertification and improve local livelihoods. These efforts often integrate agroforestry, the establishment of village nurseries and woodlots, and the use of drought-resistant species like various Acacia species.

3.6.2. Water harvesting

Water harvesting in White Nile, El Gedaref, and Kassala states of Sudan includes constructing small dams and Haffirs (ponds for storage), using water spreading techniques to direct runoff, and implementing RWH techniques, such as roof water harvesting and in situ water harvesting for both domestic and agricultural use. Projects often focus on providing water for livestock, human consumption, and enhancing crop production in rain-fed agriculture systems.

3.6.3. Soil and water conservation measures

SWC in White Nile, El Gedaref, and Kassala states of Sudan include a range of physical SWC measures, such as the construction of physical structures like terraces and bunds, as well as agronomic practices, such as contour plowing, crop rotation, and mulching (Table 10). These methods aim to prevent soil erosion and improve water retention in the region's agricultural areas. Details on beneficiaries, co-benefits, and implementers are summarized in Table 11.

Table 10. Major soil and water retention measures that are practiced in the three states of Sudan (Source: Authors' creation)

SWC measures	Description	White Nile	El Gedaref	Kassala
Physical structures				
Terraces and bunds	These are structures built along slopes to slow down water runoff, which helps to prevent soil erosion and allows water to infiltrate the soil.	✓	✓	✓
Check dams	Structures are placed across gullies and small streams to slow water flow, reduce erosion, and increase groundwater recharge.	✓	✓	✓
Agronomic and vegetative measures				
Contour ploughing	Ploughing and planting along the natural contours of the land, which creates small ridges that slow down water flow.	✓	✓	✓
Crop rotation	Alternating crops in a field to improve soil health, reduce erosion, and manage pests	✓	✓	✓
Strip cropping	Growing different crops in alternating strips, often in combination with a close-growing crop like grass or a legume to help protect the soil from erosion.	✓	✓	✓
Intercropping and mixed cropping	Planting multiple crops together in the same field provides better ground cover and can improve overall soil stability and water use efficiency.	✓	✓	✓
Mulching	Covering the soil surface with organic material reduces evaporation, suppresses weeds, and protects the soil from rain impact.	✓	✓	✓

Table 11. Benefits of soil and water conservation measures (Source: Authors' creation)

State	SWC beneficiaries, co-benefits & implementers
White Nile	• *Beneficiaries:* Smallholder farmers & host communities (plus ~250,000 refugees)[7]. • *Co-benefits:* Improved crop yields and soil moisture; flood risk mitigation (e.g., via riverine tree planting providing safer cooking fuel). • *Implementers:* State agencies (e.g., Ministry of Agriculture, Forests National Corp) with UN partners (UNHCR-led reforestation drive), FAO projects, UNEP, and supporting NGOs.

[7] https://www.unhcr.org/news/stories/restoring-sudans-forest-cover-one-tree-time

El Gedaref	• *Beneficiaries:* Rainfed farming communities (primarily smallholders in mechanized farms)[8]. • *Co-benefits:* Higher and more stable yields; better groundwater recharge and reduced erosion/flood damage (through contour bunds, deep chiseling, check dams). • *Implementers:* State Ministry of Agriculture & Forestry with support from WFP (food-for-assets schemes) and development programs (e.g., EU/UNOPS climate resilience project), plus NGOs (e.g., ZOA in climate-smart farming).
Kassala	• *Beneficiaries:* Agro-pastoral households – including ~30,000 small farmers in the Gash spate irrigation scheme – and poor rural families (many women, plus IDPs/refugees)[9]. • *Co-benefits:* Improved food security and incomes; preserved rangelands and water resources (less drought impact, minimized flood damage). • *Implementers:* Local authorities (State MoA, Gash Delta scheme) with IFAD support (Gash Sustainable Livelihoods Project) and other partners (e.g., WFP asset-creation).

3.7. Recommended resilient nature-based water solutions and potential areas

3.7.1. Recommended resilient nature-based water solutions

To address the complex environmental, social, and economic challenges faced by refugee-hosting communities in the three states of Sudan (section 3.5, Table 7), a set of RNBWS was identified. Rather than applying a formal weighing or prioritization scheme, the identification was based on a set of explicit inclusion criteria. These included:

(i) documented evidence of prior application or experience with RNBWS in the three states (Section 3.6).
(ii) biophysical suitability, such as climate, hydrology, and land characteristics.
(iii) socioeconomic feasibility, including community acceptance, livelihood relevance, and institutional support.
(iv) demonstrated effectiveness in comparable contexts, drawing on previous project reports (see section 3.6).

In addition, the identified solutions were screened against the key environmental, social, and economic challenges specific to each state (Table 7) to ensure contextual relevance. Once we identified a set of RNBWS, we developed inclusion and exclusion criteria (Table 12) to map potentially suitable areas for piloting and implementing the identified solutions. These solutions, ranging from agroforestry and riparian restoration to RWH and integrated landscape management, aim to enhance resilience, restore ecosystems, and improve livelihoods for both host communities and refugees.

[8] https://sudan.un.org/en/289115-european-union-and-unops-partner-enhance-food-security-and-resilience-rural-communities

[9] https://www.thenewhumanitarian.org/report/48537/sudan-ifad-funds-food-and-water-project-eastern-kassala-state

Table 12. Identified potential resilient nature-based water solutions and inclusion and exclusion criteria for mapping potential areas (Source: Authors' creation)

RNBWS category/practices	Inclusion criteria	Exclusion
1. Tree-based resilient nature-based water solutions		
Agroforestry practices		
Acacia Senegal plantation (Gum Arabic cultivation)	Areas with sandy or sandy-loam soils and an annual rainfall of 300mm to 800 mm for optimal cultivation.	Areas with above 800 mm and less than 300mm rainfall; clay-dominated soils.
Village (community) woodlots	Non-Mechanized/large farms; annual rainfall >250mm, available plots for wood lots, areas with good water availability	Mechanized and semi-mechanized farms; shrublands, forest lands
Shelterbelts and windbreaks	Areas that are identified as vulnerable to desertification according to land degradation assessments or NDVI trends (i.e., Areas with NDVI values below 0.2, indicating sparse vegetation and high susceptibility to wind erosion and desertification; annual rainfall <250mm, all soil types	High rainfall with no wind erosion problem; >250mm rainfall; shrublands, forest lands; areas with > 0.2 NDVI values.
Agroforestry Parkland Systems (scattered plants on farmlands)	Fragmented and smallholder farms; annual rainfall >250mm	Mechanized and semi-mechanized farms, annual rainfall <250 mm; shrublands, forest lands
Taungya Systems	Forest areas but having tree canopy cover below 30%, indicating degradation or openness; Forest areas with low NDVI values (e.g., < 0.3); central clay plain, areas with adequate rainfall > 400mm, steep slope areas	Farmlands, shrublands, grazing lands
Fruit tree planting and Homegarden	Areas classified as rural settlements surrounded by small-scale agricultural plots (or Zones showing tree clusters or gardens near buildings, detected via NDVI); irrigated fields, riverbanks, flooded plains (or low-lying areas adjacent to Rivers or Streams) wetlands	Farmlands, forest and shrublands, pasturelands
Alley cropping	Non-Mechanized/large farms, mainly in areas producing annual crops (maize and sorghum) and areas with low rainfall	Grass-shrublands, forest lands
Riparian buffer restoration (riverbank stabilization with native vegetation)		
Planting trees, shrubs, and ground cover along riverbanks to create a natural buffer zone.	Buffer zone of the rivers (strips along the river line), floodplains (low-lying areas adjacent to Rivers or Streams)	Crop lands, grass lands, and highly degraded lands
Afforestation	Low rainfall areas (< 500 mm for indigenous plants)- plantation with drought-resistant species like the Acacia species. Include mainly areas of land degradation, all soil types	Affected by fast desertification, farmlands, existing woodlands and forestlands, and areas with high biodiversity
2. Rainwater harvesting and storage		

Rooftop water harvesting	Towns, settlement areas and rural houses with corrugated iron and mud roof tops.	Grass thatched roof
Haffirs (storage ponds)	Suitable for areas with large water storage potential (near seasonal streams, Areas with potential for irrigation (i.e., Agricultural lands located within 1–2 km of perennial or seasonal water sources (rivers, streams, reservoirs) and with gentle slopes (<5%) suitable for water distribution; water shortage areas, and unreliability of rainfall; Low permeable soil (or areas with clay-dominated or Vertisols as identified from soil maps); suitable landscape for pond construction (i.e., Flat or gently sloping areas (<5% slope) near water sources with clay-rich soils for water retention); Catchments with good runoff generation (or Catchments with steep slopes (>5%) and low vegetation cover, favoring high surface runoff)	Steep slopes, sufficient rainfall for rainfed agriculture; High soil permeability- sandy soils, no catchment, wetlands, intensively used irrigated lands
Water-Spreading Techniques	Dry areas, shortage of rain, techniques are employed in rain-fed areas to maximize the use of limited and erratic rainfall, areas along water courses	Farm field away from rivers or seasonal streams, Shrublands, forestlands, grass lands
Floodwater Diversion/Spate Irrigation:	Areas with seasonal streams, flat lower areas for flooding, soil not susceptible to waterlogging (sandy dominated soils), farmland close to seasonal streams; Hilly upstream areas for runoff, with adjacent flat, clay-dominated soils to store moisture	High rainfall areas, steep slopes with no adjacent flat areas, areas with no seasonal streams
Dams and Reservoirs:	Gentle to moderate slopes that allow for efficient water storage and minimize construction complexity; Low-lying areas where surface water naturally accumulates, identified by topographic depressions in DEM data; catchment with sufficient annual runoff, impermeable or low-permeable soils.	High sediment load zones, mountains or rugged areas, high-permeable soils
Well digging	Zones with shallow water table (<10 m) and permeable soils, identified from groundwater and soil maps, Dry areas with high water shortage	Sufficient surface water supply
3. Soil and water conservation		
Terraces	Gentle to moderate slopes, areas receiving less than 500/600mm, soil with low to moderate permeability, farmlands.	High steep slope, mechanized large-scale farms, protected or cultural sites
Contour bunds, fanya-juu	Rainfed cultivated lands, level and gently sloping areas	Irrigated area, grasslands, shrublands, steep slopes >50%
teras	Semi-arid area, rainfall ranging from 200-500mm, annual crops	Irrigated area, grasslands, shrublands and forest areas, buffer zones

Check dams	Areas with visible gully erosion features, identified through DEM-derived slope and flow accumulation or high-resolution imagery in all land uses; braided water courses and reduce erosion disasters	Farmlands (mechanized and semi-mechanized)
Flood embankments	Seasonal flash flood (or low-lying areas adjacent to Rivers or Streams); Riverbanks of Atbara and White Nile	Farmlands, Steep slope areas; All other areas than riverbanks
Contour ploughing	Extensive cropland areas (>5 ha) with low infrastructure density, identified from land use maps or satellite imagery. gentle slope	Grasslands, shrublands, Steep slope
Crop rotation	Smallholder fragmented farms, gentle slope	Grasslands, shrublands, forestlands, Steep slope
Intercropping and mixed cropping	Smallholder fragmented farms, gentle slope	Grasslands, shrublands, forestlands, Steep slope
Strip cropping	Smallholder fragmented farms, gentle slope	Grasslands, shrublands, forestlands, Steep slope
Mulching	arid and semi-arid farming areas, degraded or erosion-prone soils, moderate to low rainfall regions (250-600mm), large farms	Low-lying zones with frequent flooding or poor drainage, identified from DEM and hydrological data, high rainfall areas, grasslands, forestlands, shrublands
Chisel plowing	Large cropland areas (>5 ha) with clay-rich or compacted soils showing low infiltration rates, identified from soil maps and land use data	Loose soil layers, non-mechanized/large farms
4. Ecological restoration		
Exclosures	Degraded rangelands and farmlands, moderate to steep slopes, semi-arid and arid areas, low rainfall areas, degraded shrublands; tree cover of < 30%.	Highly productive agricultural lands, urban and settlement areas, waterbodies, and forest areas
Rangeland management	Degraded rangelands with regeneration potential (i.e., NDVI between 0.1 and 0.3, indicating sparse vegetation (native grasses or shrubs) but not completely bare soil; tree cover < 30%, moderate slopes, and non-cultivated areas.	Cultivated lands; waterbodies, forest and protected areas, urban or settlement areas, extremely arid zones,
Participatory forest management	Shrub and forest lands with tree cover > 30%	Farmlands, flood areas and water bodies

3.7.2. Spatial map of potential areas for identified nature-based solutions

The spatial mapping of suitable areas for identified RNBWS shows that the extent of suitable areas varies by interventions (Table 13). In Kassala, the largest suitable areas were found for contour bunds/fanya-juu (995,755 ha), floodwater diversion/spate irrigation (983,909 ha), afforestation (976,720 ha), flood embankments (861,344 ha), and well digging (711,086 ha). In El Gedaref, the largest suitable areas were found for mulching (983,466 ha), terraces (919,547 ha), contour bunds/fanya-juu (838,978 ha), contour ploughing (660,000 ha), and community woodlots (616,500 ha). In White Nile, the largest suitable areas were found for flood embankments (969,017 ha), mulching (792,068 ha), chisel plowing (762,890 ha), and afforestation (746,662 ha). The spatial analysis confirmed that a given area could be suitable for multiple RNBWS options (Figure 7), and overlapping RNBWS suitability areas are presented in Appendix Table 2.

Across the three states, SWC interventions cover the largest potential area with 3.74 million ha in Kassala, 3.99 million ha in El Gedaref, and 4.67 million ha in White Nile. Tree-based RNBWS represents the second-largest category in all states, with White Nile showing the highest potential (2.95 million ha), followed by Kassala (2.72 million ha) and El Gedaref (2.27 million ha). Rainwater harvesting and storage show the highest potential in Kassala (2.53 million ha), while being lower in El Gedaref (1.67 million ha) and White Nile (1.01 million ha). Ecological restoration interventions exhibit the lowest potential overall; however, White Nile (0.99 million ha) demonstrates substantially greater restoration suitability compared to Kassala (0.62 million ha) and El Gedaref (0.48 million ha).

Table 13. Potential areas (ha) for the identified resilient nature-based water solutions (Source: authors' analysis)

Tree-based resilient nature-based water solutions			
Resilient nature-based water solutions	Kassala	El Gedaref	White Nile
Acacia Senegal plantation (ASP)	120,164	21,568	5,135
Community Woodlots (CWL)	416,351	616,500	372,469
Shelterbelts and windbreaks (SBW)	332,763	245,464	302,978
Agroforestry Parkland Systems (scattered plants on farmlands) (APS)	180,067	304,408	447,317
Taungya Systems (TS)	31,838	98,596	66,758
Fruit tree planting and Homegarden (FTPH)	239,177	162,001	317,131
Alley cropping (AC)	413,899	305,032	681,958
River buffer planting (RBP)	6,467	4,368	5,746
Afforestation (AF)	976,720	510,441	746,662
Rainwater harvesting and storage			
Rooftop water harvesting (RWH)	247,327	196,348	197,116
Haffirs (storage ponds) (H)	263,829	500,967	245,545
Water-Spreading Techniques (WST)	8,464	4,133	8,476
Floodwater Diversion/Spate Irrigation (FWD/SI)	983,909	33,892	219,788
Dams and Reservoirs (DR)	317,525	271,080	241,185
Well digging (WD)	711,086	666,515	90,814
Soil and water conservation			
Terraces (Tr)	108,731	324,808	137,430
Contour bunds, fanya-juu (CB/FJ)	995,755	838,978	737,841

Teras (T)	447,792	919,547	678,021
Flood embankments (FE)	861,344	193,435	969,017
Contour ploughing (CP)	216,347	660,048	412,746
Crop rotation/Intercropping and mixed cropping/ Strip cropping (CR/IC/SC)	123,391	59,042	178,249
Mulching (M)	552,543	983,466	792,068
Chisel Plowing (ChP)	435,512	10,931	762,890
Ecological restoration			
Exclosures (E)	214,127	261,628	434,490
Rangeland management (RM)	288,144	23,737	431,791
Participatory forest management (PFM)	112,882	197,080	124,821

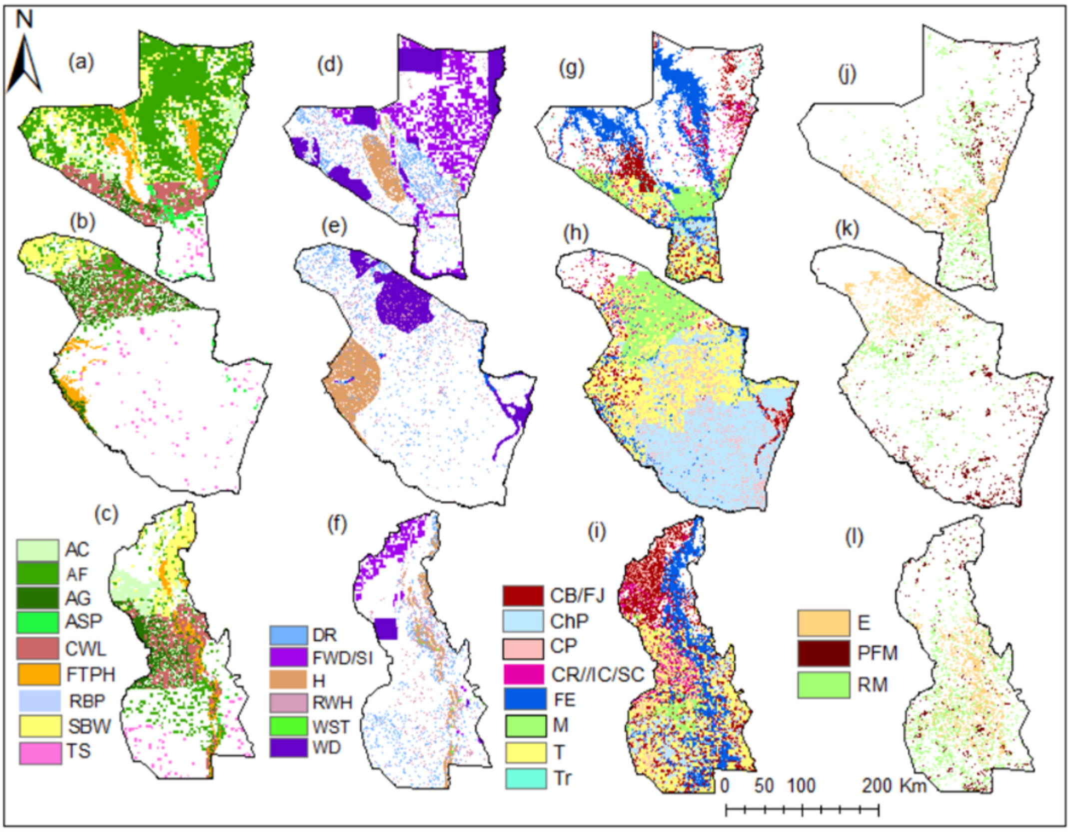

Figure 7. The spatial distribution of suitable areas to implement tree-based resilient nature-based water solutions (a–c), rainwater harvesting and storage (d–f), soil and water conservation (g–i), and ecological restoration (j–l). See the descriptions of the abbreviations in Table 13 (Source: authors' creation).

The identified potential RNBWS provide a wide range of ecological and socio-economic benefits for communities. For example, tree-based RNBWS stabilize soils, sequester carbon, enhance biodiversity, regulate microclimates, and retain water, while supplying timber, fruits, gum, fodder, and income for communities. These practices improve AGB and carbon sequestration rates. Rainwater harvesting and storage improve water availability for domestic, agricultural, and livestock use, increase drought resilience, and support food security. SWC practices maintain soil fertility, enhance moisture retention, prevent erosion, and sustain crop productivity. Ecological restoration approaches, such as exclosures, rangeland management, and participatory forest management, restore degraded ecosystems, conserve biodiversity, protect grazing lands and forest resources, and strengthen ecosystem services.

Figure 8 presents the spatial variability of NDVI values and AGB in the three states. AGB (Figure 8 d–f), estimated from NDVI values (Figure 8 a–c), ranges between 2.8–59.1 t ha^{-1} in Kassala, 2.4–55.5 t ha^{-1} in El Gedaref, and 2.5–49.4 t ha^{-1} in White Nile, indicating the spatial variation in vegetation productivity. The results in Table 14 indicate variations in vegetation density, biomass, and carbon storage across different LULC types. Forestlands, shrublands, and grasslands exhibit the highest NDVI (>0.5), AGB (48.7–59.1t ha-1), and carbon sequestration potential (89–108.4 tCO_2 eq ha^{-1}), indicating the key role of tree-based RNBWS in climate mitigation and ecosystem functioning. In contrast, cultivated lands, bare land, and settlement areas display low NDVI values (0.09–0.11) and AGB (9.2–10.2 t ha^{-1}).

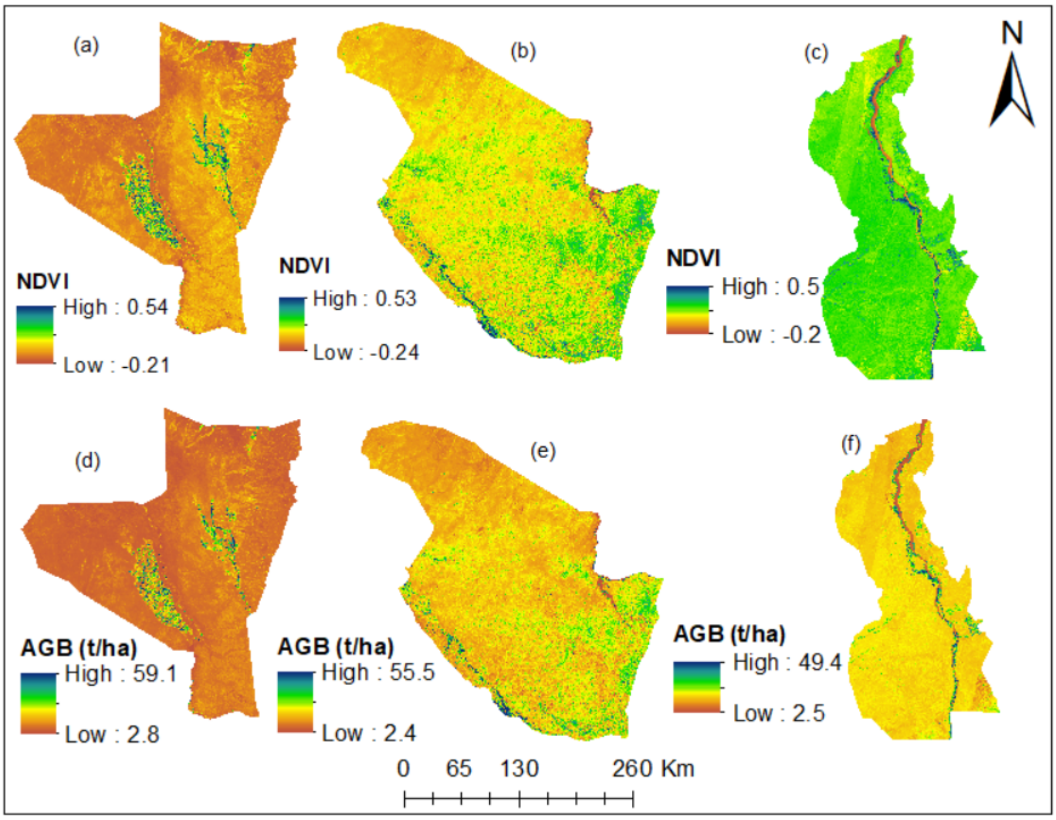

Figure 8. The spatial distribution of (a) NDVI values and (b) AGB (Source: authors' creation).

Table 14. AGB and carbon stock estimates across different LULC types using satellite data (Source: authors' analysis).

LULC	NDVI	AGB (t ha-1)	Carbon content (t C ha-1)	**Carbon sequestration (tCO2 eq ha-1)**
Waterbodies	-0.24	2.4	1.2	4.4
Forestlands	0.54	59.1	29.5	108.4
Cultivatedlands	0.11	10.2	5.1	18.8
Bare land	0.09	9.3	4.7	17.1
Settlement areas	0.09	9.2	4.6	16.9
Grasslands	0.50	48.7	24.3	89.3
Shrublands	0.50	50.2	25.1	92.2

3.7.3. Key environmental and social challenges and resilient nature-based water solution

Table 15 summarizes the links between key environmental and social challenges and the identified RNBWS in the three states. The matrix focuses on key environmental (e.g., floods, deforestation, land resources degradation) and social (e.g., water insecurity, fuelwood shortage) challenges extracted from Table 7 (see section 3.5), and five broad RNBWS categories from Table 12 (section 3.7).

Table 15. Matrix linking key environmental challenges and bundled Resilient Nature-Based Water Solutions (RNBWS) across Kassala, El Gedaref, and White Nile (Source: Authors' creation)

States	Key environmental and social challenges	Resilient Nature-based water solutions				
		Tree-based solutions	**Riparian buffer restoration**	**Rainwater harvesting**	**Soil and water conservation**	**Ecological restoration**
Kassala, El Gedaref, and White Nile	Water Scarcity / Limited Water	–	–	✓	✓	–
	Flood Risk (Flash Floods)	–	✓	✓	✓	–
	Deforestation / Fuelwood Pressure	✓	–	–	–	✓
	Land, Soil & Rangeland Degradation	✓	–	–	✓	✓

Note: A check (✓) indicates that a given RNBWS category is well-suited to address the challenge in the three states, while a dash (–) means it is not a primary solution there but has a supporting role in addressing the key challenge.

The synthesis matrix (Table 15) shows how RNBWS categories respond to these shared challenges. Rainwater harvesting and storage and SWC measures are central to addressing water shortages and flood impacts by capturing seasonal runoff and reducing erosion. Tree-based solutions and ecological restoration directly tackle deforestation and biomass pressure while restoring degraded lands. Although the overall solution–challenge alignment is similar across states, priorities differ by context, for example, Kassala emphasizes RWH due to severe dry-season shortages, while White Nile places greater emphasis on floodplain buffers and community forestry.

Overall, the matrix communicates an integrated, bundled set of nature-based approaches rather than isolated interventions, visually reinforcing that RWH and SWC jointly address water scarcity and flooding, while tree-based solutions and ecological restoration target deforestation and land/rangeland degradation. It also highlights that multiple nature-based options can coexist within the same landscape, maximizing co-benefits, and aligns strongly with evidence-based, landscape-scale RNBWS planning frameworks. However, translating this integrated potential into tangible impact requires explicit consideration of social, economic, demographic, and security dynamics, and how these factors evolve, to ensure that interventions remain feasible, inclusive, and resilient under changing conditions.

3.8. Key success and failure factors

In these displacement-hosting states of Sudan, the success of RNBWS hinges on strong community engagement that integrates host communities and the displaced population, coupled with the use of locally adapted practices. Based on previous projects in the studied states (see section 3.6), community-based forest resource management has proven effective when it incorporates awareness creation, gender inclusion, and participatory planning involving both long-term residents and displaced newcomers. Initiatives such as fruit tree planting and home gardens have shown promise for supporting both host and displaced families' livelihood and food security, provided that quality planting materials are available and participants receive training on tree management and water conservation. Additionally, planting drought-resistant indigenous species like Acacia senegal and Acacia nilotica aligns with the semi-arid conditions common in these states, improving survival rates and reinforcing the resilience of RNBWS interventions. Complementary measures, such as promoting improved cookstoves to reduce wood and charcoal use, also help ease deforestation pressure, especially where an influx of displaced households has increased fuelwood demand and thus supports the long-term sustainability of these interventions.

Conversely, displacement-hosting communities face several systemic challenges that can undermine RNBWS. Rapid population growth, due in part to incoming displaced people, contributes to continued deforestation through expanded agriculture and heavy reliance on wood and charcoal for energy, placing severe pressure on local forests. Limited financial resources for essential operations such as tree tending and weeding present another hurdle; in this context, funding must cover both host and displaced needs, often leaving new plantations under-resourced. Inadequate irrigation infrastructure, along with periodic pest and disease outbreaks, further constrain agroforestry productivity. Poor access to market information and limited market opportunities for NPs reduce economic incentives for both host and displaced farmers to be involved in RNBWS. Finally, competition over land and water between host and displaced groups can fuel resource conflicts, while the high cost of modernizing AFS poses an additional challenge. Together, these factors heighten vulnerability in displacement-hosting areas. To address them, integrated strategies tailored to displacement settings are needed, combining technical support, inclusive community planning, market development, and alternative energy solutions. These measures can relieve pressure on natural resources, improve livelihoods for both groups, and strengthen the resilience and long-term sustainability of RNBWS in these communities.

4. Limitations of the Study

The study's results should be interpreted with caution, given the challenging context in which the analysis was conducted. Insecurity, restricted field access, and rapidly evolving displacement dynamics in Kassala, El Gedaref, and White Nile significantly limited opportunities for on-site observation, stakeholder engagement, and ground-truthing of findings. Data availability was constrained, and while secondary datasets produced by humanitarian actors, including organizations such as UNHCR, offer valuable insights, limitations related to access, spatial and temporal coverage, and local validation—combined with security and access constraints—meant that such sources could not fully substitute for site-specific primary data collection. Although these gaps could potentially be addressed through targeted fieldwork and closer collaboration with local partners, insufficient time and the absence of such partnerships made this infeasible within the scope of the study. Despite these constraints, the analysis provides a robust, evidence-informed baseline and a strategic starting point for understanding key socio-environmental challenges in the three states, which future participatory and field-based research can build upon to further refine and validate the proposed solutions.

5. Conclusions and Recommendations

This study demonstrates that over the past two decades, land degradation, water insecurity, and ecosystem deterioration have intensified markedly across Kassala, El Gedaref, and White Nile states, driven by a confluence of climate variability, conflict-induced displacement, agricultural expansion, and increasing demand for natural resources. The observed decline in forestlands, shrublands, grasslands, and stable land areas, coupled with the expansion of degraded and settlement areas, highlights the growing vulnerability of ecosystems and livelihoods in displacement-hosting regions.

Using an integrated methodology that combined literature review, geospatial analysis, LDN assessment, and multi-criteria suitability mapping, the study identified and mapped four categories of RNBWS interventions: (i) tree-based solutions, (ii) rainwater harvesting and storage, (iii) SWC measures, and (iv) ecological restoration interventions. The results indicate extensive and overlapping potential suitability across multiple RNBWS options in all three states, indicating that landscape-scale and integrated portfolios of RNBWS hold significant potential to promote livelihoods and mitigate climate risks in these fragile and conflict-affected settings.

The findings further show that SWC measures and tree-based RNBWS offer particularly large potential spatial opportunities, whereas RWH and ecological restoration interventions could play a critical complementary role in addressing water scarcity, flood risks, rangeland degradation, and livelihood vulnerability. Importantly, the analysis indicates that many locations are suitable for multiple interventions simultaneously, underscoring the potential for synergistic planning that maximizes ecological, hydrological, and socio-economic benefits.

Overall, the study provides insights into spatially explicit evidence to inform the integration of RNBWS into state-level development planning, humanitarian programming, and climate adaptation strategies. Crucially, the intensifying pressures documented in these Sudanese states mirror broader patterns observed across dryland refugee-hosting regions in the Horn of Africa and the Sahel, where displacement, environmental degradation, and water insecurity similarly converge to intensify pressure on fragile ecosystems and livelihoods. By aligning environmental restoration with livelihood resilience, RNBWS represent a cost-effective and context-appropriate pathway to address the intertwined challenges of degradation, displacement, and water insecurity in Sudan’s displacement -hosting landscapes. Furthermore, the integrated approach and RNBWS framework presented here may hold relevance for similar fragile, conflict-affected displacement settings beyond Sudan.

Key recommendations

(i) Adopt landscape scale and integrated RNBWS planning:

- **Rationale for this recommendation**: In Sudan’s displacement-hosting landscape, environmental degradation, water scarcity, and livelihood insecurity overlap spatially, often in the same watersheds and community zones. Tackling these linked issues requires coordinated planning across entire landscapes, bundling multiple RNBWS in the same areas to maximize co-benefits for both displaced and host communities. Our spatial analysis indicates that many potential zones are suitable for multiple NbS interventions concurrently (e.g., combining reforestation with water-harvesting and floodplain restoration), which can amplify ecosystem services, improve water regulation, and diversify incomes when implemented together.
- **Next step:** Convene an initial national-level engagement with relevant government counterparts, humanitarian and development partners, and potential financiers (e.g., MDBs, climate finance entities, and bilateral donors) to share results and discuss pathways to incorporate findings (integrated RNBWS at landscape scale)

into project pipeline development. This would focus on aligning with national priorities and preferred investment and financing pathways, with the ultimate intention to produce a project concept note that could be suitable for detailed scoping via project preparation facilities. Once project preparation funding is secured, proceed to a multi-stakeholder planning process (involving national and local authorities, humanitarian agencies, community representatives of refugees and hosts) to co-design pilot integrated RNBWS portfolios in a few target watersheds, grounded in existing national and state policies and with clear geographic and institutional boundaries for the pilot phase. This process should be complemented by targeted market assessments to identify viable livelihood opportunities, value chains, and economic incentives linked to RNBWS adoption, as well as the development of a clear scaling strategy outlining pathways, partnerships, and financing mechanisms for broader uptake. Together, these steps will help validate the approach, allowing iterative learning and adaptation before scaling to broader displacement-affected regions. Furthermore, ensure that RNBWS planning and implementation adopt conflict-sensitive and do-no-harm approaches, particularly in contexts where land access, water allocation, and restoration activities may alter existing power dynamics or resource-use relationships between displaced and host populations.

(ii) Prioritize tree-based and soil–water conservation interventions at scale:

- **Rationale for this recommendation:** Refugee-hosting areas in the target states suffer severe deforestation, soil erosion, and degraded farmlands due to high resource pressure. Tree-based RNBWS (e.g., agroforestry, community woodlots, riparian reforestation) and soil–water conservation measures (terracing, check-dams, infiltration trenches) have proven to deliver multi-faceted benefits in these contexts and should form the backbone of restoration strategies. These interventions cover the widest suitable area in our analysis and yield tangible outcomes: they rehabilitate soil fertility, reduce flood and dust-storm risks, increase water retention, and provide valuable products like fuelwood, fodder, shade, and tree crops that improve livelihoods and reduce tensions over natural resources between hosts and displaced populations.
- **Next step**: Launch community-driven demonstration projects (e.g., cash-for-work reforestation and watershed rehabilitation involving both refugees/IDPs and host community members) to test and showcase the livelihood gains and environmental recovery from scaling up tree planting and soil conservation, informing larger programs and policy support for these solutions.

(iii) Mainstream RNBWS into humanitarian and development frameworks:

- **Rationale for this recommendation**: RNBWS must become a formal part of refugee response plans, state development strategies, and climate adaptation programs in Sudan's displacement-hosting regions, rather than treated as standalone environmental projects. This means integrating RNBWS approaches into joint planning, financing, and implementation mechanisms used by humanitarian and development actors (for example, including designated NbS components in refugee response plans, area-based recovery programs, and peacebuilding initiatives). In practice, this could involve adding RNBWS consideration into the design of needs assessment frameworks by explicitly including water, land and ecosystem-related indicators so that the identification of needs helps reveal opportunities for RNBWS interventions. These can then be aligned with cash-for-assets or food-for-assets schemes and community public works in camps and host communities, and supported through resilience and disaster risk reduction budgets.
- **Next step**: Work closely with UNHCR, State Ministries, and relevant coordination forums to co-design and embed RNBWS interventions in ongoing program cycles – for instance, by incorporating our findings in the next revision of state-level refugee response or environmental management strategies. Because prior chapters did not detail this mainstreaming, our immediate next step will be stakeholder consultations (with UN agencies, NGOs, local government, community leaders) to adapt the RNBWS recommendations into concrete project proposals and policy actions that align with humanitarian–development–peace objectives in each state.

(iv) Strengthen community-based governance and participation:

- **Rationale for this recommendation**: In displacement contexts, long-term stewardship of natural resources hinges on inclusive governance arrangements. Implementation of RNBWS must directly involve both host communities and displaced populations in planning, decision-making, and benefit-sharing, and it requires clarity on land access and resource rights. For example, establishing joint community natural resource management committees (with representation from local residents and refugees/IDPs) can help manage new tree plantations or water points, mediate any resource-use conflicts, and ensure equitable sharing of benefits (e.g., harvests or grazing access), thereby fostering local buy-in and reducing tensions.
- **Next step**: Facilitate participatory planning workshops and form or reinforce community governance structures in the pilot intervention areas. This includes confirming land tenure or usage agreements (so displaced groups can safely engage in tree-planting or soil conservation on communal lands) and training these local groups to maintain and monitor the RNBWS interventions over time, laying the foundation for sustainable, community-led management.

(v) Align RNBWS selection with biophysical and socio-economic contexts:

- **Rationale for this recommendation**: The three target states encompass diverse climates, landscapes, and livelihood systems, so a one-size-fits-all solution is inappropriate. While the detailed analysis in this document highlights important biophysical variation, such as rainfall patterns, soil types, and slopes, it also points to the need to more systematically integrate socio-economic, institutional, and demographic factors into decision-making. RNBWS must therefore be designed through a combined assessment of both biophysical suitability and socio-economic feasibility, recognizing that these dimensions are interdependent and must be aligned. This implies the need for further context-specific analysis of livelihoods, market access, land tenure, governance structures, and social dynamics to complement the biophysical assessment. In practice, practitioners should co-select and design RNBWS interventions based on this integrated understanding, for instance, focusing on water-harvesting earthworks in dry areas where water is scarce, or floodplain re-greening in zones prone to seasonal floods, while ensuring that interventions are not only technically appropriate but also socially acceptable, economically viable, and institutionally supported for both displaced and host populations.
- **Next step**: Within the context of a funded program, develop context-specific RNBWS design guidelines using the spatial suitability data and community input from each locality. This could involve producing state-specific RNBWS "menus" and site selection criteria (in collaboration with local experts and community knowledge holders) to guide field teams on which nature-based interventions fit best in a given environment or community context, thereby validating our analytical findings through real-world application and feedback.

(vi) Invest in monitoring, learning, and adaptive management:

- **Rationale for this recommendation**: To ensure RNBWS deliver the intended benefits in volatile displacement-hosting settings, it's crucial to track progress and be ready to adjust strategies. Establish a robust monitoring and evaluation (M&E) system that measures both environmental and socio-economic outcomes – for example, changes in vegetation cover, soil moisture retention, water availability, and indicators of community well-being or livelihoods, and the distribution of benefits across populations – in areas where RNBWS are implemented. Where feasible, incorporate financial and monetized metrics (such as return on investment and cost-effectiveness, or quantitative indicators that can be monetized through proxy values) to help demonstrate value for money and support resource allocation decisions. This data will enable evidence-based adjustments (adaptive management) if certain interventions underperform or yield unintended effects, and will help build a case for long-term funding by demonstrating successes in relation to both public and private goods.

Engaging local community members (including refugees/IDPs) in participatory monitoring can also enhance transparency and skills transfer, as well as inclusive resilience and sustainability.

- **Next step**: Define a monitoring framework with clear indicators and baselines for each pilot RNBWS project, including selected financial or monetized indicators (e.g., return on investment, cost-benefit proxies) where appropriate. Pair scientific tools (like satellite vegetation monitoring and water resource assessments) with community feedback mechanisms to gather comprehensive data. Regularly review results with stakeholders, capture lessons learned, and refine the RNBWS implementation approach over time – creating a continuous learning loop that strengthens outcomes and scalability across Sudan's displacement-affected areas.

(vii) **Invest in impact evaluation:**

- **Rationale for this recommendation**: While the identified RNBWS demonstrate strong potential to address the environmental, economic, and social challenges in Kassala, White Nile, and El Gedaref states, their promotion for large-scale adoption will be bolstered by rigorous impact evaluation.
- **Next step:** A priority next step is to design and implement a structured programme of monitoring, evaluation, learning, and impact assessment (MELIA) to systematically assess the effectiveness, cost efficiency, and scalability of these interventions across different contexts. This should include the use of baseline data, counterfactual analysis where feasible, and independent evaluation mechanisms to generate robust evidence. Strengthening this evidence base will not only inform adaptive management and improve intervention design, but also provide a credible foundation for scaling and mobilizing sustained investment under future initiatives, including RENEW.

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Appendix 1. Major soil type of Kassala, El Gedaref, and White Nile states

Soil type	Kassala		El Gedaref		White Nile	
	Area (ha)	%	Area (ha)	%	Area (ha)	%
Arenosols	12196	0	0	0	1225076	33
Cambisols	1783527	37	1165237	20	8263	0
Fluvisols	691739	14	650	0	34882	1
Leptosols	62904	1	9305	0	40687	1
Luvisols	956845	20	48541	1	323065	9
Vertisols	1117426	23	4645460	78	2117595	56
Regosols	238975	5	101514	2	0	0
Lixisols	11329	0	0	0	0	0

Appendix 2. Overlapping suitability areas of identified NbS

NbS category	Kassala		El Gedaref		White Nile	
	NbS	Area (ha)	NbS	Area (ha)	NbS	Area (ha)
Tree-based resilient nature-based water solutions	SBW, FTPH, FE, AF	26,758	AG, FTPH, AC	2,141	SBW, FTPH, FE, AF	4,281
	SBW, FTPH, FE	24,617	AG, AC	2,141	SBW, AF	1,070
	SBW, AF	25,687	AG, AC, AF	1,070	SBW, FTPH, FE	4,281
	SBW, FTPH	4,281	FTPH, AC	1,070	FTPH, AF	3,211
	FTPH, FE	21,406	CWL, AG, FTPH, AC	2,141	FTPH, FE	47,094
	SBW, FTPH, FE, AF, AC	4,281	CWL, AG, FTPH	1,070	SBW, FTPH, AF	1,070
	SBW, FTPH, AF, AC	1,070	AG, FTPH	25,687	SBW, FTPH, AC, FE, AF	1,070
	FTPH, FE, AF, AC	8,562	FTPH, FE	2,141	SBW, FTPH, AC, FE	1,070
	SBW, FE	1,070	CWL, FTPH, FE	1,070	CWL, AG, FTPH, AC	4,281
	SBW, FTPH, FE, AC	2,141	CWL, FTPH	2,141	CWL, FTPH, FE	25,687
	FTPH, AC, FE	3,211	AG, FTPH, FE	4,281	AG, FTPH	12,844
	FTPH, AC	4,281	CWL, AG, FTPH, FE	1,070	CWL, AG, FTPH, FE	2,141
	FTPH, AF	7,492			CWL, FTPH, AC	1,070
	FTPH, AC, FE, AF	3,211			FTPH, AC	2,141
	SBW, AC	1,070			CWL, FTPH, FE, AF	10,703
	SBW, FTPH, AF	1,070			FTPH, AC, FE	9,633
	FTPH, AC, AF	2,141			FTPH, AC, FE, AF	5,352
	ASP, CW, FTPH, FE	1,070			CWL, FTPH	3,211
	CWL, AC	1,070			CWL, FTPH, AC, FE	4,281
	CWL, AF	1,070			AG, FTPH, AC, AF	2,141
	CWL, AF, AC, FE	1,070			AG, FTPH, AF	3,211
	CWL, FTPH, FE, AF	2,141			CWL, FTPH, AC, FE, AF	1,070
	CWL, AF, FTPH	1,070			CWL, FTPH, AF	1,070
	CWL, AF	2,141			AG, FTPH, AC	2,141
	CWL, FTPH, FE	1,070			CWL, AG, FTPH	5,352
					CWL, AG, FTPH, AF	1,070
					AG, FTPH, FE	1,070
					AG, FTPH, AC, FE	1,070
					AG, FTPH, FE, AF	1,070
Rainwater harvesting and storage	FWD/SI, WST	2,054	H, RWH	1,027	H, WST	5,135
	FWD/SI, H, RWH	1,027	H, WST	1,027	H, RWH	1,027
	H, WST	1,027				
Soil and water conservation	CB/FJ, ChP	1027	ChP, T	2,054	CB/FJ, ChP	2,054
	CB/FJ, ChP, CP, T	1027	CB/FJ, ChP, T	2,054	CB/FJ, ChP, Tr	1,027
			CB/FJ, ChP	1,027	CB/FJ, ChP, CP, CR/IC/SC, T	1,027
			CB/FJ, ChP, M	2,054		
			CB/FJ, M	3,081		
Ecological restoration	PFM, RM	17,436	PFM, RM	6,295	PFM, RM	26,338

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