



CTCN Sudan Case Studies

Combined Report (Field and NDVI Analysis)



Executive Summary

This report documents four case studies of water-harvesting interventions implemented across Sudan, illustrating how locally adapted technologies enhance water security, livelihoods, and resilience in semi-arid environments. The studies span diverse contexts, from the Red Sea's dry catchments to the irrigated plains of Kassala and the conflict-affected landscapes of South Darfur. All interventions address a shared challenge: declining water availability due to erratic rainfall, erosion, and sedimentation. Field evidence shows clear improvements in local water access, recharge, and agricultural productivity. In Anikwan, a masonry sand dam enabled permanent settlement and raised household income fivefold. In Baba, a diversion weir reactivated an abandoned irrigation canal after a decade of inactivity. In Matateib, a series of stilling basins reduced sediment inflow by over 80%, extending recharge basin lifespan and improving well yields. Conversely, the Arba'at Dam collapse in 2024 exposed the fragility of major infrastructure, disrupting Port Sudan's water supply and emphasizing the need for dam-safety and maintenance systems. Satellite NDVI analysis (2000–2024) reveals largely stable vegetation across all catchments, with only localized greening near structures, reflecting that intervention benefits are hydrological and social rather than landscape-wide. Together, the cases highlight that effective water-harvesting in Sudan depends as much on simple, community-managed designs and governance as on engineering. Sustained monitoring, maintenance, and replication of these locally proven models will be key to strengthening climate resilience across Sudan's drylands.

Table 1 Summary of CTCN water-harvesting case studies in Sudan. Overview of intervention types, outcomes, challenges, and NDVI trends (2000–2024) across four sites.

Site	State / Catchment	Intervention Type	Year(s) of Construction	Primary Objectives	Key Outcomes	Challenges	NDVI Trend (2000–2024)
Anikwan	Red Sea / Durdeib	Masonry sand dam across Wadi Anikwan	2019	Recharge shallow aquifer, improve domestic and livestock water, reduce migration	Water available months beyond rainy season; income rose from 50 → 250–300 SDG/day; permanent settlement; vegetation persists longer	Rapid siltation; informal maintenance; limited technical follow-up	$R^2 = 0.018$ *, $p = 0.018$ – Slight catchment greening
Arba'at Dam	Red Sea / Port Sudan	Rock-fill dam with clay core	2003	Urban water supply for Port Sudan; flood control	16 million m ³ storage before collapse; after 2024, loss of 5 million m ³ water; 80 % of wells buried; severe supply drop from 36 → 7.5 L/p/d	Structural failure from siltation, overtopping, and poor maintenance	$R^2 = 0.007$, $p = 0.138$ – No clear catchment trend; local decline near dam
Baba Sand Dam	South Darfur / Andur Basin	Combined diversion weir + sand dam	2018–2020	Restore irrigation, enhance recharge, reduce erosion	Irrigation restored after 10 yrs; 40 gardens reactivated; 120 farmers resumed winter cropping; groundwater levels rose in 35 wells	Variable flash-flood hydrology; sedimentation; flood-risk to nearby IDP camps	$R^2 = 0.000$ – 0.002 , $p > 0.3$ – No significant trend
Matateib Recharge Basin	Kassala / North Delta (Gash)	Cascading sediment-trap basins + recharge basin	2018–2019	Reduce clogging, improve infiltration, extend basin lifespan	80 % reduction in suspended load (1069 → 501 NTU); increased well yields; recharge lasts through dry season	Periodic sediment removal still needed; scalability depends on labor	$R^2 = 0.012$, $p = 0.009$ ** – Local greening near basin

Significance levels: * $p < 0.05$; ** $p < 0.01$; ns = not significant.



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1. Introduction

Water harvesting interventions in Sudan are central to the country's climate adaptation strategy, aiming to mitigate water scarcity, enhance livelihoods, and restore degraded ecosystems. Implemented across multiple ecological zones, these interventions vary in type and scale, from sand dams to sediment traps and recharge basins, but share the objective of improving water availability and supporting productive land use.

This report presents four case studies from Red Sea, Kassala, and South Darfur States that document community experiences and technical outcomes of different water-harvesting systems:

- **Anikwan check/sand dam** (Red Sea State)
- **Arbaat Dam** (Red Sea State)
- **Baba Sand Dam** (South Darfur)
- **Matateib / North Delta sediment traps** (Kassala State)

Each case study combines field-based findings with remote-sensing analysis of NDVI (Normalized Difference Vegetation Index) to assess vegetation trends before and after implementation. Together, these analyses provide insight into both local impacts and broader environmental patterns across semi-arid Sudan.

2. Case Studies

2.1 Anikwan (Red Sea State)

2.1.1 Context and Background

Anikwan village lies in the northern part of the Durdeib catchment within Dordienb locality, one of the driest areas in Red Sea State, Sudan. The village is home to approximately 1,800 residents who depend primarily on rain-fed agriculture and livestock rearing (sheep, goats, and camels) for both subsistence and transport.

The landscape is characterized by basement rock outcrops, from which a seasonal wadi originates and flows southward toward Durdeib town. This wadi provides temporary runoff during intense but short-lived rainfall events. The community's main water source before the intervention was a mini water-yard borehole and a handpump, dependent on seasonal shallow groundwater recharge from the nearby wadi.

Over the years, declining borehole yields and erratic rainfall had made water scarcity a central challenge. Women and children often walked up to several hours daily to fetch water from distant towns such as Hamlab, Saineet, or Durdeib, leaving little time for education or productive work. Local residents described being “in constant movement,” as seasonal migration became a coping mechanism for both herders and families.

This chronic water shortage had severe social and economic consequences: average household income rarely exceeded 500 SDG per day (≈ 0.5 USD), and hygiene practices were extremely limited due to the scarcity of water. Contamination risks at shared water points were high because livestock often used the same sources.

2.1.2 Intervention Description

To address the persistent water crisis, a mortared masonry sand dam was constructed across Wadi Anikwan in 2019 as part of an integrated catchment management Program, Rural Water for Sudan (Aqua4Sudan). The hydrological assessment identified moderate to high shallow groundwater potential in the wadi sediments, despite the low reliability of surface water.

The sand dam was designed with a 25-meter width and a 3.5-meter foundation depth, sufficient to act as a subsurface barrier that slows runoff and enhances infiltration into the wadi sand body. A settling basin was later added upstream to reduce sediment load and protect the wadi bed from scouring.

The structure was strategically placed upstream of the existing mini water yard and downstream of a sealed borehole, which was converted into an observation well to monitor groundwater recharge.

The sand dam's main objectives were to:

- Recharge shallow aquifers and sustain water availability beyond the rainy season;
- Reduce surface runoff and erosion;
- Improve access to safe domestic and livestock water; and
- Strengthen livelihood resilience through small-scale irrigation and diversified income activities.

2.1.3 Implementation and Management

The dam was constructed using locally sourced stone and cement mortar, under the supervision of local contractor with a total construction cost of 13,000 USD. Community members contributed labor and materials voluntary and participated in construction activities promoting ownership and skills development.

Construction followed traditional Sudanese sand-dam design principles—capturing flash floods, allowing infiltration beneath the crest, and storing water within the sand.

Two years after completion, the residents of Anikwan settled permanently near the dam, ending decades of mobility caused by water scarcity. As one villager, Yahya, explained:

"We have decided to stay here after the sand dam and the hand pump availed the water for us. We even make our festivals and celebrations near the hand pump."

During the first two seasons, maintenance was informal, relying on community initiative rather than an institutionalized committee. However, over the past three years, no maintenance effort was made to repair downstream energy dissipation structure. Erosion from the steep upstream slope occasionally accelerates siltation, requiring manual removal after major floods.



Figure 1, The Anikwan sand dam in Red Sea State shortly after the rainy season. The masonry structure spans the wadi channel, retaining runoff and coarse sediment to enhance infiltration and sustain groundwater recharge in the dry months.

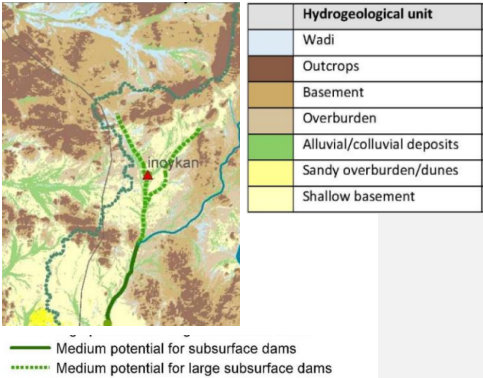


Figure 2, Hydrogeological map of the Anikwan catchment showing the site location and underlying units. The wadi lies within zones of medium potential for subsurface and large subsurface dams, underlain by basement and alluvial–colluvial deposits.

2.1.4 Impacts and Outcomes

The sand dam has had transformative local impacts. Water is now available for several months beyond the rainy season, and the time spent fetching water has dropped drastically. This has freed time for income-generating activities, leading to a remarkable increase in daily earnings a five- to sixfold improvement.

With more time and stable water access, families have diversified their livelihoods, engaging in small-scale agriculture, livestock herding, and artisanal gold mining. Migration has decreased sharply, and Anikwan has transitioned from a transient to a settled community.

Access to water has also improved hygiene awareness. Villagers have expressed intentions to improve sanitation practices, now that water is no longer a limiting factor.

Environmental observations indicate extended vegetation greenness after the rainy season. Trees remain green longer into the dry period, and natural regeneration is visible along the wadi bed and terraces, a visible change compared to pre-intervention conditions.

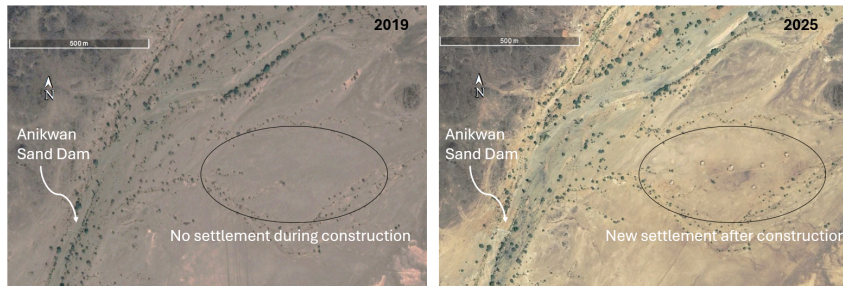


Figure 3 Satellite imagery shows the influx of returnees to Anikwan area after the dam construction

2.1.5 Challenges and Lessons Learned

Despite its success, the intervention faces several challenges:

- Rapid siltation after intense storms reduces storage efficiency;
- Maintenance is not yet organized through a formal committee;
- Technical follow-up and monitoring are limited due to remoteness.

However, the sand dam remains socially embedded and technically appropriate, relying on local materials, traditional know-how, and strong community ownership. The simplicity of design allows for low-cost maintenance and replication in other wadis of similar geomorphology.



Figure 4 Anikwan dam in 2025. While the dam main body is in good condition, downstream energy dissipator requires urgent maintenance.

2.1.6 Summary Interpretation (Link to NDVI Results)

NDVI analysis (3.5.1) shows no statistically significant greening or degradation following the dam's construction in 2019 ($R^2 < 0.02$; $p > 0.05$). Vegetation remains primarily rainfall-driven, and changes are below the MODIS detection threshold.

This finding is consistent with local reports: while water availability and vegetation persistence have improved at the micro-scale, such changes occur within a narrow riparian corridor and may not yet be

detectable by medium-resolution satellite data. Continued monitoring with higher-resolution imagery (e.g., Sentinel-2) is recommended to capture localized effects

2.2 Arbaat Dam (Red Sea State) | Study of dam failure

2.2.1 Location and Background

The Arba'at Dam, located in the Red Sea State of eastern Sudan, lies at the mouth of the Arba'at catchment, which drains into the Red Sea coastal plain near Port Sudan City. The dam was completed in 2003 by the Government of Sudan to secure the city's water supply. With a design capacity of 16 million cubic meters (m³), it became the main freshwater source for Port Sudan and nearby villages, covering more than half of the city's annual demand.

By 2024, 21 years after construction, the dam continued to supply water despite heavy siltation, limited maintenance, and declining reservoir capacity. The Arba'at wellfield and alluvial recharge basin downstream provided critical groundwater storage, recharged annually by releases from the dam.

However, the combination of intense rainfall, aging infrastructure, and sedimentation culminated in a catastrophic failure on 24 August 2024. The collapse followed heavy rains in the upper catchment, leading to fatalities, 64 people missing, and severe damage to more than twenty villages. Approximately 65,000 people were directly affected, and the disaster disrupted water supply for around 760,000 residents of Port Sudan, including 35% internally displaced persons (IOM, 2024).

2.2.2 Hydrological and Technical Description

The Arba'at Dam is a rock-filled embankment dam with a central clay core, measuring 240 meters in length and 28 meters in height. It features reinforced concrete spillway and outlet structures, and according to the International Commission on Large Dams (ICOLD, 2011) classification, it falls within the "significant" hazard category.

Sediment accumulation and loss of storage capacity progressively reduced the dam's performance. Maintenance records indicate cracks and weathering on the masonry protection layer, as well as erosion in the energy dissipation basin, signs of foundation weakness.

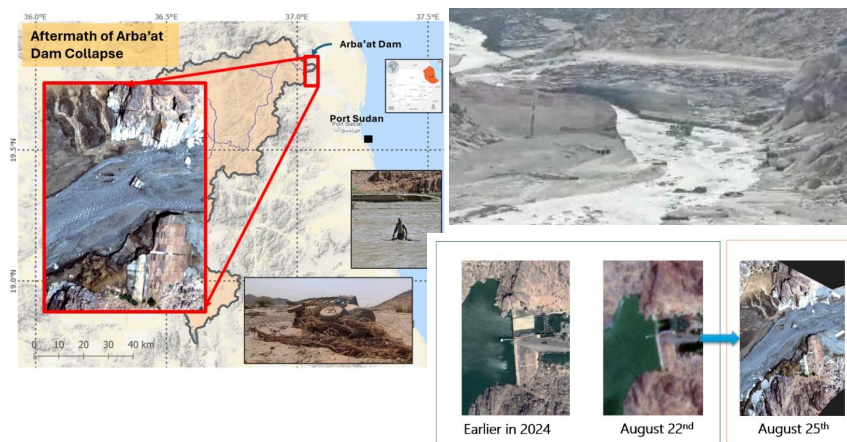


Figure 5. Location and imagery of the Arba'at Dam collapse: (top-left) Dam site at the mouth of the Arba'at catchment; (top-right) aerial photo of the breached embankment; (bottom-right) satellite imagery before, during, and after collapse. Sources: Daffa Development; PlanetScope SuperDove; Pleiades Neo Airbus; Dam Implementation Unit, Sudan

2.2.3 Intervention History and Functionality

The dam's failure occurred 21 years after construction, during a period of exceptionally high rainfall. The precise causes remain under investigation, but preliminary analysis identifies two major contributing mechanisms:

Structural Deterioration and Seepage

- Uncontrolled seepage through cracks in the dam's masonry protection layer led to internal erosion of the clay core.
- Foundation piping and erosion were observed in the stilling basin slab, consistent with uplift and internal flow instability.
- The absence of monitoring and maintenance limited early detection of these vulnerabilities.

Overtopping and Excess Runoff

- Saturated catchment conditions from repeated rainfall in July and August 2024 likely increased runoff.
- In the 24 hours preceding the collapse, rainfall reached 80 mm, or 83% of the annual average (ARC-2; Novella, 1983).
- The spillway design capacity (1,100 m³/s) was insufficient for such events. Historical floods in 1978 and 1983 reached 1,228–1,229 m³/s (Zhang, 2013), suggesting the dam was underdesigned for extreme conditions.

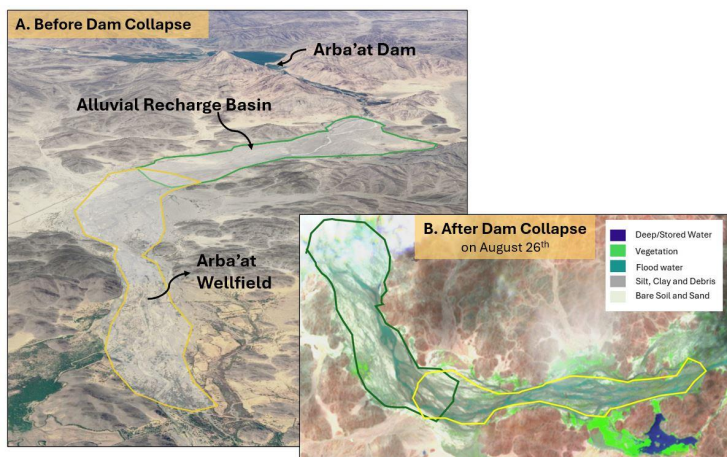


Figure 6, Arba'at Dam, recharge basin, and wellfield: (A) Google Earth image showing dam and aquifer infrastructure; (B) Sentinel-2 imagery illustrating 12 million m³ of clay, silt, and debris deposited across the recharge basin after the collapse (August 26, 2024).

2.2.4 Impacts and Observations

Before the collapse, the Arba'at Dam provided 59% of Port Sudan's freshwater, supplemented by boreholes, desalination plants, and nearby small dams (Salalab, Mouj, and 4th Gate). Despite recurrent shortages, water supply averaged 36 liters per person per day (L/p/d), far below the national urban standard of 150 L/p/d.

Following the collapse, this dropped to 7.5 L/p/d, creating an acute crisis.

The main impacts include:

1. Loss of stored water: 5 million m³ of reservoir storage was released.
2. Burial of boreholes: Around 80% of downstream wells were filled with silt and clay.
3. Infrastructure damage: 18 km of pipelines and manholes were destroyed.

4. Recharge blockage: Clay deposits covered 21 km² of the recharge basin, preventing infiltration.
5. Groundwater stress: The Arba'at aquifer (21.75 million m³) is now at risk of depletion due to reduced recharge.

Table 2, Water Supply Sources Before and After the Arba'at Dam Failure

Source	Capacity (m ³ /day or storage)	Supply (m ³ /day)	Before	Supply (m ³ /day)	After
Arba'at Dam Storage	16 million m ³	16,438	0		
Arba'at Wellfield	21 million m ³	3,750	0		
Public Desalination Plants	15,000	1,500	1,500		
Private Treatment Plants	4,200	1,600	1,600		
Commercial Supply	1,500	1,370	1,370		
4th Gate Dam	5.5 million m ³	1,500	0		
Salalab Dam	0.5 million m ³	500	500		
Mouj Dam	2.5 million m ³	500	500		
Total Daily Supply	—	27,158	5,470		
Water Supply (L/person/day)	—	36	7.5		

2.2.5 Remote Sensing Analysis (NDVI Trends)

NDVI data from MOD13Q1 (2000–2024) were analyzed to assess changes in vegetation cover in the Arba'at catchment and dam vicinity.

- Catchment-scale NDVI (mean of 5 × 5 km window) showed no statistically significant trend ($R^2 = 0.007$; $p = 0.138$ ns), indicating vegetation stability.
- Local NDVI near the dam and recharge basin revealed a significant pre-collapse increase (** $R^2 = 0.015$; $p = 0.003$ **) reflecting greening along the reservoir and riparian corridor.
- Post-collapse data indicate stabilization, with no clear recovery signal yet visible.

These patterns are consistent with the hydrological shift from surface water storage and infiltration to post-collapse sediment sealing, reducing moisture retention.

2.2.6 Lessons and Recommendations

- **Regulatory Oversight:** A robust authority must enforce safety standards, conduct inspections, and address non-compliance. Effective governance and strong institutions are essential to dam safety, particularly for large, complex storage dams. Technical solutions are most effective when supported by capable organizations.
- **Operation and maintenance requirements** should inform dam size and design. Challenges in Sudan, such as inadequate maintenance, weak monitoring, and poor operations, underscore the importance of effective governance. Without improvement, other large high-risk dams may also become unsafe.
- **Capacity Building:** Offer continuous training and professional development for engineers, operators, and technicians.
- **Data Management:** Systematically collect, review, and share hydrological, geological, and structural data. A well-resourced water authority is required to enforce standards, conduct inspections, manage data, and oversee long-term safety programs. Without this foundation, even well-designed dams remain at risk.
- Set up steady funding for regular and preventive maintenance, not just for building new dams.

Commented [ME1]: These were targeted for the response plan at early stages after dam collapse. Below I have added lessons relevant to the scope of CTCN project

2.2.7 Additional Notes

1. Under normal rainfall years, restored aquifer recharge could meet **100% of Port Sudan's demand**.
2. The **collapsed dam foundation** may continue functioning as a **subsurface barrier**, allowing partial recharge upstream.
3. Emphasis should be placed on **preventive maintenance, dam monitoring, and improved water governance**, including cost recovery and staff training.

2.3 Baba Sand Dam (South Darfur)

2.3.1 Context and Background

Baba village is located on one of the smaller branches of Wadi Talata, in the downstream section of the Andur Basin, northeast of Nyala, the capital of South Darfur. The community's livelihoods depend largely on rainfed farming of millet and sorghum, supplemented by small-scale irrigation of vegetables and fruits along the wadi during the winter months.

The village has a single water yard and a few hand pumps, which together provide a modest and often unreliable water supply for domestic use. Agriculture is heavily dependent on seasonal rainfall, while the wadi provides an important but irregular source of water for dry-season cultivation.

The area has been strongly shaped by the Darfur conflict that began in 2003. Many upstream farmers fled their land, leaving behind extensive fallow or bare cropland. This reduction in vegetation cover and interruption of agricultural practices altered the hydrological balance — reducing infiltration, increasing surface runoff, and intensifying soil erosion.

Over time, these processes caused morphological changes in the wadi system. The main channel near Baba village shifted its course, diverting flow away from the traditional irrigation canal and reducing surface water availability and groundwater recharge. As a result, irrigation ceased, vegetable gardens were abandoned, and local food security deteriorated.

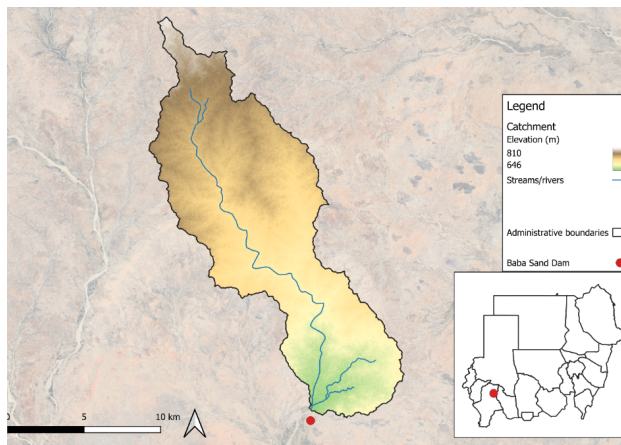


Figure 7. Location of the Baba Sand Dam in the downstream section of the Andur Basin, South Darfur. The map shows catchment boundaries, elevation gradients, and drainage network. The inset situates the project area within Sudan.

2.3.2 Intervention description

To address declining surface flows and restore irrigation potential, a combined diversion weir and sand dam was constructed in Baba village across the Wadi Talata. The structure was designed to reconnect the wadi with the abandoned irrigation canal, while simultaneously retaining floodwater and enhancing shallow groundwater recharge.

The hydraulic design was based on a detailed topographic survey and probabilistic modeling to account for the hydrological sensitivity of sandy alluvial wadis in the Andur Basin. The plan also considered crop water requirements, the reduced carrying capacity of the canal, and sedimentation patterns accumulated over a decade of disuse.

The final design included a masonry weir with three small open gates, allowing controlled diversion of floodwater between the main wadi and the irrigation canal. The structure was anchored in a natural outcrop layer within the khor bed to increase stability and reduce scouring.

2.3.3 Implementation and Management

The sand dam and weir were built using local materials under the technical supervision of regional hydraulic engineers. Construction involved community labor and took place before the rainy season to ensure the structure could function immediately during the next flood events.

In the first season after construction, flash floods deposited coarse sediment upstream of the weir, naturally raising the bed level and producing the desired partial dredging in the Baba irrigation canal. Building on these results, an additional 0.4 meters was added to the weir crest during the following season to further enhance storage and infiltration.

Local committees were trained to operate the gates, monitor water flow, and remove sediment at the canal entrance when necessary. This participatory approach strengthened ownership and ensured the system could be maintained using available local capacity.

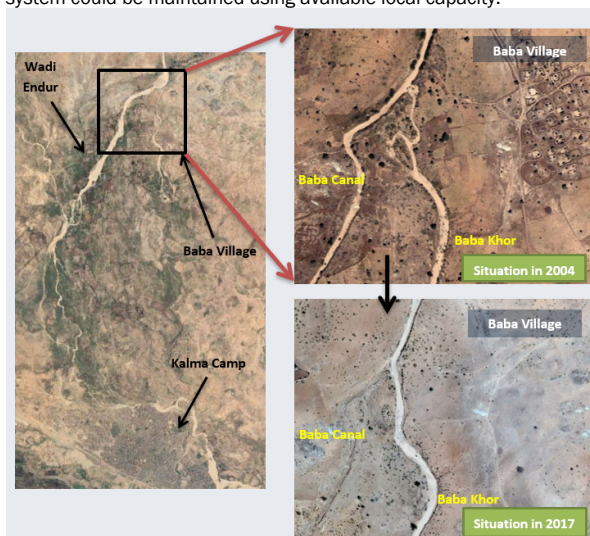


Figure 8. Comparison of the Baba Canal and Wadi Talata before and after intervention. The 2004 image (top) shows the historical canal and wadi alignment before displacement and erosion. The 2017 image (bottom) illustrates channel shifting and canal abandonment prior to project implementation. The intervention restored flow, reactivated irrigation, and improved connectivity between the wadi and canal.

2.3.4 Impacts and Outcomes

The intervention produced immediate and measurable improvements in water availability and agricultural productivity.

- For the first time in more than 10 years, water once again flowed through the Baba irrigation canal.
- Over 40 gardens were irrigated directly by surface water.
- Approximately 120 farmers resumed winter irrigation, producing vegetables and fruits that had disappeared from the local diet.
- More than 35 open wells recorded increased static water levels, confirming improved shallow aquifer recharge through near-bank infiltration.
- The village water yard yield rose significantly as a result of higher groundwater levels.
- The weir stabilized the wadi channel and created a hydraulic jump that dissipated flood energy, reducing downstream bank erosion.



Figure 9 Local farmers utilizing the newly irrigated land by the diversion canal

Together, these outcomes revitalized livelihoods, diversified income sources, and improved local food security. Baba village experienced a clear shift from reliance on rainfed subsistence farming toward more stable, irrigated production supported by managed water resources.

2.3.5 Challenges and Lessons Learned

Despite these positive results, several challenges persist:

- The hydrology of sandy wadis remains highly variable, and flash floods can both benefit and damage the structure if not well maintained.
- Sedimentation continues to occur upstream of the weir, requiring regular removal to maintain storage capacity.
- The expansion of IDP camps near the floodplain around Nyala City has increased exposure to flood hazards, as settlements now extend into low-lying wadi areas.
- Institutional arrangements for catchment-wide sediment management are still lacking, which may reduce the long-term lifespan of similar interventions.

Key lessons include the value of locally adapted engineering solutions, community engagement in operation and maintenance, and the need to integrate water-harvesting design with flood-risk management and settlement planning.



Figure 10 Baba dam after 2 seasons after construction. Source: ZOA International

2.3.6 Summary Interpretation ([Link to NDVI Results](#))

NDVI analysis (Section 3.5.1) of the Baba site and surrounding catchment shows no statistically significant long-term vegetation trend following the sand dam construction ($R^2 < 0.01$; $p > 0.05$). Vegetation patterns remain strongly seasonal, linked to rainfall variability.

However, local observations — such as increased riparian vegetation and expanded irrigated plots — confirm small-scale greening effects that are not detectable at the 250-meter MODIS resolution. These subtle changes are likely visible only at field scale.

Further monitoring using higher-resolution Sentinel-2 imagery is recommended to quantify vegetation recovery along the wadi and irrigation canal. The NDVI results thus complement field evidence, indicating localized hydrological recovery within a stable regional vegetation context.

2.4 Matateib / North Delta (Kassala State)

2.4.1 Context and Background

Matateib village is located near the seasonal Gash River in the North Delta locality of Kassala State, eastern Sudan. The area has an estimated population of about 8,750 residents, most of whom depend on farming as their main source of income. The village lies within the Algash Agricultural Scheme, Sudan's second-largest spate irrigation system, covering a vast floodplain area sustained by the annual Gash floods.

The geology of North Delta is dominated by hard clay soils deposited by the river system. These fine sediments limit deep groundwater formation, making shallow aquifers the only viable water source. Communities rely primarily on open wells tapping these shallow groundwater layers.

A unique feature of the area is the presence of subsurface sand lenses located at depths between 20 and 60 meters. These coarse sand layers act as natural underground reservoirs, capable of storing water diverted from the irrigation scheme's main canals. To enhance their recharge, the community constructed artificial infiltration basins designed to collect and percolate floodwater from the Gash River into these sand bodies.

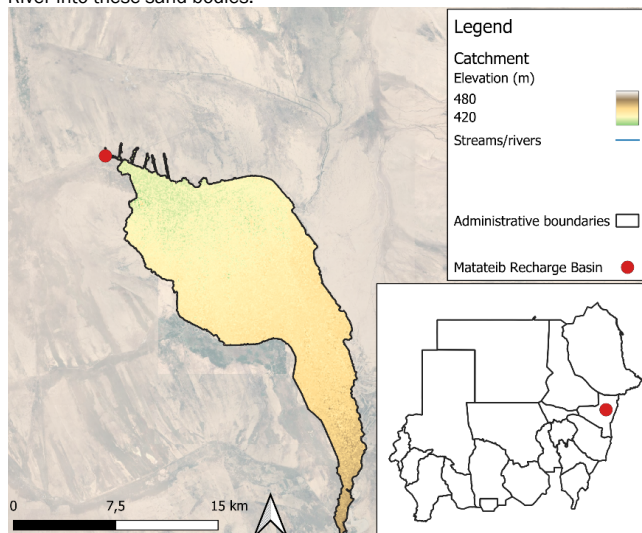


Figure 11. Location of the Matateib recharge basin in North Delta, Kassala State. The map shows the catchment boundaries, elevation gradients, and drainage network feeding the Gash River system. The inset situates the recharge basin within eastern Sudan, illustrating its position at the northern fringe of the Algash Agricultural Scheme.

2.4.2 Intervention Description

Over time, the artificial recharge basins suffered from rapid clogging due to the high sediment load in seasonal floodwater. The accumulation of fine silt at the basin surface reduced infiltration rates and lowered well yields, especially during dry seasons.

Traditionally, the North Delta community maintained the basins through manual desilting, removing the upper layers of deposited sediment to restore permeability. However, this process became increasingly unaffordable given the deteriorating economic conditions and rising costs of labor and equipment.

To address these challenges, the project introduced a simple, low-cost sediment pre-treatment system to reduce clogging and extend basin lifespan. The intervention included:

- A redesigned elongated diversion canal leading to the recharge basin;

- A series of small stilling basins (each approximately 50 m × 50 m and 1 m deep) constructed along the canal to slow floodwater velocity and promote sediment deposition before reaching the main recharge basin.

These stilling basins act as a cascade of sediment traps, dissipating flow energy and allowing suspended solids to settle sequentially. As a result, only partially clarified water enters the main infiltration basin – substantially reducing surface clogging and improving infiltration performance.

2.4.3 Implementation and Management

The system was designed and implemented through collaboration between local engineers and community members, using locally available materials and manual labor. The elongated diversion canal was reshaped from the old intake, and the stilling basins were excavated using community participation.

Local committees are now responsible for monitoring sediment accumulation in the small basins and conducting occasional maintenance, which is far less demanding than the previous large-scale desilting of the main basin. The staged sedimentation approach enables communities to manage clogging incrementally and affordably, ensuring long-term sustainability.

2.4.4



Figure 12. Aerial views of the Matateib artificial recharge system in North Delta, Kassala State. The upper image shows the Matateib recharge basin and nearby agricultural plots along the Gash irrigation canal. The lower annotated image illustrates the sediment pre-treatment system introduced under the project: an elongated diversion canal with three sequential stilling basins (each 50 × 50 m, 1 m deep) designed to slow flow and trap sediment before water reaches the recharge basin. Turbidity values measured at each stage (1069 → 1042 → 799 → 156 NTU) confirm an 80% reduction in suspended load, demonstrating the system's effectiveness in minimizing basin clogging and extending operational life.

2.4.5 Impacts and Outcomes

The new sediment management system has had a significant impact on recharge efficiency and groundwater availability.

Monitoring results demonstrated:

- A reduction of more than 80% in suspended sediment load between the intake point and the recharge basin inlet – from 1,069 NTU to 501 NTU;
- A dramatic decline in the amount of material reaching the basin, resulting in a much lower clogging rate;
- Extended basin lifetime and a reduction in maintenance frequency and cost, bringing upkeep back within community affordability levels;
- A substantial increase in open-well yield, with water availability now lasting through the summer months, unlike previous years when many wells ran dry.

These outcomes demonstrate the effectiveness of simple hydraulic flow management in improving groundwater recharge and maintaining local water supply reliability.

2.4.6 Challenges and Lessons Learned

While the intervention succeeded technically, several broader challenges remain:

- Sediment management requires continuous attention, while clogging has decreased, fine silt still accumulates in the small stilling basins and must be removed periodically.
- The system's scalability depends on community labor availability and sustained engagement for maintenance.
- Broader catchment-level sediment control measures are lacking, meaning that extreme floods could still overwhelm the system.

Key lessons include the value of simple, locally maintainable sediment control solutions and the importance of community participation in sustaining artificial recharge systems under limited financial resources.



Figure 13. Left: The recharge basin during the wet season, showing full storage of diverted floodwater (Source: Plan International). Right: The same basin during the dry season, where vegetation growth indicates moisture retention and localized groundwater recharge (Source: field work 2024).

2.4.7 Summary Interpretation (Link to NDVI Results)

NDVI analysis (Section 3.5.1) of the Matateib area shows no statistically significant overall vegetation change ($R^2 < 0.02$; $p > 0.05$), indicating that greening remains largely driven by rainfall rather than large-scale irrigation effects.

However, localized vegetation persistence observed near the recharge basin and canal areas suggests enhanced soil moisture and more stable shallow groundwater conditions following the intervention. These site-level improvements are consistent with the increased well yields and reduced seasonal drying reported by the community.

Future monitoring using higher-resolution imagery (e.g., Sentinel-2) is recommended to detect smaller-scale vegetation recovery patterns that are not visible at MODIS resolution.

3. NDVI

3.1 Data Source and Processing

To evaluate vegetation response around the four water-harvesting intervention sites (Anikwan, Arbaat, Baba, and Metateib), we analyzed the Normalized Difference Vegetation Index (NDVI) derived from the MODIS MOD13Q1 Version 6.1 product (250 m, 16-day composites). All datasets were downloaded from the NASA AppEEARS portal (<https://appears.earthdatacloud.nasa.gov/>), which provides temporally consistent MODIS data corrected for atmospheric effects and quality-filtered using the MODLAND QA flags.

For each site, NDVI data were extracted for both a single-point location (representing vegetation in the immediate surroundings of the intervention, typically within 250–500 m) and a watershed polygon delineated from the upstream drainage area of the structure. The 16-day composites were aggregated to monthly means to reduce data noise and minimize the influence of occasional cloud contamination. The time series covers January 2000 – June 2024, providing more than two decades of continuous vegetation observation across pre- and post-intervention periods.

3.2 Analytical Approach

Because NDVI in semi-arid Sudan is strongly seasonal—following rainfall pulses—the raw signal cannot directly reveal long-term vegetation trends. Therefore, we applied a Seasonal-Trend Decomposition using LOESS (STL) to each NDVI time series. STL decomposes the data into three additive components: Seasonal (annual rainfall cycle), Trend (long-term changes), and Residual (remaining variability). After decomposition, the de-seasonalized NDVI was analyzed to identify long-term changes independent of the seasonal cycle.

3.3 Statistical Analysis

To quantify the direction and magnitude of long-term change, a simple linear regression was fitted to the de-seasonalized NDVI series for each site and spatial scale. The regression model takes the form $NDVI_residual(t) = \alpha + \beta t + \epsilon_t$, where β represents the slope of the long-term trend.

Two key statistical measures were used:

- Coefficient of determination (R^2): expresses how much of the variation in NDVI residuals is explained by the fitted linear trend. Values close to 1 indicate strong explanatory power, while values near 0 indicate weak explanatory power.
- p-value of the slope (β): tests the null hypothesis that $\beta = 0$ (no trend). A low p-value (<0.05) means the trend is statistically significant and unlikely due to random noise.

STL + linear regression was chosen because NDVI data are typically non-stationary and strongly seasonal. STL effectively removes periodic cycles, and regression on residuals provides a transparent and interpretable measure of long-term vegetation change.

3.4 Results Summary

Table 3 Statistical summary of NDVI trend analysis (2000–2024) for Intervention and watershed scales. This table presents the coefficients of determination (R^2), p-values, and qualitative interpretation of long-term NDVI trends derived from STL decomposition followed by linear regression. The “point” analysis represents the area immediately surrounding the intervention (<500 m), while the “watershed” analysis represents the broader catchment area. Arrows indicate the direction of vegetation change (↑ increase, — no significant trend). Significance levels: * $p < 0.05$; ** $p < 0.01$; ns = not significant.

Site	Spatial Scale	R^2	p-value	Trend Direction	Interpretation
Anikwan	Watershed	0.018	0.018 *	↑ slight increase	Catchment-wide greening; improved soil moisture
	Point	0.002	0.309 ns	—	Local vegetation stable
Arbaat	Watershed	0.007	0.138 ns	—	No clear catchment trend
	Point	0.015	0.003 **	↑ increase	Vegetation increase near dam pre-collapse
Baba Sand Dam	Watershed	0.000	0.873 ns	—	Strong seasonality dominates
	Point	0.002	0.309 ns	—	No significant trend despite restored irrigation
Metateib	Watershed	0.006	0.168 ns	—	Catchment stable
	Point	0.012	0.009 **	↑ increase	Local greening linked to improved recharge

(* $p < 0.05$; ** $p < 0.01$; ns = not significant)

NDVI Trends at Intervention Locations — Watershed vs Point (2000–2024) with Site-specific Intervention Dates

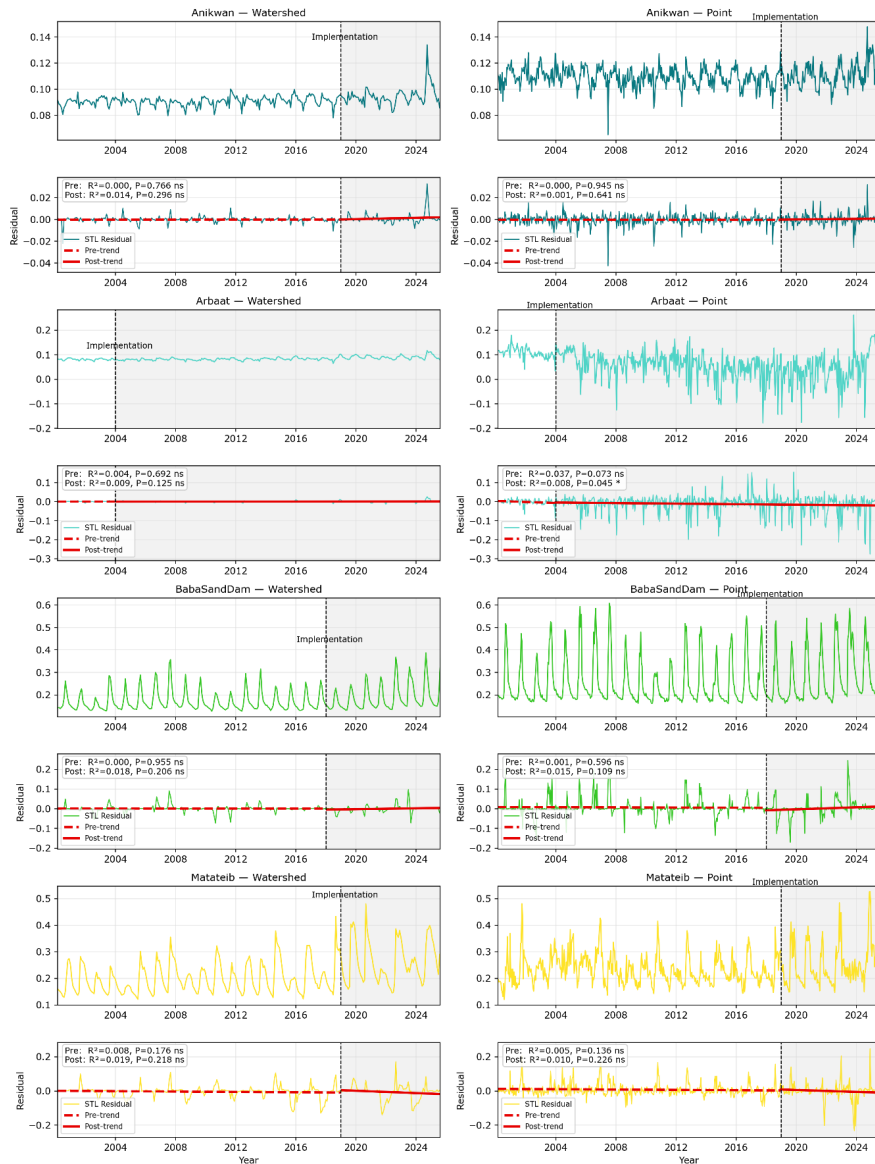


Figure 14 NDVI trends at four intervention locations (2000–2024), shown for both watershed (left) and point (right) scales. Each panel presents the NDVI time series (top) and post-STL residual trends (bottom), with dashed and solid red lines representing pre- and post-intervention linear regressions, respectively. The vertical dashed line marks the intervention year, and the shaded area indicates the post-intervention period. Across all sites, NDVI shows strong seasonal and interannual variability, with no statistically significant long-term greening trends except for a weak localized decline at the Arbaat point site ($p < 0.05$).

3.5 Results for each intervention

3.5.1 Anikwan (Red Sea State)

Intervention: Check dam / sand dam (constructed 2019)

Spatial focus: Local site and surrounding watershed

Summary of NDVI analysis:

NDVI values show high seasonality but no statistically significant long-term greening trend at either the watershed or local scale. The STL decomposition and regression analysis indicate that both the pre- and post-2019 periods have stable NDVI averages with R^2 values below 0.02 and non-significant p-values ($p > 0.05$).

Interpretation:

The absence of a measurable vegetation increase after dam implementation likely reflects the early stage of ecosystem recovery and the dominance of interannual climate variability. As the intervention was implemented recently (2019), measurable vegetation impact may still be developing. Field observations suggest improved soil moisture retention and the potential for enhanced vegetation growth in coming years, but these are not yet detectable in satellite NDVI records.

Conclusion:

NDVI remains stable, implying vegetation cover has neither degraded nor significantly expanded. Continuous monitoring is recommended to detect delayed responses once hydrological conditions and soil-water storage equilibrate around the structure

3.5.2 Arbaat (Red Sea State)

Intervention: Arba'at Dam (constructed 2003–2004)

Spatial focus: Dam site and surrounding catchment

Summary of NDVI analysis:

The STL-based trend analysis shows no significant pre- or post-2004 trend at the watershed scale ($R^2 < 0.01$, $p > 0.1$). At the local (point) scale, a weak but statistically significant negative trend ($R^2 = 0.008$, $p = 0.045$) was observed after 2004, suggesting a localized decline in vegetation greenness.

Interpretation:

This localized decline may indicate the progressive sedimentation and reduced water storage efficiency of the dam over time, limiting its capacity to support vegetation during dry seasons. Alternatively, it could reflect increased grazing or land-use pressure around the dam's perimeter after construction. Despite this, the broader watershed remains stable, showing no signs of large-scale degradation or greening.

Conclusion:

While Arba'at continues to provide localized water storage, NDVI evidence suggests reduced vegetation productivity around the immediate dam area. Complementary analyses using rainfall and soil moisture data could clarify whether this reflects hydrological changes or anthropogenic disturbance.

3.5.3 Baba Sand Dam (South Darfur)

Intervention: Sand dam and recharge structure (constructed 2018–2020)

Spatial focus: Local site and watershed

Summary of NDVI analysis:

Both pre- and post-intervention NDVI trends show no statistically significant changes ($R^2 < 0.02$, $p > 0.1$). The post-2020 period exhibits minor positive fluctuations, suggesting short-term vegetation response but not a sustained greening trend.

Interpretation:

NDVI stability reflects the dominance of rainfall variability over vegetation dynamics. While field observations report improved water access and soil infiltration downstream, these changes are too

localized or recent to manifest in NDVI. The strong seasonality of the region masks subtle intervention-driven effects in coarse-resolution NDVI data.

Conclusion:

No clear vegetation change can yet be attributed to the sand dam. Monitoring with higher-resolution imagery (e.g., Sentinel-2 NDVI or NDWI) could help isolate fine-scale vegetation responses in the recharge zone and cultivated plots.

3.5.4 Matateib (Kassala State)

Intervention: Cascading sediment traps and artificial recharge basin (constructed 2018–2019)

Spatial focus: Local site and sub-catchment

Summary of NDVI analysis:

At both the watershed and point scales, NDVI trends remain statistically non-significant ($R^2 < 0.02$, $p > 0.2$). NDVI fluctuations closely follow seasonal rainfall pulses, with no observable structural break or greening acceleration after 2019.

Interpretation:

Despite the absence of significant NDVI change, the recharge basin and sediment traps likely improved groundwater infiltration and water availability for vegetation regeneration. However, in this semi-arid context, rainfall-driven seasonality dominates NDVI signals. Soil moisture or evapotranspiration metrics may provide a more sensitive measure of intervention effectiveness than vegetation greenness alone.

Conclusion:

NDVI-based analysis indicates overall vegetation stability. Ground measurements and localized monitoring are needed to validate the hydrological and ecological benefits reported by field teams.

3.6 Interpretation and Discussion

Results show localized greening near structures in Anikwan, Arbaat, and Metateib, while Baba remains dominated by strong seasonal variability. At watershed scale, trends are weak, indicating that regional drivers—rainfall, land-use change, grazing, or displacement—overshadow localized intervention effects. At point scale, slight but significant NDVI increases align with improved soil moisture and recharge observed after intervention installation.

3.7 Limitations and Considerations

NDVI alone cannot isolate intervention effects, as vegetation greenness responds to multiple external factors such as rainfall variability, land management, conflict-driven land abandonment, and sensor noise. Positive NDVI trends indicate greening but not necessarily increased biomass or water availability. Thus, NDVI trends should be interpreted as indicative rather than definitive evidence of ecological recovery.

3.8 Next Steps

Future work should integrate NDVI with rainfall anomalies (CHIRPS/ARC2) to normalize for precipitation effects, add soil moisture and groundwater proxies (GLDAS, SMAP, GRACE), and map land-cover transitions using Sentinel-2 or Landsat imagery. Combining remote sensing with local monitoring will help distinguish climatic variability from sustained ecological improvements linked to water-harvesting interventions.

4. Conclusion

Analysis of four Sudanese case studies demonstrates that locally adapted, community-managed water-harvesting interventions are technically feasible and provide significant socio-economic benefits. While their ecological impact is not apparent at the landscape scale, these interventions improve water security, livelihoods, and local resilience. Sustainable water management in Sudan's drylands should prioritize simple, well-maintained systems over large, complex infrastructure that lacks strong governance.

Key Findings:

The case studies highlight a clear contrast between the outcomes of small- to medium-sized community projects and those of large, centralized infrastructure projects.

➤ Success of Locally-Adapted Interventions

Simple, well-constructed structures are effective at the local level. These projects demonstrate that improved water access leads to tangible economic and social benefits:

- Anikwan, Red Sea State: A masonry sand dam supported a shift to permanent settlement and increased average household income fivefold by providing a reliable water source for months after the rainy season.
- Baba, South Darfur: A combined diversion weir and sand dam restored an irrigation canal after a decade of disuse, reactivating 40 gardens and enabling 120 farmers to resume winter cropping.
- Matateib, Kassala State: Cascading sediment-trap basins reduced suspended sediment in floodwater by over 80%, improving the efficiency and lifespan of a key groundwater recharge basin and increasing well yields.

➤ Risks of Large-Scale Infrastructure and Neglected Maintenance

In contrast, the collapse of the Arba'at Dam in 2024 serves as a warning. The failure, caused by heavy silt accumulation, structural issues, and inadequate maintenance, disrupted Port Sudan's main water supply and rendered 80% of the downstream wells unusable. This incident demonstrates that large infrastructure is vulnerable without regular inspection, ongoing maintenance, and effective management. Sound technical design alone is insufficient; long-term operation is equally critical.

➤ Measuring impact at the suitable scale:

NDVI data from 2000 to 2024 show no significant large-scale increase in vegetation in the project areas. Initially, this may suggest that the interventions had limited environmental impact.

However, this does not diminish the tangible successes observed locally. Most benefits relate to water access and local economies, often at a scale too small for satellite imagery to detect. Fieldwork revealed greener vegetation near the structures, improved soil moisture, and the return of farming. Both satellite data and local observations are necessary to fully assess project impacts. These case studies provide a clear strategy for enhancing climate resilience in Sudan's drylands:

- Prioritize simplicity and community management. Replicate proven, low-cost designs such as sand dams, weirs, and sediment traps that local communities can manage and maintain.
- Strengthen Governance and Maintenance Protocols: For all water infrastructure, especially large dams, implement robust systems for routine inspection, preventive maintenance, and transparent governance to prevent future failures.
- Adopt a Hybrid Monitoring Approach: Combine remote sensing for broad-scale observation with on-the-ground data collection to accurately assess ecological and socio-economic outcomes.
- Promote Diversified Water Sources: Relying on a single large source is risky. A more resilient approach incorporates a mix of surface water, groundwater, and, where feasible, desalination, supported by managed aquifer recharge systems.

Ultimately, progress depends as much on good governance, sustained maintenance, and community ownership as on sound engineering.

