Review Article | Open Access

Basheer et al., 2023. 25 (1&2): 51-65. J. Environ. Agric. Sci. (ISSN: 2313-8629)

Sustainable Utilization of Water Resources in Agriculture Sector of Sudan, After The Secession of South Sudan

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Received
December 20, 2022

Accepted
February 18, 2022

Published Online
June 30, 2023

Abstract: Extreme climate events and anthropogenic activities pressurize water resources and aggravate water security challenges. Sustainable use of water in Sudan has two major issues: agriculture and the separation of South Sudan. Thus, this study aims to assess Sudan's water resources, estimate future water demands, and shed light on the prospects of sustainable utilization. Irrigated agriculture consumes approximately 86% of blue water. Rainfall is erratic and concentrated over a short period; groundwater resources require technical and economically feasible means of extraction. Storage capacity facilities are limited to short-term storage. Therefore, integrated water resource management strategies, such as surface water and rainwater harvesting techniques, should be applied to utilize seasonal stream water and increase rainfed agricultural production. The use of artificial groundwater recharge techniques, where appropriate, could increase the storage capacity and maximize utilization.

Keywords: Africa; Nile Basin; sustainable utilization; transboundary water cooperation; water management; water resources.

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Cite this article as: Basheer, A.K., A.B. Ali, N. A. Elshaikh and G.H. Agbna. 2023. **Sustainable utilization of water resources in agriculture sector of Sudan, after the secession of South Sudan**. Journal of Environmental & Agricultural Sciences. 25(1&2): 51-65.

1. Introduction

Water is an important natural resource, especially of major importance in the semi-arid and arid regions, including MENA region and Sudan (Allam et al., 2019; Hindiyeh et al., 2023; Simonin et al., 2023). Irrigated agriculture is a major water consumer throughout the world (Bashir et al., 2019; Sarwar et al., 2021), especially in areas with dry climates, which consume about 50-85 % of total water use. In Sudan, water resources are facing increasing pressure due to rising demand for irrigation water, changing climatic conditions and rapid population growth (Hamdy, 2001; Hindiyeh et al., 2023). Therefore, it is challenging to meet the water demand of agriculture sector using conventional water resources and without sustainable management of these resources (Kau et al., 2022; Mekonnen and Hoekstra, 2016; Ricciardi et al., 2020). Sudan water resources are generally classified as conventional and non-conventional resources. Rainfall, surface water (Nilotic and Non-Nilotic water) and groundwater are included in the conventional resources of water, while treated wastewater and desalinated water are non-conventional water resources (Basheer et al., 2023; Djumaet al., 2016; Nasreldin and Elsheikh. 2022).

Globally, River Nile with its main tributaries (Blue Nile, White Nile, and River Atbara) is the longest river system (Othoche, 2021). It flows 6,600 km, crossing more than 35 degrees latitude and occupying more than 3.0 million km^2 area. The River Nile water is a main contributor to agriculture production while most surface water from seasonal streams is lost except on a

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small scale in some states of Sudan (Abdelkareem and Al-Arifi, 2021; Hamada, 2017).

Moreover, the seasonal streams (Wadis) in Sudan, due to the topographic nature and diversity of the climatic regions, are the major water resources in Sudan. Seasonal streams are more important in the areas with complex basement formation, zones of groundwater salinity and areas which are isolated from the Nile system. Surface water diversion and its utilization, for domestic and irrigation purposes, is widely practiced in Sudan (Bushara et al., 2021). This can be seen in most states of Sudan e.g., North Kordofan, River Nile and Blue Nile States with large towns and villages (Dile et al., 2018). These areas have more water requirements which are met by harvesting surface water in large water reservoirs (Hafirs). Moreover, farmers use traditional techniques of water harvesting or restricting water in agricultural lands using a basin irrigation system. On the other hand, groundwater is also a key water resource, critical for essential activities for providing basic necessities of the local population, livestock and also used for agriculture in most parts of Sudan (Amara and Saad, 2014; Bashir et al., 2023).

Moreover, groundwater is the major source of water for domestic and drinking purpose for a large segment of local population (>80%) and their livestock (Abdalla and Mohamed, 2012). Groundwater plays a very vital role in the regulation of environment by maintaining stream flows, and wetlands, and supporting vegetation (de Graaf et al., 2019; Mather et al., 2022; Sarwar et al., 2021). Around 15 mha area is categorized under rainfed agriculture. Rainfed agriculture contributes a vital share in the national economy and is important for regional food security. About half of the area under rainfed agriculture, in Sudan, is cultivated through mechanization (Elagib et al., 2019; Mohammed et al., 2010; Rosa et al., 2020).

Separation of South Sudan according to the peace agreement (Machakos Protocol), had several provisions linked with water security and agriculture to address conflicts regarding competition for land and water resources (Carolan, G. 2021; Salman, 2011). Transboundary water utilization from the River Nile and its tributaries is governed under international agreements to ensure fair and equitable use of water resources (Deribe and Berhanu, 2021; Hussein, 2019; Octavianti and Staddon, 2021).

Changing climatic conditions, anomalies and uncertainty of rainfall intensity, duration and frequency, high evapotranspiration losses and poor hydropolitical management may potentially worsen the water crisis of Sudan in the near future (Alriah et al., 2021; Zhang et al., 2012). Standardized precipitation anomaly index of Sudan showed a rapid increase in dryness across the country (Sahoo and Govind, 2022). Models have predicted that anomalies in the hydrological system are expected to further worsen in future (Hamadalnel et al., 2022), which will pressurize excessive utilization of groundwater resources. However, groundwater resources of Sudan need precise assessment, both in terms of quantity and quality of water. Groundwater resources also require technical and economic feasibility for water extraction to meet regional requirements for water use for different purposes (Khan et al., 2021; Scanlon et al., 2023; Widaa and Saeed, 2008). Globally water security is threatened by rising water withdrawals to meet the increasing demand. This causes water resource degradation and associated ecosystem disturbances. This issue is further intensified due to changing climatic conditions and increasing pollution (Garrick and Hall, 2014; Mullin, 2020; Vörösmarty et al., 2000).

United Nations launched the Sustainable Development Agenda for the year 2030, in 2015. This was a plan of action for people, planet and prosperity consisting of Sustainable Development Goals (SDGs). In addition to economic growth, these SDGs ensure sustainable development through environment protection and social inclusion (Hák et al., 2016). Several transformations, including priority investments and regulatory challenges, were proposed for achieving SDGs including sustainable water utilization (Sachs et al., 2019).

Targets of different SDGs are interconnected, and linked with water resources (Alcamo, 2019) to ensure water availability and sustainable management of water for all segments of society. These SDGs are aimed at reducing pollution to improve water quality and substantial enhancement of water-use efficiency across different sectors. SDGs also target sustainable withdrawal and utilization of water to address its scarcity, supplemented with efficient management of water resources through integrated management across water consuming sectors. The inclusion of transboundary cooperation, protection and restoration of water-related ecosystems (aquifers, forests, lakes, mountains, rivers, wetlands), expansion of international cooperation are also included in the mandate of SDGs. They also intend to provide capacity-building for the developing and less developed nations in water-associate events and plans, for the development of technologies associated with desalination, recycling and reuse of water, wastewater treatment, water harvesting, water use efficiency, (Arora and Mishra, 2022; Hoekstra et al., 2017).

Sudan is lacking systematic water resources management (Dirwai et al., 2021; Pacini and Harper. 2016). Therefore, limited data is available for the assessment of water resources for the present time and future demands. Consequently, under changing climatic scenarios and increasing water scarcity, the national water policy of Sudan needs improved management and serious measures to protect water resources at the national and transboundary levels (Alnour et al., 2022; Hamouda et al., 2009).

Water resources in Sudan, and Nile Basin, need strong efforts for development and integrated management for sustainable utilization through improved and efficient water use, water harvesting and transboundary cooperation (Ayyad and Khalifa, 2021; Mumbi et al., 2022; Orme et al., 2015). Therefore, this work aims to shed light on the situation of the conventional and non-conventional water resources after the secession of the south and highlights the water demands in Sudan after separation in 2011. Also, the article will highlight the prospects of planning, development, efficiency, and utilization to reach sustainable water resources in agriculture.

2. Current Status of Water Resources in Sudan

Water resources in Sudan could be classified as rainfall, surface water (Nilotic and Non-Nilotic), groundwater and non-conventional resources (Table 1).

2.1. Conventional Water Resources

2.1.1. Rainfall

Nile Basin, in Sudan, is characterized by significant spatiotemporal variability in rainfall patterns (Basheer and Elagib, 2019; Mohamed et al., 2022). Annual rainfall is minimal at the Sudanese-Egyptian border, reaching its maximum (>900 mm rainfall) in the southwest of Sudan. Hydrometeorologically Sudan has been divided into four major rainfall zones, (a) The northern part of Sudan (desert zone; lies between 17˚ N and 23˚ N) with annual rainfall >75 mm. (b) The Red Sea zone in the northeastern part of the country; (latitudes 23 to 18˚ N and longitude 36˚ E, which has the Mediterranean climate with annual rainfall ≥75 mm. (c) Semi-desert zone (latitudes 15˚ and 17˚ N) characterized with 75 to 300 mm annual rainfall. In this zone the rainy season is short (confined to 2 - 3 months), while remaining months are usually rainless.

Table 1. Annual Rainfall Pattern (BCM/Year)

Average depth (mm)	Rainfall (BCM)	% of total
<100	15.7	3.0
100-300	46.0	8.86
300-600	124.5	23.9
600-900	331.8	63.9
Total	519	100

Rainfall is generally observed as isolated showers, with significant interannual and spatial variation in their amount, duration, and intensity (Sahoo and Govind, 2022; SMA, 2006). The coefficient of variation of the annual rainfall can reach 100%, in the northern part of Sudan (FAO, 2005). Annual rainfall in the Savanna zone (between latitudes 9˚ and 15˚ N) ranges between 300 to 900 mm. However, in the northern part of Sudan, annual rainfall can exceed 500 mm. Most of this rainfall is concentrated in only four months (July to October), while annual rainfall in the southern part generally exceeds 1000 mm, and is concentrated in June to October (SMA, 2006).

In Sudan, rainfed agriculture is mainly practiced during this season. Coefficient of variation in interannual rainfall variation can reach 30% in the region. Dry season extends for about seven to eight months. Due to large interannual variability in rainfall, cultivated area and productivity also vary significantly (Table 1) (FAO, 2005). The mean annual rainfall is estimated at around 276 mm (Fig. 1), corresponding to about 519 (BCM/year).

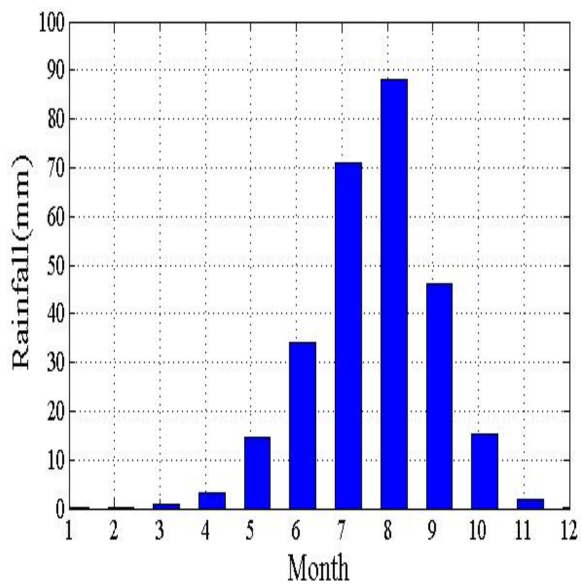

Fig. 1. Mean Monthly Rainfall over Sudan (FAO, 2005).

Table 2. Summary of Sudan's Available Water Resources and Associated Limitations

Water Resources	Quantity BCM	Constraints
Current share of Sudan from the Nile water agreement (at central Sudan)	20.5	Seasonal variations, water storage facilities scarce , expected to be shared with riparians.
Water from Wadis	5.0-7.0	Significant variation in the amounts, short duration flows, monitoring or harvesting of water is problematic, some shared with neighbors.
Renewable groundwater	4.0	Deep water, high cost of water extraction, remote areas, poor infrastructure.
Present total	30.0	
Expected from reclamation of swamps	6.0	High initial cost, expected social and environmental issues and limited acceptance of society
Total	**35.5- 37.0**	

Source: Ahmed, (2009)

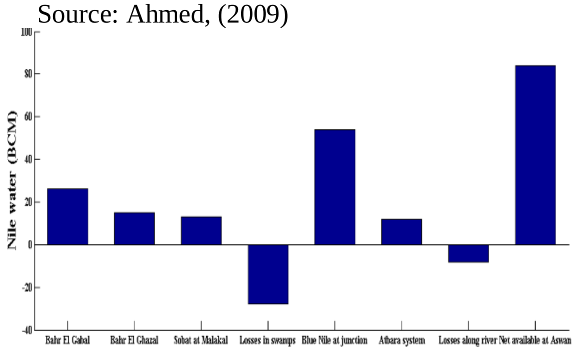

Fig. 2. Discharge of Nile River System (BCM/Year) (MOIWR, 2012).

2.1.2. Nilotic Water Resources

The Ethiopian Plateau (Tana Lake) and central Africa Great Lake Region (Victoria) are the major sources of Blue and White Nile, respectively. Lake Victoria is the downstream of the Kegera River that flows from Burundi through Tanzania, and this is the most distant source of the Nile. Blue Nile has around 59% share in the Nile water, while Tekezaze-Atbara has 12%. This percentage significantly changes during flooding time (July to October). While the share of White Nile shares around 29% of the Nile water (Table 2), (Fig.2) (Dile et al., 2018; Eldaw, 2003).

There is significant temporal variation in the water flow of the Nile (Fig. 3). Eleven African countries (Egypt, Democratic Republic of Congo, Burundi, South Sudan, Eritrea, Tanzania, Ethiopia, Rwanda, Sudan, Uganda, and Kenya) share the water resources of the Nile. Considering the geographic area of Sudan, 60% of the area lies in Nile Basin. Whereas 24% area of the Nile Basin lies in Sudan (Salman, 2011). Several international agreements regulate the water-linked interactions between the abovementioned African countries from 1891 up to 1959. The first Nile Water Agreement was signed (1929) between Sudan and Egypt, accepting the Egyptian right to annual use of 48 BCM. Contrarily, Sudan was offered annual right to use only four BCM. Interestingly Ethiopia was not given any right to use Nile water (FAO, 2005).

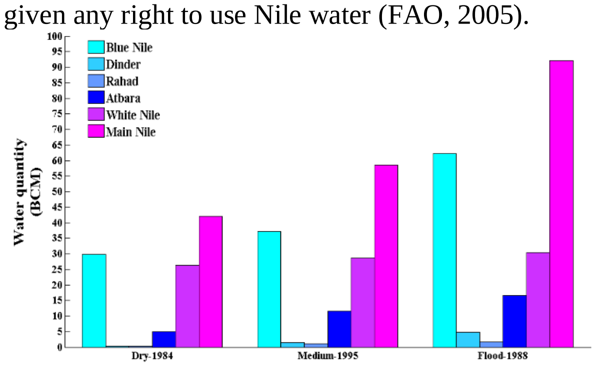

Fig. 3. Annual Discharge of Nile and Tributaries in Selected Years (BCM) (MOIWR, 2011).

Table 3. Water Storage Reservoirs of Sudan

Dam reservoir	Location (River)	Construction year	Design capacity BCM	Present capacity BCM
Sinnar	Blue Nile	1925	0.93	0.40
Jabel Awlia	White Nile	1937	3.5	3.5
Roseries	White Nile	1966	7	7
Khashm Elgerba	Atbara River	1966	1.3	0.65
Merowe	The River Nile	2005	12	12
The Upper Atbara and Setit Dam (under Construction)	Atbara River	2011-2016	3	-
Total			27.73	23.55

Source: (MOIWR, 2011)

Nile Water Agreement (1959), between Sudan and Egypt, gives annual water rights (18.5 BCM, as measured at Aswan; 20.5 BCM at Sennar dam), and the corresponding annual share for Egypt was 55.5 BCM of water (Ali, 1993). Nevertheless, the volume of storage facilities in Sudan is far less than the amount needed. In Sudan, dams were constructed for the provision of irrigation water during the drier period of the year. These dams have varying water storage capacities (Table 3). Moreover, these dams are also involved in the generation of valuable hydroelectric power.

After South Sudan has been separated from Sudan the conflict on water resources is present on the surface, therefore the water issue between the two countries should be discussed in detail. International water-related agreements could be encompassed in the agreement category which are automatically binding successor countries as they are considered as linked to the country. However, newly emerged nations generally reject bounding to the water agreements concluded by predecessor countries, like Tanzania, or depending on the advantages to the emerged nation.

2.1.3. Non-Nilotic Water Resources

Watersheds of Angasana Hills (south-east), Al Botana Hills (central), Jebal Marra (west), Nuba Mountains (southwest), Red Sea Hills (east), and the Ethiopian Plateau (Baraka and Gash) are Non-Nilotic water resources of Sudan. These watershed systems have numerous Khors and Wadis of various sizes. In large wadis or khors, annual discharge may reach 100 million cubic meters (MCB). Small wadis or khors can have annual discharge <1.0 MCB (Abdalgadir et al., 2003).

The largest wadis include Gash (Mareb) and Baraka, having annual water flow of 200 to 800 MCM. This water flow mainly occurs from July to September. These Wadis begin in Eritrea and end in the continental deltas of Gash, and Toker, and reach the Red Sea. In the western Sudan, Azum, Ebra, Elkou Hawar, Kaja, Salih and Toal are the largest Wadis, with 120 to 500 MCM annual water flow (Adam, 1993). In Sudan, total annual runoff of all the Wadis is estimated between 5 to 7 BCM (Elteyeb, 2002).

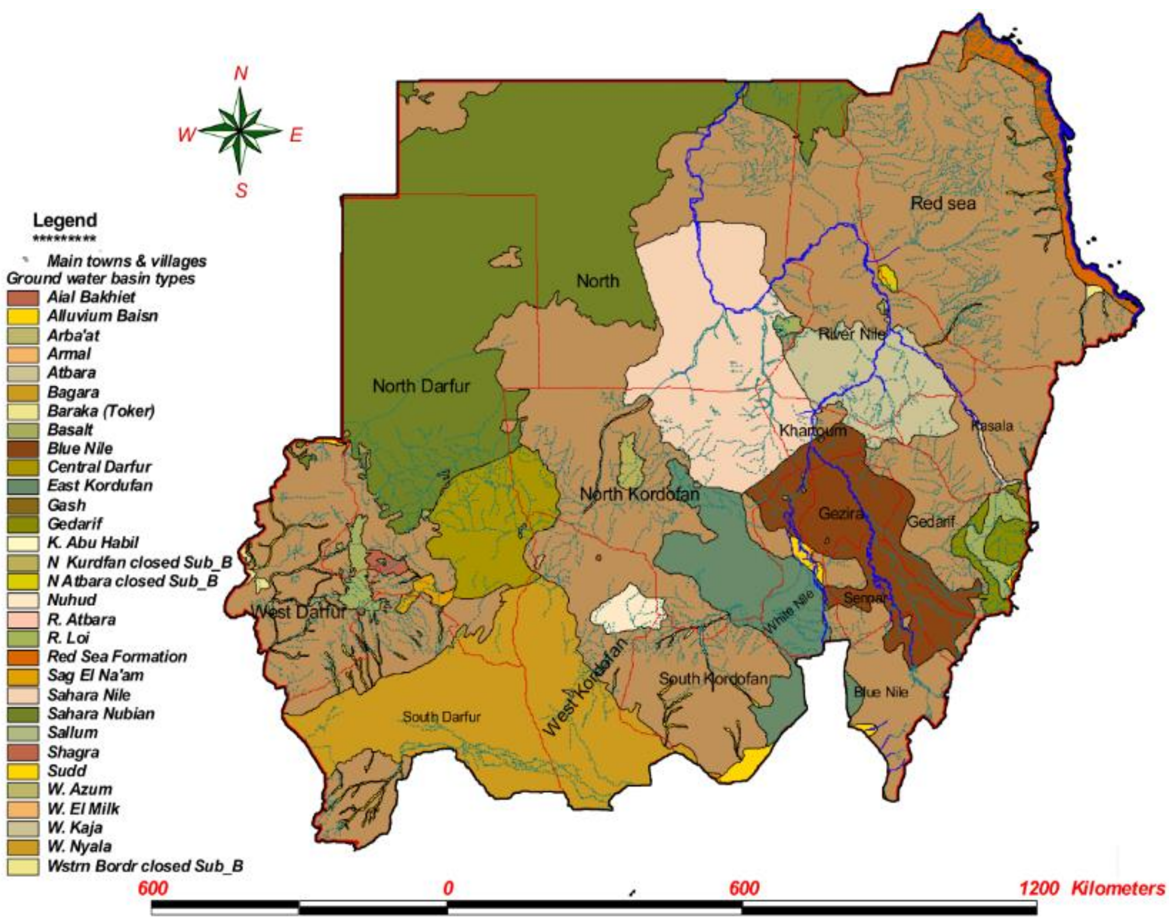

Fig. 4. Groundwater Basins of Sudan (Information Center, 2011)

Table 4. Groundwater Capacity and Quality of Different Basins of Sudan (Information Center, 2011)

Groundwater Basin	Area (km^2)	Quantity of Water (BCM)	Water Quality (dissolved solids ppm)	Annual Average Recharge (MCM)
Nubian Basin	637073	12600	100-800	1008
Umm Rwaba Basin	400,957	3150	500-600	300
Nubian/Basalt Basin	29,016	715	400-500	325
The Alluvial Basin	-	2.5	-	1800
Total		16502.2		3433

Groundwater is available for approximately half of the geographical area of Sudan (Dossou-Yovo et al., 22019; Kheralla, 1984; Mohammed et al., 2023), with depths ranging between 40 - 400 m and has total dissolved solids of about (100 to 2000 p.m.). The main aquifers in Sudan are sedimentary Nubian sandstone, Umm Rawaba formation, Nubian/Basalt and the Alluvial Basin. These aquifers are present in a simple form or a complex one, depending on their geological formations (Table 4 and Fig.4) (Eldaw, 2003; Salama, 1979). The Nubian basin comprises 28.15% of the country's area and provides good quality water which is suitable for not only animal consumption but also for humans. The Nubian basin is shared with Libya and Egypt (Puri, 2001).

The basin storage capacity is 12600 BCM with an annual recharge rate of about 1008 MCM. The Nubian basin is divided into the Central Darfur, Sahara Nile, Sahara Nubian, Nuhud, Sag El Na'am and River Atbara Basins (Ali and Zahran, 2023). The Umm Rwaba basin encompasses NW-SE trough with a surface area of about 0.401 million km^2. The basin storage capacity is about 3150 BCM and the annual recharge is about 300 MCM. During the rainy season, White Nile serves as the major source of water recharge in the basin and also the surface flow (Salama, 1979).

The Nubian/Basalt basin covers an area of about 29,016 km^2. The basin storage capacity is about 715 BCM with annual recharge of about 325 BCM. Seepage of water from River Setit, (branch of River Atbara) into the sandstone formation and surface flow during the rainy season are the major source of water recharge.. This basin is subdivided into the Gadaref and Shagara basins.

The runoff from khors is confined to three months (June–September) per year. Water storage capacity Nubian/Basalt basin is around 2.5 BCM with an annual recharge rate of 1800 MCM. There is substantial runoff during this period. Therefore, aquifer in the region thoroughly recharged after wet seasons. High storability and transmissivity values are major characteristics of alluvial deposits. Due to shallow depth of aquifer, local populations have developed cost effective methods to extract water for domestic and irrigation purposes. Historically, these basins are remains of the oldest civilization and ancient centers of crop cultivation using underground water (Grigg, 2008; Salama, 1979).

2.1.4. Non-Conventional Water Resources

Due to decreasing water resources and uncertainties due to changing climatic conditions water desalinization has emerged as a developing industry in Sudan. Three are two desalination plants commissioned (2004) to transform water from the Red Sea and supply fresh water to Port Sudan city. These desalination plants have daily capacity to desalinate 10,000 m^3 of water (2500 and 7500 m^3 per day). The small plant takes the saline water (42000–45000 ppm salt concentration) from the Red Sea.

Table 5. Discharge Capacities of Khartoum State Treatment Plants (Ministry of Infrastructure, 2012)

Treatment plant	Daily discharge 1000 m^3	Annual discharge 1000 m^3
Soba	50	18300
Ministry of Defense	1.95	713.7
Ministry of Interior	1.2	439.2
Dams Implementation Unit	1.6	585.6
Ministry of Health	0.3	109.8
Student Support Fund Cities	0.4	146.4
Lybia Market	5	1830
Khartoum North	13	4758
Total	**644.5**	**235887**

The other plant faced several issues, mainly depth of water extraction and extremely high salt concentration in water. Desalination plants were established to extract saline water from deep wells with extremely saline water. Therefore, further research is required to increase desalination capacity and improvement in plant design (Eltoum et al., 2002).

Irrigation of urban wastewater in croplands is widely used and is further receiving attention, mainly due to freshwater scarcity in semi-arid and arid areas. Previously wastewater was discharged to rivers and onto open areas, but with increasing population disposal in rivers and open areas was environmentally not accepted. This problem gradually increases due to rising population pressure and industrial sector in such towns. Recently the authorities of Khartoum state gave more attention to the safe disposal of this water by using it in agriculture, which diverted this amount of water to irrigate Yarmook and Soba projects in the south of the state. Also, there are about eight treatment plants of different capacities distributed across the cities of the state (MI, 2012; IC, 2011). The total capacities of these plants are about 235.887 MCM annually (Table 5).

3. Water Consumptive Uses and Future Demand in Sudan

In the Nile River basin, consumptive use has been rapidly growing, especially during the last 50 years, and is projected to further increase (Ali and Zahran, 2023; Khalifa et al., 2023). This rapid increase in consumptive use is led by unprecedented population growth, irrigation urbanization, environmental issues, seasonal variability in water flow, low water use efficiency, inadequate management of infrastructure, etc. These factors have rapidly pressed limited water resources in the Nile River basin. A majority (80%) of consumptive use is consumed for irrigation purpose. Crops grown in Sudan require more water due to inefficient irrigation system and high-water requirements. While, human, animal and industrial consume less than 20% (Fig.5). There are about 1.85 million hectares covered by developed agricultural schemes. The actual cultivated area is more than 1.35 million ha and is expected to rise to 2.31 million ha in the near future (Abdalla, 2001).

During the season of 2007/2008, irrigated agriculture consumes about 16 BCM with good irrigation efficiency in most schemes in Sudan, which play a very important role in the amount of water used. This efficiency depends on present performance, crop pattern and irrigation requirements. Moreover, irrigation conveyance efficiency is also critical in the plains of Sudan where clay soil dominates (Abdalla, 2001; Ali et al., 2017; Ibrahim et al., 2023; Nafi et al., 2019).

In Sudan, irrigation efficiency is high. Gezira scheme consumes 40% of the present withdrawal and has high water use efficiency (around 85%). However, major issues are siltation, growth of aquatic weeds in the canals and deterioration of irrigation infrastructure. On the other hand, water losses through evapotranspiration are generally high (Abdelhadi et al., 2000; Amarnath et al., 2018; Khalifa et al., 2023; Omer, 2008).

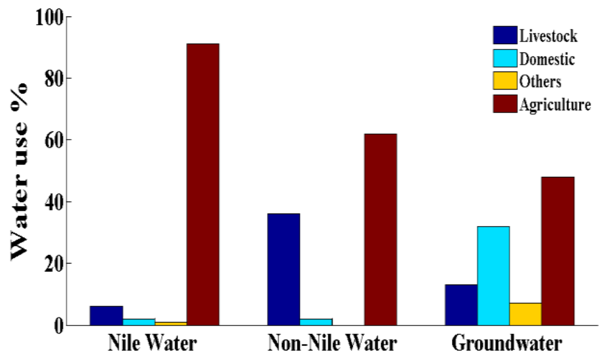

Fig. 5. Sector Wise Water Consumption from Different Resources in Sudan.

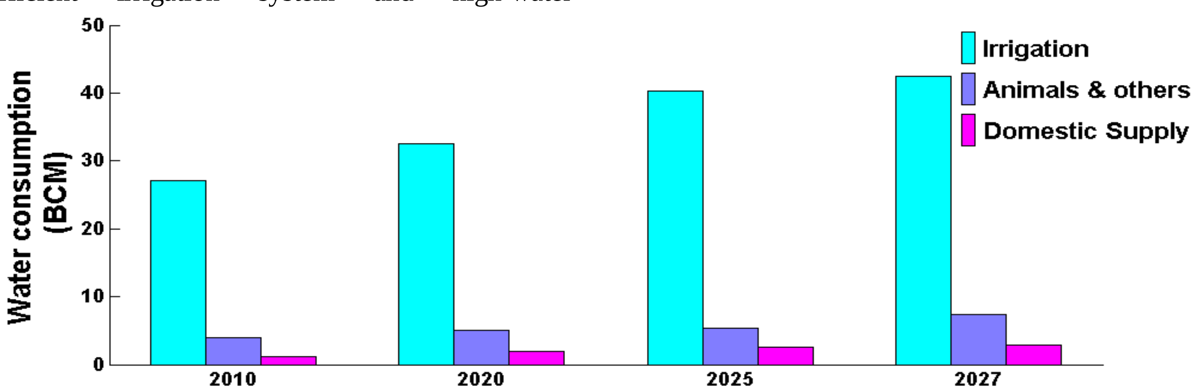

Fig.6. Annual Projection of the Water Consumption by Year 2030 in Sudan. (MOIWR, 2012).

Irrigation requirements are expected to reach 42.5 BCM in 2027 (Abdalla, 2001; MOIWR, 2011). Domestic use, human and animal needs and industrial usage are projected around 10.1 BCM (Fig. 6). The total demand will be 59.2 BCM in case of higher evaporation losses from proposed hydropower reservoirs (6.6 BCM increment). This will be beyond the reach of the total available water amount including the southern swamps conservation share. This shortage will not fill even if all seasonal stream water is harvested.

4. Potential of Sudan Water Resources Development and Management

To achieve increased resilience of water resources, a wide range of water management practices, including preservation of wetlands and forests, enhanced storage of surface reservoirs and depleting aquifers, and water transportation, are required (Scanlon et al., 2023).

4.1. Rainfall Water Management

Sustainable management for rainfed lands can be achieved by maximizing the infiltration of rainfall and minimization of unproductive losses. Selecting drought-tolerant crops or cultivars, improving soil health, mulching, suitable irrigation management and other agronomic strategies can help to increase plant water uptake (Bali et al., 2023; Rehman et al., 2021). Moreover, effective management of crops, soil fertility, and water deficits during dry spells, through supplemental irrigation, are important management strategies for sustainable crop production(Cuevas et al., 2019; Nangia and Oweis, 2016). Appropriate water harvesting techniques for micro-irrigation combined with supplemental irrigation and conservation tillage can also be helpful (Gaddikeri et al., 2023; Govind, 2022).

4.2. Nilotic Water Development and Management

4.2.1. Irrigated Water Management

The main use of Nile water is irrigation, which consumed about 15.9 BCM/year in the last ten years. The irrigated sector produces 100% sugar, 95% cotton, 36% sorghum, 32% groundnut and fruits and vegetables (Farah, 1999). Water use productivity is less than 0.2 kg m^{-3} for means for cotton, sorghum, groundnut and wheat. However, this water productivity is lower than the global average and has significant potential to reach 1 kg m^{-3}. Some crops consume huge quantities of water like sugar cane. Although the total sugar cane cultivated area is about 135000 hectares representing about 10% of the cultivated areas of Sudan it consumes about 30 % of Sudan's water share of the river Nile (18.5 BCM).

Sugar beet can grow successfully in the agroclimatic conditions of Gezira state. During preliminary adaptability trials, high root yields and sugar content were recorded resulting in a raw sugar yield of 50-55 t ha^{-1} (Abdelhadi and Salih, 2012). The total applied water for all the given irrigations measured as average was in the range of 12.852-14.280 m^3 ha^{-1}. It was also stated that the crop is very suitable for Gezira Scheme rotation. Also, studies showed that sugar beet needed about 19-20 irrigations with an average of 476.2-714.3 m^3ha^{-1} of water per irrigation, while sugar cane needs almost 42382 m^3 ha^{-1} to produce about 87.14 t ha^{-1} (Abdelgader et al., 2013). Nevertheless, sugar cane gives 4.2 t ha^{-1} pure sugar while sugar beet gives 7.5 t ha^{-1} pure sugar. Regarding water use efficiency sugar beet gives about 0.53 kg m^{-3} while sugar cane gives about 0.1 kg m^{-3}. Therefore, instead of sugar cane, cultivation of sugar beet is recommended. This has certain implications for the processing of sugar since the current sugarcane factories cannot produce sugar from sugar beet without major adjustments, especially from the energy side point of view.

Extensive research must be directed to develop and adopt high-efficiency irrigation techniques and management practices to reduce water losses and increase water use efficiency. Cultivation of drought-tolerant crops (or cultivars), and effective irrigation scheduling are potential solutions. Irrigation in the Gezira Scheme or more broadly in the central clay plains where the potential irrigated agriculture in Sudan is realized. There are very simple facts and rules of thumb that apply when dealing with irrigation water management under the heavy-cracking clay plain. Soil with higher clay contents, which produces cracks on drying, is not suitable for crop production. Delaying or reducing the irrigation interval will subject the crop to water stress. Contrarily, over-irrigation tends to stay at the surface (due to the pore clogging, especially in clayey soils) producing waterlogging, consequently causing anaerobic conditions in the soil. Anaerobic conditions inhibit several plant processes and compromise plant growth, development and economic yield of crops (den Besten et al., 2021; Liu et al., 2020; Zhang et al., 2021).

Irrigation water management under the central cracking clay plains as has been represented by Gezira Scheme requires a full understanding of the physical characteristics of this soil leaving few but more viable options to improve water productivity for example in the Gezira Scheme and these could be as follows; (1)

Improve timeliness of irrigations not to exceed 12-14 days since any delay after that will introduce the beginning of water stresses for any crop (heavy clay tend to withhold water more strongly when certain amount of available water is depleted). Improve water management infrastructure of the irrigation network in terms of overflow structures and gates and avoid unnecessary and improper digging of minor canals. Water user association regulation cannot be implemented without empowering the associations through hands-on training and capacity building in all agricultural production capabilities. (2) Apply without delay all the recommended technological packages resulting from verified on-farm research (this includes type amount and time fertilizer application, sowing of improved varieties, removal of weeds and controlling of insects and diseases using integrated pest management recommended practices).

4.2.2. Cooperation Between the Nile Basin Countries

The Nile Basin expanded to eleven countries: Rwanda, Burundi, Kenya, Tanzania, the Democratic Republic of Congo, Uganda, Ethiopia, Eritrea, Sudan, Egypt and the Republic of South Sudan. The Nile Basin countries (in 1997) initiated a negotiation for a long-term cooperative framework.

The Nile Basin Initiative (NBI) was approved in 1999, and the joint program was envisaged for sustainable development and management of Nile waters through Shared Vision Program (SVP), to promote economic growth, poverty reduction and control of environmental degradation. Under the umbrella of SVP several projects were initiated to achieve the set objectives and sharing benefits.

Adverse effect of climate change on the Nile River is predicted in the future. This will dramatically change the water resources in the Nile Basin countries, particularly Sudan (Elshamy et al., 2009; Basheer et al., 2016). Share of Sudan in the Nile water is expected to increase by acting with Egypt and South to reduce evaporation losses from the swamps. This requires working with South Sudan as an independent country now. Whereas a large amount of water can be saved from the White Nile system as suggested by the Nile Basin Initiative (NBI). Some studies suggested digging canals to collect water from some rivers and deliver it to the White Nile, which will produce about 19 BCM/year (Ganadi, 2006). Although the capability of these projects, it should seriously consider the social and environmental impacts. These projects could be considered as a solution to reducing water shortage and increase Nile water discharge. Sudan, Egypt and South Sudan should cooperate between them to implement these projects. Further, all these projects may help to solve the issue of water in the near future between Sudan and South Sudan. The amount of available water from these projects in the future can be predicted from the different sources (Fig. 7).

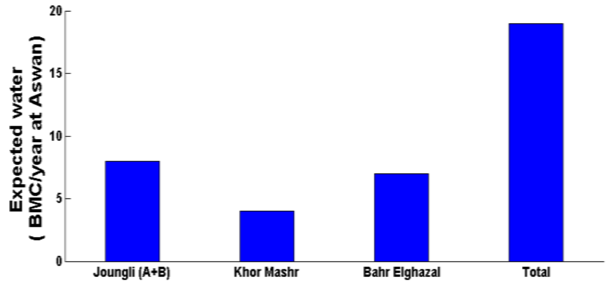

Fig.7. Capacities of Water Saving Projects in the White Nile System (Ganadi, 2006).

4.2.3. Protection of River Nile Water Against Pollution

The river Nile experiencing rapid deterioration in the water quality. This is due to increasing pollution loads arising from high population and economic growth in the region (Alnail et al., 2013). Nile Water Agreement (1959) between Egypt and Sudan did not focus on protection of river Nile water against pollution, although it is one of the main factors which decrease the amount of water and deteriorate its quality in the region.

Post-conflict environmental assessment of Sudan indicates that the wastewater contains an elevated biochemical oxygen demand, around 800–3000 ppm (UNEP, 2007). An investigation conducted at Assalaya (a sugarcane processors in the Sudan), reported addition of factory wastewater into the river. Wastewater had chemical oxygen demand (COD), BOD, and TSS of 2160, 1200, and 2080 mg L^{-1}, respectively. Discouraging the industrial waste spillage, sewerage and agricultural drainage in the river and establishing cooperation between the stakeholders of Nile basin can be helpful in pollution control (UNEP, 2007).

4.3. Seasonal Streams and Water Harvesting

The major categories of water harvesting are classified as follows: excavation of reservoirs (Hafirs), micro catchment basins, bunds (rill and contour), diversion and groundwater recharge dikes and earth or concrete dams. These techniques were adopted to increase the availability of water, for human consumption and for animal consumption, throughout the year. Moreover, these techniques are expected to provide water for both domestic and purpose, increase crop yield sustainability, minimize risks in rainfed agriculture, improve pastures, reduce the use of groundwater in agriculture, save soil fertility, and increase groundwater recharge.

Design optimization of seasonal streams is required for sustainable development and reliable data and its analysis. Long-term evaluation and monitoring of discharge capacity are critical for construction of water reservoirs. Moreover, updated information about meteorological data, topographic features, and structural and soil characteristics are required for effective designing of water reservoirs. Despite the availability of good water quality (from Wadis) adequate environmental and socioeconomic assessment, both up and downstream, are critical before designing and developing of any hydrological structures. This will be helpful to avoid or reduce negative environmental impacts.

4.4. Groundwater Management

Sudan has adequate groundwater resources, across its geographical territories, which are used for domestic and agricultural practices (Shamet et al., 2021). Therefore, a precise overview of groundwater resources is required to achieve sustainable management of groundwater resources (Arora and Mishra, 2022). Comprehensive studies can be helpful for identification and accurate quantification of water resources and assessment of water quality. Moreover, determination of annual capacities of water resources will be key to efficiently meet domestic, industrial and agricultural water requirements. Subsequently, integrated maps of water resources can be developed.

Protection of groundwater resources from pollution should be implemented, especially in drought-prone areas. International cooperation between the countries sharing water resources with Sudan's can prove vital for basin development. For this purpose, regional agreements and their effective implementation mechanisms are required. In addition, enhancement of institutional collaboration, joint venture and policy making regarding water pumping policies for a better understanding of the aquifer mechanism. Furthermore, establishment of modern monitoring techniques, data information bases, and data exchange programs can change the dynamics of water availability.

Precipitation is the main source of aquifer recharge, other sources include seepage (from stream and lake or pond), inter-aquifer flows, irrigation return flow and urban recharge. These sources play an important role in groundwater recharge (Valdivielso et al., 2022). Application of the direct methods of artificial groundwater recharge (surface and sub-surface spreading techniques), and indirect methods (such as induced recharge method) in the Sudan aquifers will lead to sustainable management of this resource (Saha et al., 2022; Sherif et al., 2023). The most important purposes of artificial recharge are the storage of freshwater, raising the water table level, reclamation of aquifer, water quality preservation, flood control etc. Moreover, artificial recharge is also helpful in water quality improvement, avoiding intrusion of saline and low-quality water, subsidence abatement, and disposal of cooling and wastewater (Saha et al., 2022; Sherif et al., 2023).

The most suitable artificial groundwater recharge method is the one that can maintain a high infiltration rate at the economical level and with the sustained desirable quality of water (Wadi et al., 2022). Selection of site-specific appropriate methods will require thorough research to assess suitability according to the availability (quantity and quality) of water resources, recharge capacity and other features of the aquifer (Ismael et al., 2021). The possibility of application of these methods, especially in the valleys and seasonal streams will save large amounts of water which is currently being lost by evaporation and runoff. However, socio-environmental impacts of these methods should be kept in mind.

Use of smart information and communication technology (ICT) techniques, e.g., integrating geographical information systems and remote sensing, and other similar modern technologies, can be utilized for better assessment of water resources, improved protection and utilization (Amarnath et al., 2018).

5. Conclusion

This study aimed to evaluate the current status of water resources in Sudan and their utilization, and assess future demands, and scenarios of sustainable development. In Sudan, Water security is highly vulnerable and dependent on climatic conditions, conventional water resources, with a negligible contribution from unconventional water resources. However, the country has not exploited the full potential of conventional water resources. Efforts should be directed to better manage and utilize conventional water resources and increase the use of unconventional water resources, such as wastewater and seawater desalination. In light of climatic changes, the use of water for surface irrigation, the expansion of growing sugarcane crop, and the separation of South

Sudan are considered the major challenges facing sustainable water resource development in Sudan. Therefore, accurate and precise assessment of conventional water resources in Sudan is dire need of time, which will be helpful in sustainable utilization, development, and management of vital natural resource. The agricultural sector is considered to be the main consumer of water resources in Sudan. Therefore, any conservation strategy should focus on reducing these quantities. Consequently, introduction of efficient irrigation systems or increasing the efficiency of existing irrigation systems along with supplemental irrigation in the rainfed regions can increase sustainability of water resources. Enhanced cooperation with other Nile Basin countries can be helpful in the development water reservoirs and increase storage capacities of existing water reservoirs. Groundwater resources require adequate assessment, monitoring, development, protection. Development of databases and monitoring system for rainfall and streams (Wadis) are required for effective designing of water reservoirs and implementation of efficient water harvesting techniques and development of the seasonal streams.

Competing Interest Statement: All the authors declare that they have no competing interests.

List of Abbreviations: BCM: Billion Cubic Meters. MCM: Million Cubic Meters.

Author's Contribution: A.K.B. planned and conducted this research, collected data, wrote, and revised the manuscript under the supervision of A.E.M., while N.A.E. and A.B.A. revised the manuscript and produced all tables and figures. All the authors read and approved the manuscript.

Acknowledgment: Authors would like to thank the Ministry of Irrigation & Water Resources and Electricity for support in providing us with the data. Our thanks are extended to the Ministry of Agriculture and Forests, Sudan Meteorological Authority and Nile basin initiative for data. Also, authors are thankful to anonymous reviewers for giving constructive comments to revise the manuscript.

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