Water Harvesting Techniques as a Tool for Prosperity in Alsalam Locality, White Nile State, Sudan

by

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Abstract

Alsalam Locality (AL) is in White Nile State, about 200 km south of Khartoum. It is a very special locality that accommodates a large number of refugees from South Sudan and displaced people from White Nile State itself. The climate of AL is similar to that of the arid and semi-arid region. It usually faces either flash floods or harsh, difficult water shortages. Indigenous water harvesting techniques are used, e.g., terraces and Hafirs. However, their design and construction did not follow scientific methods. The objective is to assess the water harvesting (WH) potential of the selected area and to conduct a suitability analysis to delineate WH locations and the WH methods for each location. The study surveys water availability in AL and concludes that new WH locations can be introduced to improve water availability and to reduce the risk of flash floods. For Check Dams, the study guides experts on design, site selection and construction supervision. Water security in AL can be maintained if the local communities and the government manage the WH projects. The sustainability of the WH projects requires adequate funding for proper maintenance and management. Humanitarian organisations can provide financial support for these projects, which will provide services to refugees and displaced people in the region.

The data used in this study include spatial digital data that characterise the study area, such as daily rainfall estimates, potential evaporation, soils, land use, land cover, digital elevation model, etc. These digital data were clipped to the study area, processed and reclassified for further use. The wide-area geospatial streamflow model was used to obtain water balance parameters and generate runoff generation capacity for the area. The processed digital data were then overlaid to obtain the potential WH locations. The study divided AL into 21 basins. On average, the runoff generation capacity of these Basins ranges from 1% to 8% of total annual rainfall. Suitability analysis identified 10 new WH locations to improve water availability in the area, which will positively impact the lifestyles of local communities in the future.

Keywords: *Sudan*, *Water Scarcity, Rainfall, Hafirs, Climate Resilience, Water Harvesting, Runoff.*

1.0 Introduction

Worldwide, there is awareness of the potential of water harvesting (WH) to improve crop yields and to supply water for domestic and livestock use. In its simplest sense, WH is the collection of rainfall through storage for later use or for use elsewhere. The main objective of WH is to manage rainwater from the moment it falls and ensure that most of it is used productively before it returns to the atmosphere by evaporation. This helps mitigate the problem of temporal and spatial variability of rainfall. WH helps alleviate poverty and improve the socio-economic state. Moreover, it reduces pressure on natural resources and the environment, particularly in arid and semi-arid areas.

Several WH techniques are used worldwide in many locations (Ahmed A. B., 2014; Ahmed and Nagger, 2003). Alkaradaghi et al. (2022) conducted a study with common features related to the present one. They selected the Qaradaqh basin in Iraq, a water-scarce area in an arid and semi-arid region, to identify optimal rainwater harvesting sites using MCDM-based GIS techniques. They concluded that the basin had significant potential to implement rainwater harvesting.

Securing water in rural areas with an average annual rainfall of 450 mm to 800 mm, concentrated within a short three-month period from July to September, as in Alsalam Locality (AL) (Fig. 1), is difficult (Abdelsalam, 2014). In such cases, a comprehensive, multi-layered strategy that integrates different WH techniques could be adopted. The dual phenomena of intense, destructive rainfall followed by prolonged drought create a cycle of vulnerability for agriculture, livestock, and domestic life. Therefore, WH techniques, community empowerment and supportive policy are essential for building sustainable and resilient rural livelihoods (Ahmed 2015).

In Sudan, several indigenous WH techniques are used, e.g. Hafirs and check dams (Ahmed A. B. 2014), which require technical skills that are usually not available in such rural areas. The Hafir is a shallow, excavated open basin or reservoir. Hafirs are usually used in arid and semi-arid regions where rainfall is seasonal and occurs in a short period; hence, storage is required for the rest of the year. Hafirs can be natural or man-made (natural depressions locally known as Maiaa). However, modern technology can improve the efficiency of traditional water storage methods. The White Nile State (WNS) (Fig. 1) ranks second in irrigated agriculture in Sudan, after Gezira State. However, most of its arable areas fall in arid and semi-arid regions. The irrigated scheme area in WNS is about 500,000 feddans (about 210,000 ha), growing important crops, e.g. cotton, wheat, sorghum, sugarcane, and others (Abdelsalam, 2014). Rain-fed agriculture is found in the southern part of the White Nile State, where sorghum and sesame are grown. The WNS is also rich in livestock (cattle, sheep, camels and goats), which are economic resources. Most tribes in the southern WNS are nomadic, especially those living in the uplands. However, WNS water shortages are attributed to limited rainfall and its seasonality. Therefore, WH is considered a solution to bridge the gap in water demand; AL is selected as a case study.

Outside an irrigation scheme (8,000 feddans) in AL, the rural population is mostly nomadic, roaming the region with their herds (mostly cattle and sheep). Several Hafirs were established for these nomads and their herds. Often, several Hafirs have never been filled with rainwater. They dry out before the next rainy season. The nomads encroach on irrigated schemes, leading to conflict and friction between the farmers and the pastoralists (Abdelsalam, 2014). However, to minimise these conflicts, suitable sites for WH projects and Hafirs are carefully considered.

The main objective of this study is to assess the WH potential of the selected areas to improve water availability for domestic, agricultural and other uses. Moreover, specific objectives are: to delineate several catchments and estimate their runoff generation capacities, to identify soil types, land use/land cover, soil depth, soil water-holding capacity, slopes, and proximity to settlements, and to delineate suitable areas for water harvesting and suitable WH techniques. Livestock in AL is estimated at 1,425,966 head of various kinds (Abdelsalam, 2014). This large number of livestock puts pressure on natural and water resources.

2.0 The Study Area

AL is located between latitudes (12°-13° N) and longitudes (32°-33° E). Its total area is estimated at 6,919 km^2, representing about 17% of the total WNS area of 39,701 km^2. The population of AL is estimated at 106,419 inhabitants (Central Bureau of Statistics, Sudan 2003 and 2008; Abdelsalam, 2014). However, the total population is estimated at 180,000 persons at present.

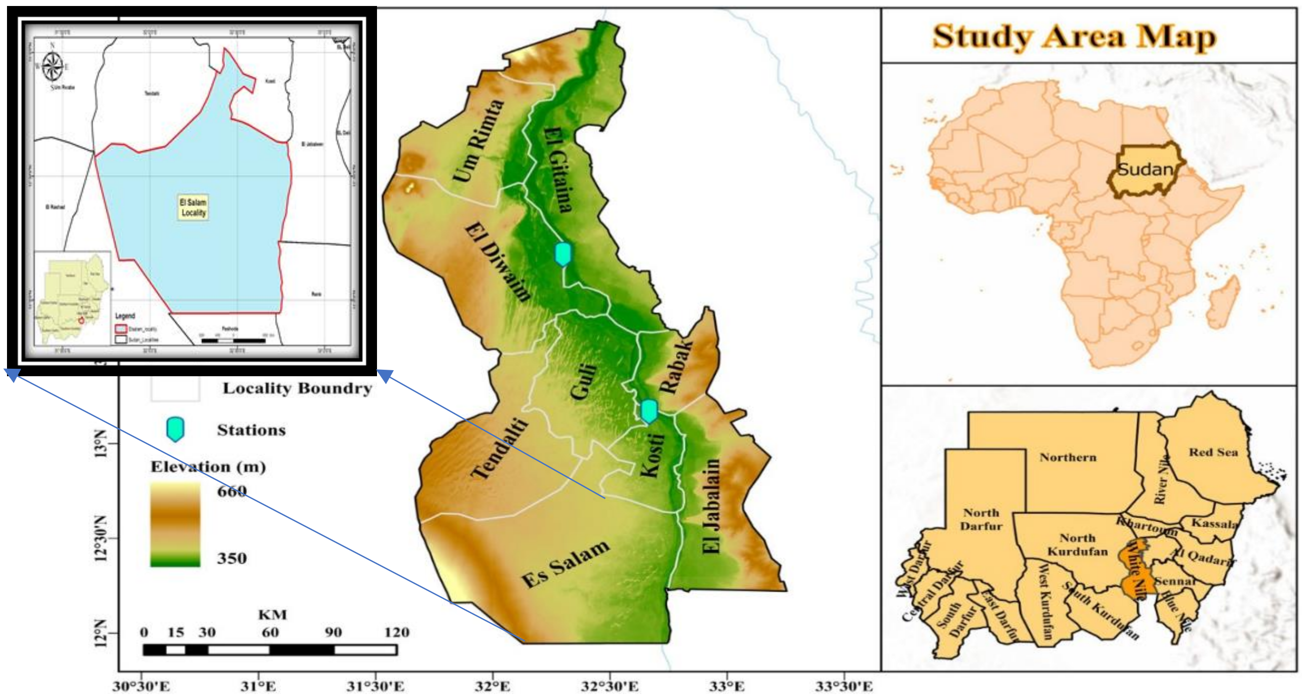

Fig (1) White Nile State Location, Alsalam Locality and some Geographic Aspects

The AL is located in the savannah belt; temperatures range from 24° C to 45° C, and the average annual rainfall ranges from 450 to 800 mm. Rain falls annually (June-October), with relative humidity of 20% to 60% (Fig 2).

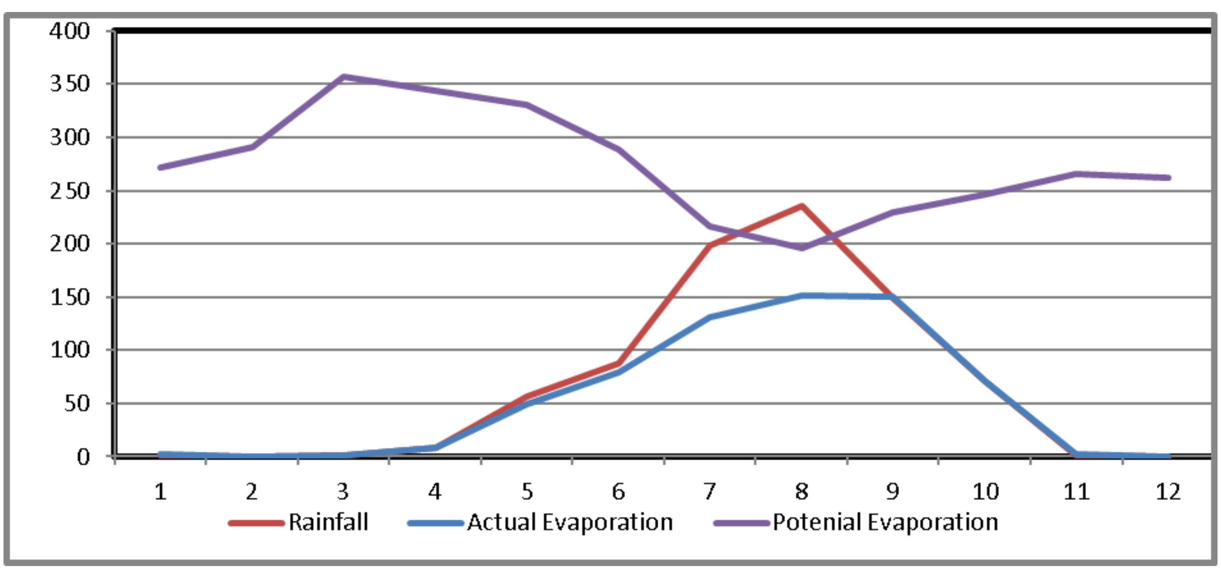

Fig (2) Mean Monthly Rainfall and Evaporation Distribution in the WNS, Sudan

3.0 The Data

Rainfall data are available at stations in Kosti and Ed Dueim within the WNS, and at Rashad and Renk beyond its boundaries. However, daily spatial rainfall estimates (RFE) are obtained by using the Climate Prediction Centre (CPC) of the National Oceanic and Atmospheric Administration (NOAA). RFE data (Xie and Arkin, 1997) are clipped and used for AL. The daily potential evapotranspiration (PET) data produced by the Early Warning Group at the USGS EROS (Verdin and Klaver, 2002) in spatial format, along with actual evaporation, were also clipped. A catchment diagram for AL is produced as in Fig. 3. A Digital Elevation Model DEM with a resolution of 90 m is also clipped to the study area. The digital slope map is generated for the area. The delineation process was applied using the DEM to derive AL basins, which are divided into 21 different basins as shown in Fig (3). The AL land cover is clipped from the FAO land cover map. Savannah represents the vast majority of the land cover, which is suitable for water harvesting.

The soil map data were clipped from the FAO soils for AL. Soil types in the study area are provided to determine where to locate and place the Hafirs, since infiltration rate is an important factor in designing and constructing such Hafirs. Data for the geological map are rare. However, a reasonable dataset was collected from which a geological map was derived for AL. Natural Resources Conservation Service (NRCS) curve number is also clipped for AL. The runoff generation potential for the study area is derived using the wide-area geospatial streamflow model (FEWS GeoSFM), a semi-distributed model (Artan et al., 2007; Asante et al., 2008).

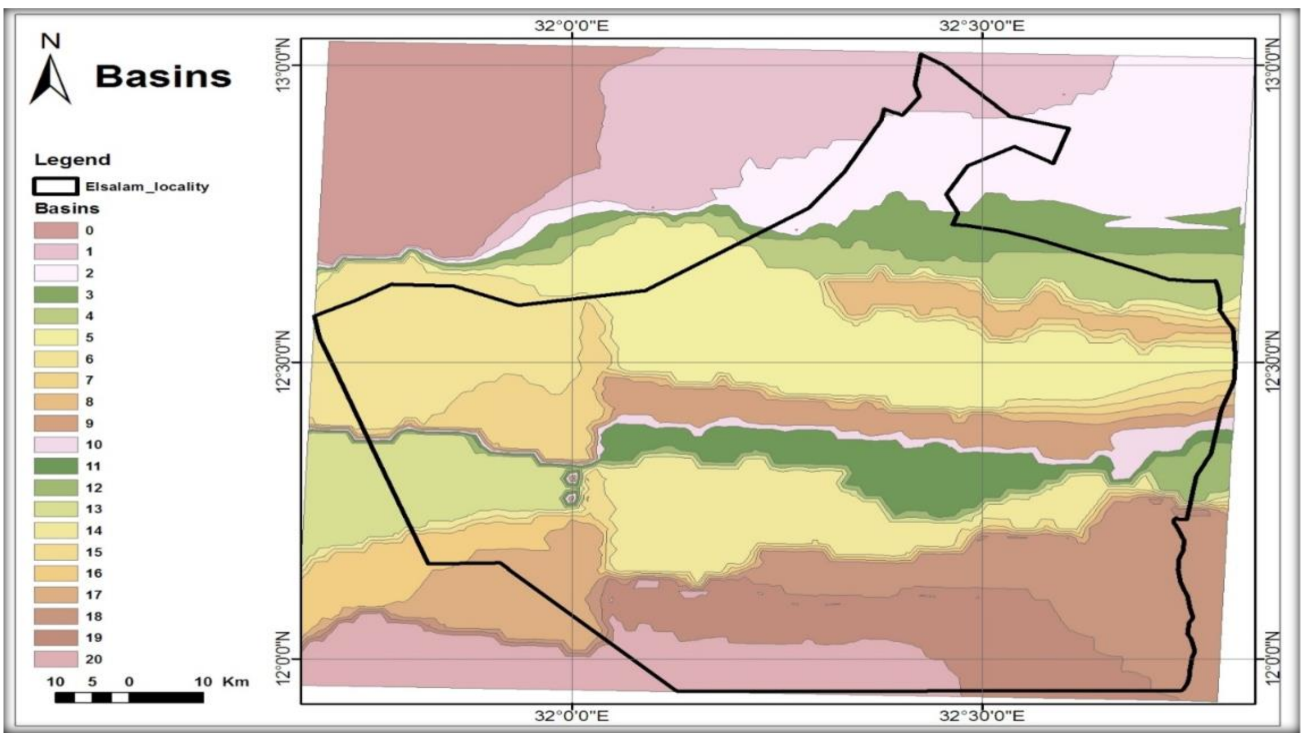

Fig (3) AL derived Basins

This model is used to obtain water balance parameters and the area runoff generation potential. The model runs under ArcView GIS at a daily time step and provides runoff, actual evaporation, groundwater loss, base flow, etc. The model outputs are then imported into Excel, aggregated into monthly values and used for other calculations. Table 1 shows the results. The water balance is expressed as Rainfall = Actual evaporation + Groundwater loss + Runoff + Residual, where the residual represents mainly the net change in soil and groundwater storage over the simulation period. Base flow is a component of the modelled runoff (Asante et al., 2008) and is listed in Table (1) for information only; it is not summed again in the balance. The runoff generation potential for AL is obtained by overlaying the Natural Resources Conservation Service (NRCS) curve number and the slopes using fuzzy functions. Continuous fuzzy membership was preferred to discrete class scoring because it avoids the sharp class boundaries imposed by coarse ordinal scales, which a systematic review of 68 published rainwater harvesting site-selection frameworks found to be the dominant practice, 21% using a binary indicator and 52% a scale of 1 to 3, 4 or 5 (Ahmed et al. 2023). It is acknowledged that analytical hierarchy process weighting is more widely applied in this literature, and that where the two have been compared on the same catchment AHP returned a higher prediction accuracy than a fuzzy-based index (Alkaradaghi et al. 2022); a comparative sensitivity test on the present layers is recommended as further work. The results are shown in Fig (4). The high runoff potential exists in the hilly areas. The south-western part of the study area is the Nuba Mountains. Fig. (5) presents settlement locations and existing Hafirs and shows the distribution of villages and Hafirs in AL. From an engineering perspective, the clustering of Hafirs, the overcrowding of villages, and the presence of some Hafirs far from villages do not guarantee good water distribution.

Table (1) Water balance as a percentage of rainfall in AL

Basin	Rainfall %	Actual Evaporation %	Groundwater loss %	Base flow %	Runoff %	Residual %
1	100	80.53	13.16	4.11	6.52	-0.21
2	100	82.10	10.99	4.24	7.14	-0.23
3	100	81.71	10.76	4.56	7.76	-0.23
4	100	83.37	13.81	1.89	3.02	-0.20
5	100	83.06	15.69	0.93	1.48	-0.23
6	100	87.21	7.51	4.23	5.22	0.06
7	100	85.87	6.83	1.89	2.32	4.98
8	100	76.83	2.85	0.79	1.25	19.07
9	100	90.28	6.37	1.76	2.23	1.12
10	100	77.16	2.89	0.80	1.10	18.85
11	100	77.66	4.53	1.25	1.56	16.25
12	100	76.69	2.89	0.80	1.13	19.29
13	100	78.30	14.18	2.01	2.70	4.82
14	100	75.92	3.40	0.94	1.42	19.26
15	100	76.75	2.86	0.79	1.13	19.26
16	100	76.12	3.22	0.89	1.33	19.33
17	100	76.55	3.26	0.90	1.34	18.85
18	100	76.71	3.20	0.89	1.35	18.74
19	100	80.11	4.66	1.29	1.57	13.66
20	100	76.47	1.35	0.88	3.16	19.02
21	100	77.82	2.92	0.81	1.18	18.08

Note: The residual is obtained as 100 − (Actual evaporation + Groundwater loss + Runoff). It represents mainly the net change in soil and groundwater storage over the simulation period, and also absorbs any model closure error. A positive value indicates storage gained and a negative value storage released. Values within a few tenths of one per cent indicate a closed balance; the larger positive residuals reflect water retained in the soil and groundwater reservoirs, both of which are initialised at low storage in GeoSFM and fill during the early part of a simulation.

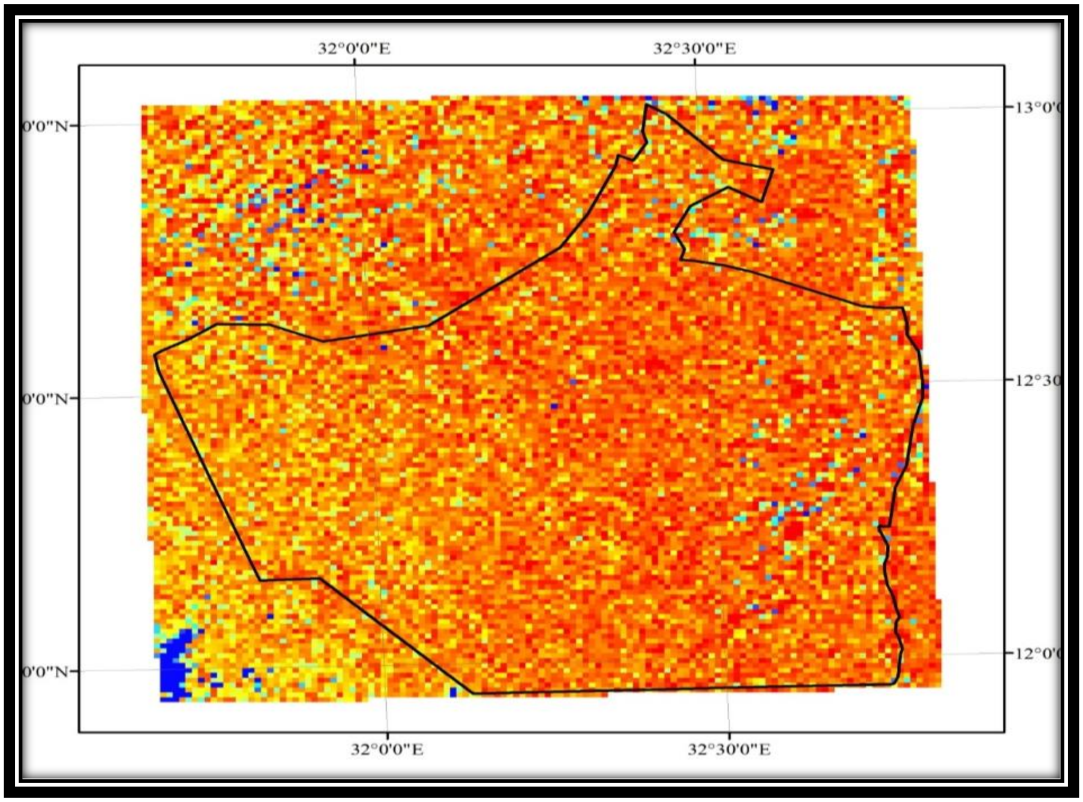

Fig (4): Runoff Generation Potential (dark blue = high, light blue = medium to high, yellow = medium, red = low).

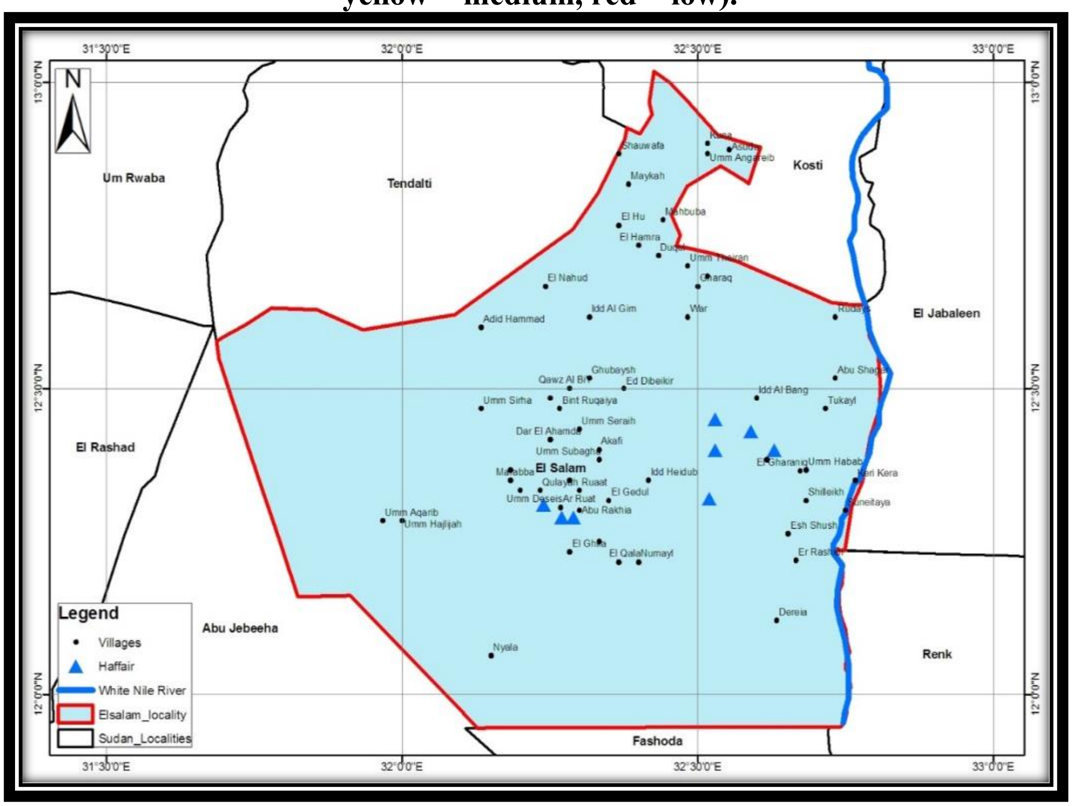

Fig (5) Location map for settlement and existing Hafirs in the study area

4.0 Selection of Suitable Sites for Water Harvesting Projects in AL

The following criteria have been adopted to select suitable sites for water harvesting infrastructure based on the Integrated Mission for Sustainable Development (IMSD) guidelines:

- The slope should be less than 15%.
- The infiltration rate should be low.
- The land use/cover should be considered in the selection of Hafirs.
- The type of soil should be silt, clay, or loamy clay.

In addition to the above points, when selecting water harvesting projects (e.g., Hafirs and check dams), consider the location of people's settlements (villages). Moreover, suitable sites for WH projects should be distributed to avoid overgrazing in the surrounding areas near the Hafirs or check dams.

The soil, vegetation, slope, land cover, catchment basins, runoff potential and settlement location maps were used to delineate suitable WH sites. The information from the previous maps is carefully analysed, reclassified and overlaid to identify suitable locations for WH projects. Results, along with existing Hafirs and settlements, are shown in Fig. (6).

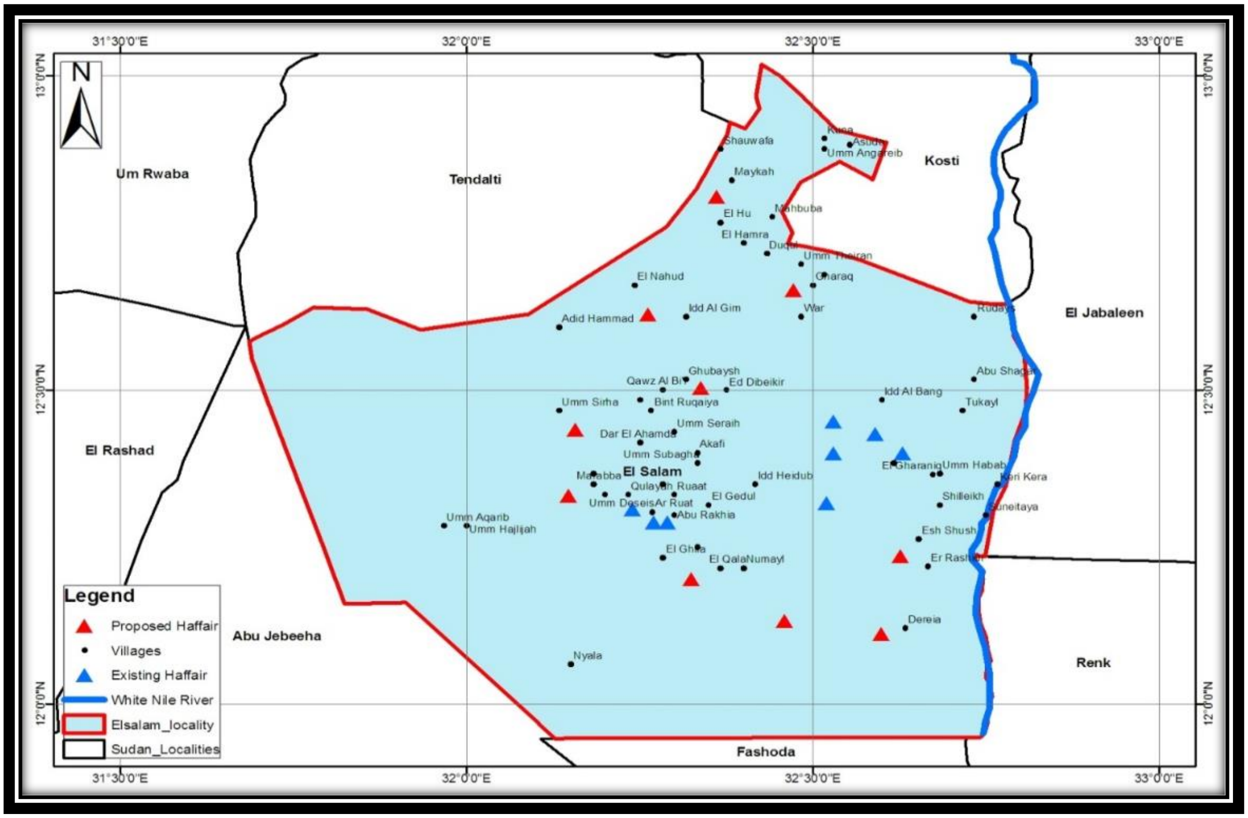

Fig. (6) Suitable Sites for the New Proposed Hafirs AL.

The selection of the WH project sites should serve local communities and their livestock. Given the region's sensitivity, well-sited projects to safeguard the population's social and economic security have been adopted to avoid conflict and localised overgrazing.

Eight Hafirs are still functioning in AL, but their capacities fall far below the water needs of local communities and livestock. The rainfall is seasonal (June to October). Therefore, to make water available in sufficient quantity, in space and time, 10 Hafirs are proposed. They are well distributed with capacities ranging from 50,000 m^3 to 1,000,000 m^3 based on need and site suitability.

5.0 Water Harvesting Techniques (WHTs)

WH is a crucial set of techniques used in *arid and semi-arid regions* to collect and concentrate natural precipitation, such as rainwater and surface runoff, for beneficial use. It is an indigenous practice that is being revived as a sustainable, climate-resilient solution to water scarcity. Moreover, it is affected by climate change and unpredictable rainfall patterns.

WH systems typically involve a catchment area to collect water and a storage/utilisation area. The techniques are broadly categorised based on the water source and scale:

- ***Rainwater Harvesting*:** Capturing rainfall directly for storage or immediate use.
- ***Rooftop Harvesting*:** Collecting rainwater from building roofs and storing it in tanks or cisterns for domestic use (Amir et al., 2024; Edwin et al. 2025).
- ***Micro-catchment WH:*** Collecting runoff from a small, treated catchment area and concentrating it in an adjacent basin for a single plant (tree, bush, or annual crop), Figs (7 and 8), (Ahmed and Nagger, 2003; Ahmed and ElDaw, 2003; Ahmed, 2005; Elamin and Mohammed, 2016).
- ***Runoff/Floodwater Harvesting*:** Collecting surface runoff before it joins a stream or is lost, or diverting floodwater from ephemeral streams (wadis) to a cultivation area (Fig 7).
- ***Macro-catchment/Floodwater Harvesting**: Collecting runoff from larger, external catchments or diverting flash floods for larger-scale agricultural use or storage in Hafirs, Figs (7,8,9,12).*

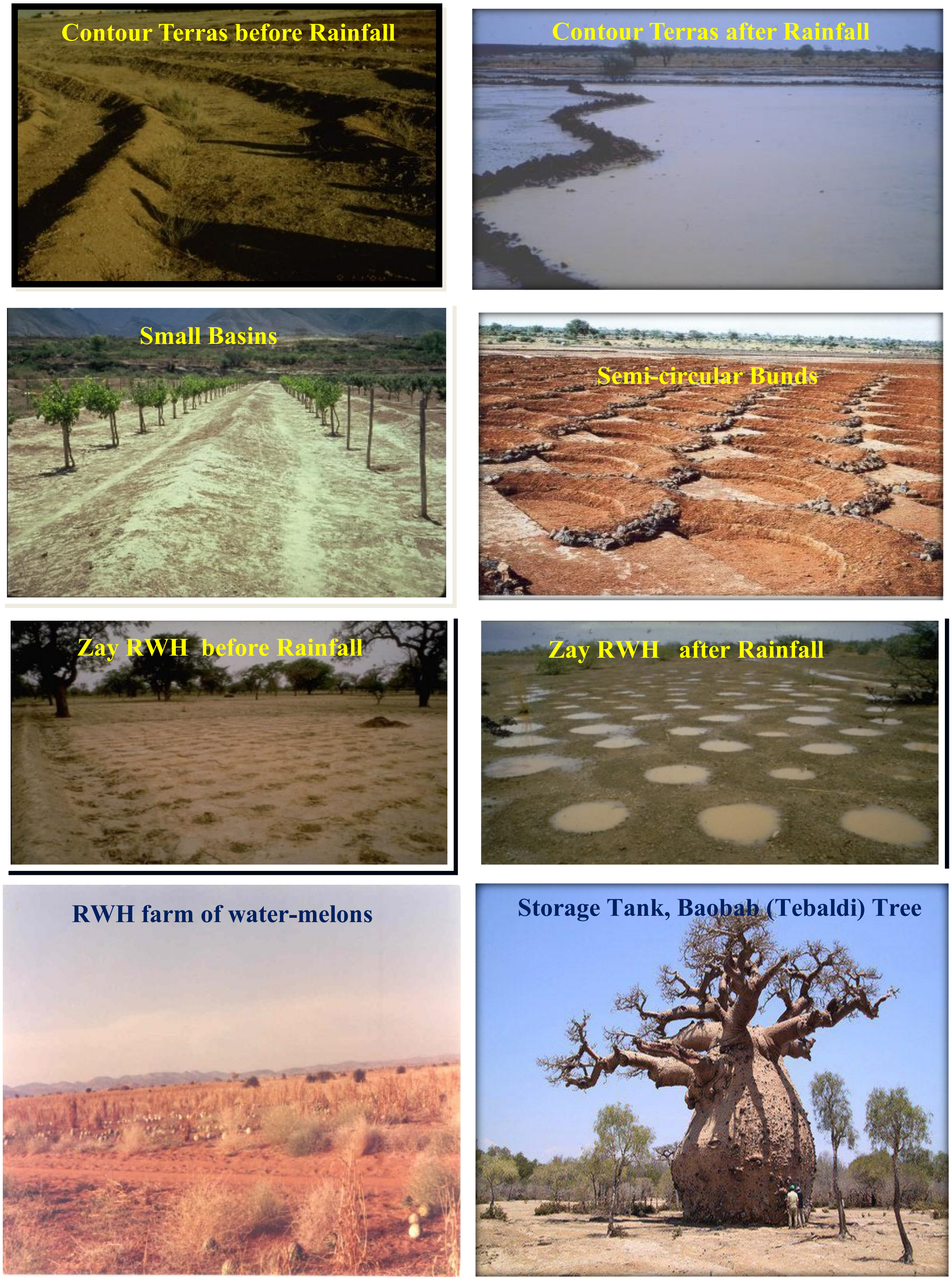

Fig (7) Micro-catchment Techniques for Agricultural Development

Fig. (8) Macro-catchment Techniques for Drinking Water

6.0 Benefits of WH for AL

One of the main benefits generated by the present study is enhanced climate change resilience among the AL community through a combination of approaches, including *Rainwater Harvesting, rangeland regeneration, and drought-tolerant agriculture.* The long-term goal is to provide climate-resilient food and water sources for thousands of households.

WH is not just a theoretical solution; it is a proven and essential strategy for addressing the water crisis in AL. By using a mix of techniques—from traditional Hafirs and Terraces, Figs (9, 10, 11), to modern subsurface dams and suitable WH techniques—communities can transform erratic rainfall into a life-sustaining resource, bolstering their resilience against climate change and conflict. However, the main challenge is how to help the communities fund these solutions. WH offers a comprehensive approach to mitigating the multifaceted water crisis in AL, addressing both humanitarian and developmental needs. It can modify the existing Hafirs or develop new ones using the improved design in (Fig 12), (MOIWR and UNICEF 2009).

Fig (9) Abu Tagya Hafir, AL.

 

Fig (10) Sheikh Saeed Hafir, AL.

 

Fig. (11) Al Kahilab Hafir, AL.

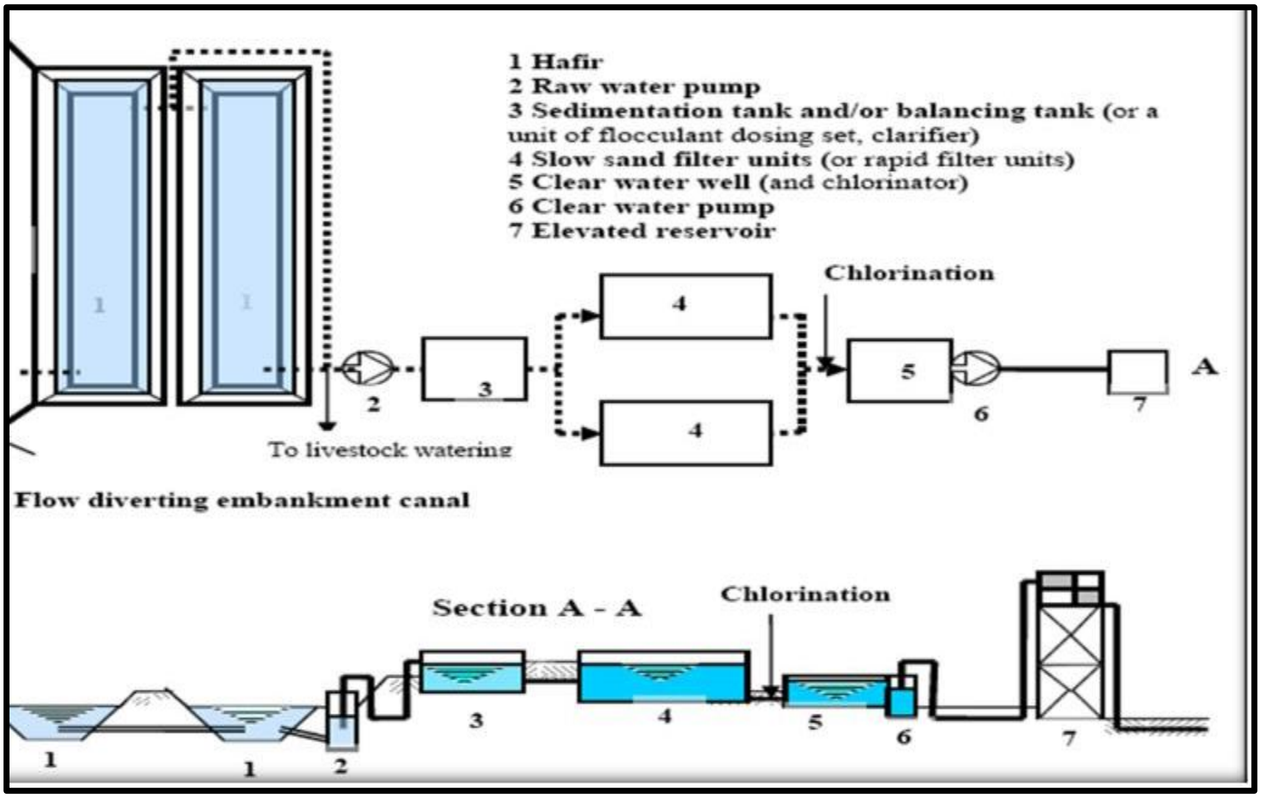

Fig (12) Schematic Flow Diagram of Improved Hafir - Sudan Experience.

By capturing and storing rainfall, communities can have a more reliable water source throughout the year. This reduces the time and effort spent on collecting water. Therefore, increases water availability and frees up women and children to pursue education and other life activities. For the agricultural communities in AL, WH is not just about drinking water; it is about survival - by improving soil moisture and supporting drought-resistant crops. Moreover, it can significantly increase agricultural productivity, enhance food security and build resilience against climate shocks. Successful WH projects often involve community-based management. This builds local capacity, creates a sense of ownership and ensures the long-term sustainability of the water systems. WH in AL will provide the following benefits:

- *Recharges Groundwater*: Structures like check dams and percolation tanks slow down runoff, allowing water to infiltrate the soil and replenish shallow aquifers and wells, sustaining groundwater levels.
- *Mitigates Environmental Degradation*: By controlling and slowing surface runoff, water harvesting techniques significantly reduce soil erosion and nutrient loss, helping to conserve the topsoil and improve land productivity.
- *Reduces Disaster Risk:* Storing excess water can help mitigate flooding of low-lying areas during intense, unpredictable rainfall events, a growing concern with climate change (Artan et al. 2004, Asante et al. 2007).
- *Cost-Effectiveness and Local Ownership:* Many techniques are simple, low-cost, and rely on local materials and labour, making them easy for communities to construct and maintain, fostering greater self-sufficiency. Examples include Semi-Circular Bunds and small basins.

Hafirs can be strategically placed to collect water from seasonal streams (wadis) and surface runoff. They provide a vital water source for both human consumption and livestock, hence reducing the need for people and animals to travel long distances in search of water. Sometimes, it is a good idea to include a crossing wall beneath the wadi bed to store the flow below the sand, creating an underground reservoir. This method's advantage reduces evaporation and keeps the water clean by filtering it through the sand. It can be a highly sustainable solution, providing a water source during the dry season without the losses associated with open-air reservoirs.

In a locality where much of the population depends on rain-fed agriculture, these micro-catchment techniques are crucial. They significantly improve soil moisture, which can increase crop yields by as much as 71%, according to studies in similar regions in Northern Kordofan, Sudan (Fig. 13), Ahmed 2005. The reported results were encouraging, with substantially higher production, while the control farm without WH failed. This directly contributes to food security and reduces the risk of crop failure, which is a major driver of poverty and displacement.

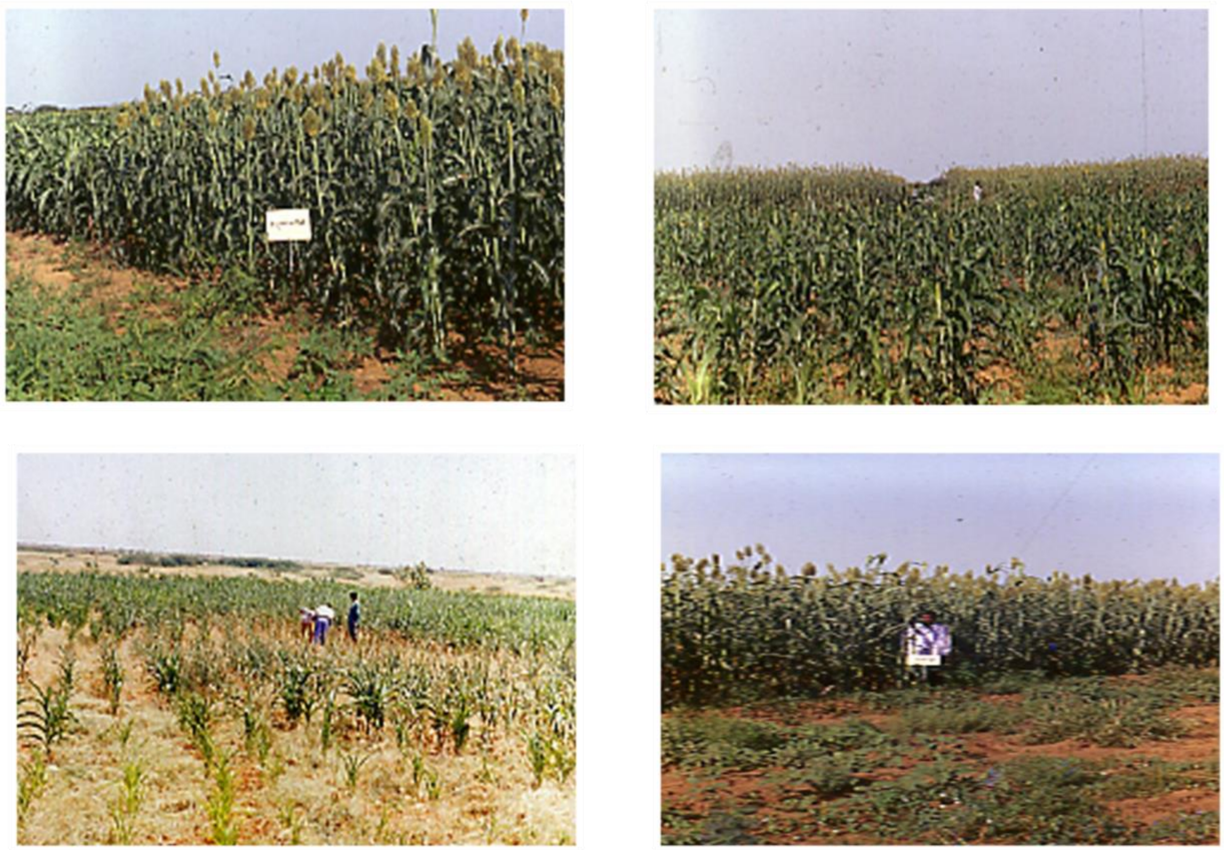

Fig (13) **Comparison between three fields with WH and the fourth without WH (Ahmed 2005)**

7.0 Challenges

High evaporation rates, seepage and sedimentation are common problems. To mitigate these, modern Hafir designs favour greater water depth rather than greater surface area and use lined bottoms to reduce seepage. Funding WH solutions for communities in AL-WNS requires a multi-pronged approach that combines international humanitarian aid, government development funding and local community-based contributions. Unfortunately, the ongoing conflicts have disrupted many traditional channels, making these communities even more dependent on external support. Local Communities, assisted by local governmental authorities, usually manage and maintain WH projects. These projects can generate funds for their sustainability.

Several UNEP reports (Barron 2009; UNEP 2015; UNDP 2020; UNEP 2022) and IPCC (2022) reported on the region's severe vulnerability to climate change, including the Nile Basin. They identified WH as a key intervention to address challenges such as low and erratic rainfall, poor crop genetic stock, and lack of basic infrastructure.

8.0 The Role of Local Communities

Local communities are the most critical actors in post-implementation management. Their involvement ensures the project's sustainability and relevance to local needs. The local communities should form a *Water User Committee* (WUC) to oversee the project's daily operations. This committee, ideally with representation from youth and women, is responsible for system management, controlling water distribution and collecting fees from users to create a revolving fund for maintenance and minor repairs. Moreover, the Committee handles *conflict resolution* by mediating disputes over water access and usage, which is a major source of conflict in resource-scarce areas.

Knowledge will be transferred to the local community members through extensive training on the project system's operation and maintenance. This ensures local expertise is developed and reliance on external technicians is minimised. The community contributes in kind by providing labour for maintenance and security. This strengthens their ownership and reduces external costs.

9.0 The Role of the Government

The government's role is not in direct management but in creating an enabling environment for communities to succeed:

- *Policy and Legal Frameworks:* The government, at both the WNS and AL levels, must provide clear policies and legal frameworks for community-based water management. This includes formally recognising WUCs and their right to collect fees and manage assets.
- *Technical and Financial Suppor*t: The government should act as a technical and financial backup system. This includes:
  i- *Monitoring and Supervision:* Conducting periodic checks to ensure water quality standards are met and systems are functioning correctly.
  ii- *Major Repairs:* Providing support for large-scale repairs that are beyond the community's capacity, such as a full pump replacement or the rehabilitation of a large reservoir.
  iii- *Capacity Building:* Offering training to community committees and local administrators to strengthen their management skills.
  iv- *Coordination:* The government's role is to coordinate with various stakeholders, including international NGOs, local civil society organisations, and different government ministries (e.g., health, agriculture), to ensure projects are integrated into broader development plans.
  v- *Conflict Mediation:* The government, through its local administration and traditional native administration, must be prepared to step in and mediate disputes that exceed the capacity of local water committees.

10.0 Conclusion

The AL-WNS region was divided into 21 distinct basins to evaluate water balance and runoff generation capacity. The analysis shows that surface runoff accounts for an average of 1% to 8% of total rainfall in the area. A comprehensive multi-criteria suitability analysis identifies ten new Hafirs. The latter will significantly increase long-term water security for the local population.

The findings demonstrate that water harvesting (WH) can substantially improve quality of life across AL-WNS communities. By ensuring a reliable supply of safe, adequate water for human and livestock consumption, WH initiatives directly bolster rural livelihoods. Furthermore, improved soil moisture levels support healthier plant growth, thereby enhancing agricultural output and overall crop yields. Hafirs project sites are identified using rigorous scientific criteria aiming to mitigate localised water scarcity.

The study underscores that active community participation and government support are critical to the effective management and long-term sustainability of WH infrastructure. Ensuring lasting impact will require optimised engineering design, high-quality construction, sustainable funding for operation and maintenance, and robust governance.

Ultimately, rainwater harvesting offers a vital strategy for addressing water scarcity and fostering sustainable water management across arid and semi-arid regions. However, operating in remote, harsh rural environments presents ongoing operational challenges. Further field data collection and in-depth hydrological studies remain essential to address the complexities of water scarcity in AL-WNS.

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