



Estimating Irrigation Operation Costs and Assessing Irrigation System Performance for Sudan's Khartoum State Irrigation Cooperatives

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HIGHLIGHTS

- In agricultural areas across Sudan and Khartoum State, land use planning and the selection of suitable plant patterns are essential.
- Support and incentives for modern, highly efficient irrigation systems have to be offered.
- Irrigation program in agricultural production is essential for the sustainability of water resources

Abstract

This study was conducted between 2018-2019, examined the distribution and utilization of soil-water resources in Sudan, focusing on irrigation cooperatives in Khartoum State. Ten cooperatives were selected from public institution inventory to represent Khartoum State. Data were collected on soil-water availability, energy consumption, pump flow rate and operation time, theoretical water withdrawal, and energy expenditures per unit area and water volume. Findings reveal that Sudan's arable land is estimated at 112 million ha, with only 18.6% under cultivation. Irrigated land accounts for 9% (1.9 million ha) of cultivated area. Khartoum State has an agricultural potential of 756,000 ha, yet only 19.4% (147,000 ha) is utilized annually. Of 203 registered cooperatives, 45 (22.17%) are active, 36 (17.73%) inactive, and 122 (60.10%) have not yet been allocated land. The total registered cooperative area is 66,780.45 ha, with active cooperatives covering 35,390.07 ha (52.99%). In 2018, total electricity consumption by pump stations in the ten studied cooperatives was 1,693,306 kWh. Pump power ranged from 22 kW (Al-hamdab and El-neye) to 255 kW (Al-bagair El-ailafon, Al-jamuiye, and Wad Ramli). Total energy fees amounted to \$76,016/year, with Al-jamuiye paying the highest (\$33,333/year) and Seyal Al-hawab the lowest (\$333/year). Annual pump operating time varied from 4,105 hours (Al-hamdab) to just 58 hours (Seyal Al-hawab). The theoretical annual water withdrawn was 15,646,858 m³, with the highest volumes in Al-Khojalab (5.61 million m³), Al-jamuiye (4.5 million m³), and Wad Ramli (2.16 million m³). The average energy cost per cubic meter of water was

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\$0.0067. The study concludes that addressing legal, financial, technical, and management issues facing irrigation cooperatives is essential for sustainable irrigated agriculture in Sudan.

Keywords: Sudan; Khartoum state; Irrigation management; Cooperative; Water management; Irrigation planning

1. Introduction

Agriculture is the main supply of food, and water is the most essential element in agriculture. The distribution and scarcity of natural water resources across the globe have made it difficult for most people to access fresh and useful water resources.

Most nations have created alternative consumption policies for water management in order to get around these challenges. The availability of fresh water has become a major global issue in the 21st century.

Seawater makes up almost all of the water resources on Earth's surface. While the total surface area of water resources worldwide is 1.36 billion km³, freshwater resources make up 2.5% of this amount (35 million km³). Water use guidelines around the world are influenced by the unequal distribution of fresh water on Earth's surface, which poses significant global issues. Agriculture uses most of the available water. Depending on the countries' land availability and level of development, this rate can range from 60 to 80%. The demand for water has increased due to growing urban and agricultural water needs, population growth, and the rapid development of industry. This has intensified inter-sectoral competition in water consumption. Water resources are under significant pressure from pollution due to the rising demand for water (Kara and Çiftçi, 2010).

According to forecasts from the Food and Agriculture Organization of the United Nations, in order to feed the growing world population by 2050, over 60% more food will be required. As a result, the demand for water will rise as well. The FAO forecasts that by 2050, the amount of food produced under irrigated projects would increase by more than 50%, but if productivity grow and irrigation techniques are improved, the amount of water extracted by agriculture may only increase by 10%. To produce 1 kg of grain, 1 to 3 m³ of water are required. Up to 15 m³ of water are needed to produce 1 kg of meat. A single person's daily food production requires between 2 and 5 m³ of water (FAO, 2017).

Sustainable agriculture is an advanced agricultural practice that requires the balanced application of many factors, together or separately. However, excessive water uses and poor irrigation practices cause environmental issues by forming salinity and sodium soils. In agricultural production, producers need to be made aware of the agricultural irrigation program to obtain higher quality and yields per unit area within the framework of sustainability of soil and water resources (Karaman and Sahin, 2024).

Cooperatives, which are farmer organizations, play an important role in food production and distribution to consumers in all agriculturally developed countries (Oczkowski et al. 2013), and agricultural cooperatives are more durable than investor-oriented counterparts (Eversull, 2014; Iliopoulos et al. 2019; Valentinov, 2007).

In Sudan, cooperatives had started in the 1930s. Although the first cooperative in Sudan's north used pumps to carry out irrigation operations, these cooperatives subsequently expanded, particularly to the country's middle and northern regions (Abdalla, 2020).

Agriculture in Sudan, particularly in Khartoum State, faces multiple challenges including poor agricultural extension services, application of traditional techniques, and inadequate infrastructure. Irrigation cooperatives specifically struggle with erratic electricity supplies and high fuel costs for operating pumps, compounded by inadequate agricultural product marketing in the region (Alhussein, 2007; Mohammed et al. 2025).

The basis of this study is the collection and analysis of all relevant data and information. Using the records of cooperative administration centers from the inventories of the public institutions and organizations in the Khartoum State, the soil-water availability of the cooperatives, the characteristics of the soil, and the electric consumption by irrigation pumps were determined. This study aims to address and resolve the irrigation infrastructure issues facing the cooperatives in Khartoum State.

2. Materials and Methods

The study investigated Sudan's soil and water resources, the Khartoum State's agricultural infrastructure, the strategic use of water, and irrigation water resources.

2.1. Material

Sudan's main sources of income are agriculture and animal husbandry. Approximately 80% of the population rely on agriculture for their livelihoods. It is impossible to disregard the sector's significance for Sudan's economic development and maintaining long-term stability.

Sudan is regarded as one of the three largest countries in Africa in terms of its area (1.88 million km²) and, given its potential for agricultural land (112 million ha), it represents 60% of Sudan's total area, as one of the most significant countries worldwide (Table 1). Among Sudan's agricultural land, just 21 million ha (11%) is currently in cultivation, while the irrigated area is about 1.9 million ha in extent (FAO, 2015).

Table 1. Land use in Sudan (FAO 2015).

Physical Areas	Area (million ha)
The area of Sudan	1.88 million km ²
Agricultural area (permanent meadows and pasture + cropland)	112
• Permanent meadows and pasture	91
• Area under cultivation (arable land + area used for permanent crops)	21
○ The percentage of cultivated land to total agricultural land in the whole country	18%
○ As a percentage of the country's overall area	11%
Arable land (temporary crops + temporary pastures + temporary meadows)	21
Area cultivated with permanent crops	0.207

The study investigated the financial budgets for 10 irrigation cooperatives in 2018-2019, which were selected from 229 number of agricultural cooperatives founded in Khartoum State in compliance with the Cooperative Law that became influence in 1999. It also calculated the costs of the electricity and diesel energy used for operating irrigation pumping.

2.2. Research Site

Sudan is located in the northeastern region of Africa, north of the Equator, between latitudes 8°45' and 22° 8' N and longitudes 21° 49' and 38° 34' E (Figure 1), and has been divided into 18 states.

Khartoum State is located between 15.8° and 16.45° north latitude and 31.5° and 34.45° east longitude, at the confluence of the White and Blue Niles (Figure 2). The state of Khartoum is separated into 7 localities. These localities include, Jabal Awliya, Khartoum, Nile East, Omdurman, Khartoum North, Karari, and Umbada (Joshi et al. 2024).

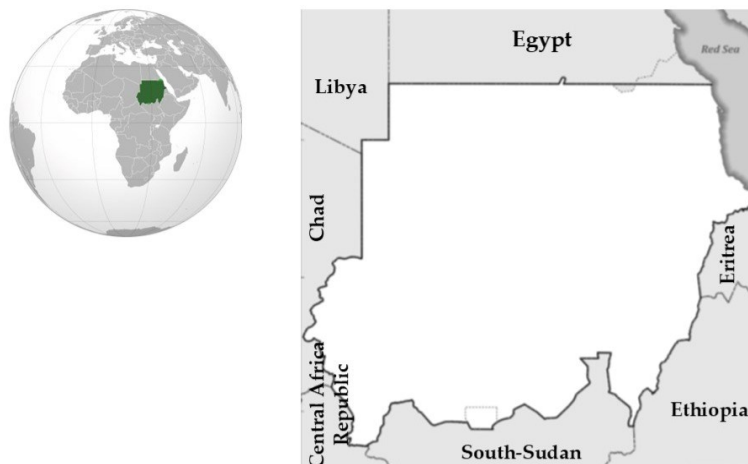


Figure 1. The location of Republic of Sudan.

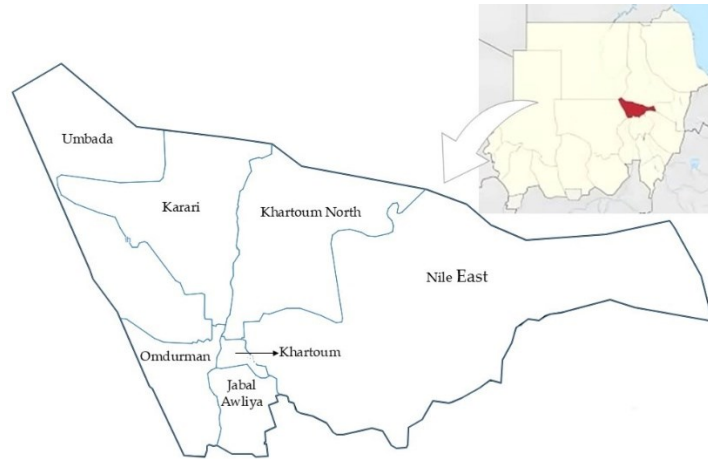


Figure 2. Khartoum State map.

The area of the Khartoum State is 22,736 km². This area contains 33% arable land. The potential of agricultural area 756 000 ha. It is estimated to be 412 m above sea level. There are just 47 000 ha of arable land utilized annually.

Three main groups can be used to categorize crop productivity in Sudan:

1. Irrigated Agricultural Projects

- Large-scale national irrigation projects such as Gezira, Al-Suki, New Halfa, and Rahad are irrigated by the River Nile and its tributaries.
- Large-scale flood irrigation projects such as Al-Gash and Tokar are irrigated by seasonal streams.
- Small-scale irrigation projects along the banks of the River Nile and its tributaries are irrigated by the River Nile and its tributaries. These projects make up the majority of irrigation projects in Sudan.

2. Rain-fed Agricultural Projects with Semi-Mechanization.

3. Traditional Rain-fed Agricultural Projects.

According to table 2, the State of Khartoum's total area makes up 1.21% of all of Sudan's area, while its agricultural potential represents 1.61% of all of the country's agricultural potential. The cultivated agricultural area in Khartoum represents 0.7% of the total cultivated area in Sudan annually (Anonymous, 2019).

Table 2. Agricultural land utilization in Khartoum State.

The Section	Area (km ²)	Agriculture Potential (10 ³ ha)	Annual cultivated Area 10 ³ ha)	Annual Irrigated Area (10 ³ ha)	Permanent meadows and pasture (10 ³ ha)
Sudan	1 882 000	112 000	21 000	1 900	91 000
Khartoum	22 736	756	147	147	924
Khartoum/Sudan%	1.21	0.68	0.70	7.74	1.02

2.3. The research area's irrigation system and water resources

Sudan's surface water area is approximately 1 million ha, with the 2,000 km long Nile River and its tributaries being the most significant portion. At Aswan, Egypt, the average yearly discharge of the Nile River is estimated to be 84 billion m³. During the short rainfall period, there are a lot of seasonal flowing watercourses (Khors). They have never measured their water quality, flow rates, or discharge quantities. It is determined that the total yearly flow of waterways outside than the Nile River is 7.0 billion m³. Furthermore, the 900 billion m³ of groundwater that is currently available and the 1.56 billion m³ annual rate of underground infiltration (Elsheikh and Nasreldin, 2022).

The Khartoum State is located in the middle of Sudan, within the confluence of the White Nile and Blue Nile (the start of the Nile River). The majority of agricultural cooperatives in Khartoum State as well as all government projects (Soba West, Al-Silet, and Sundus) depend heavily on irrigation water from the Nile River and its tributaries (Mohammed and Ciftci, 2019).

2.4. Method

The cooperatives inventories have been obtained from the inventories of public institutions and organizations in Khartoum State (General Directorate of Commerce and Cooperatives, Cooperative Administration, and the cooperatives' management centers) as part of the research methodology. In order to achieve this, ten (10) agricultural cooperatives had been selected as a sample, and details about each one was noted, including the location, irrigated area, water supply, and membership number...etc. The available soil-water in the agricultural cooperatives' service regions, the amount of energy consumed in 2018, the discharge of pump, the working time of the pump, the theoretical amount of water withdrawn, the energy cost per irrigation area, and the energy cost of water have been estimated.

The cooperatives under study, along with their location, agricultural area, and irrigation water source, are shown in (Table 3).

Table 3. Studied cooperatives details.

Cooperative Name	Locality	Agricultural Area (ha)	Main Water Resource	No. of membership
Wad Ramli	Khartoum North	2,320.5	Nile River	1700
Al-Khojalab	Khartoum North	630	Nile River + Wells	218
Al-Bagair El-Ailafon	Nile East	1,729.98	Blue Nile	1492
Al-Sarorab West	Karari	233.52	Nile River	526
Al-Dom	Khartoum North	233.94	Nile River	74
Seyal El-hawab	Nile East	523.32	Blue Nile	335
Al-jamuiye	Omdurman	3,204.6	White Nile	1101
El-neye	Khartoum North	193.24	Nile River	121
Al-hamdab	Khartoum North	193.20	Nile River	412
Dabak El-tikena	Khartoum North	840	Nile River	352

Energy for cooperatives' pumping and irrigation

The percentage of total agricultural inputs that are used for irrigation might range as 50–60 %. Energy costs for fuel and electricity can account about 80–85% of irrigation input costs (Ceran and Topak, 2020).

The Khartoum State has inadequate precipitation, which makes sustainable irrigation management practices necessary. In the region, some areas used for plant production in irrigated agriculture are growing rapidly. Irrigation water and energy costs represent a major part of irrigated agriculture expenses. As described before, most cooperatives rely on the Nile River and its tributaries for irrigation water. Consequently, energy costs for pumping represent their primary operational expense. Because of this, irrigation energy costs are the main issues facing cooperatives.

3. Results

In order to assess the irrigation management performance of agricultural cooperatives in Khartoum State, 10 registered and operational cooperatives were examined on.

The cooperatives under examination were analyzed with regards to their consumption of energy, pattern of plants, irrigation area, and water source.

3.1. Cooperatives in Khartoum State

3.1.1. Wad Ramli agricultural cooperative

The Wad Ramli agricultural cooperative is situated 62 km from the center of Khartoum on the east bank of the Nile River, north of the Khartoum North locality (Figure 3).

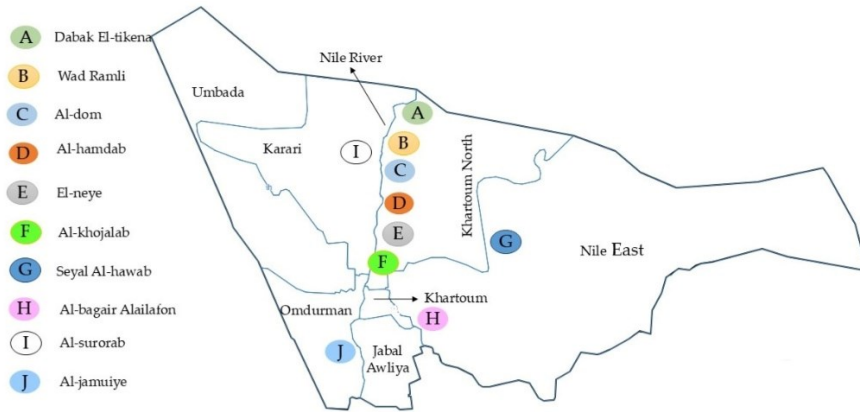


Figure 3. Estimated locations of the cooperatives in Khartoum State.

The area of Wad Ramli cooperative estimated 2,320.5 ha. The primary water supply for irrigation is the Nile River (Table 4). On the banks of the Nile River, exists a pump station with four pumps. Each pump has a 225 kW capacity and a 1 m³h⁻¹ flow rate. But in 2018, there is only one pump in use.

Table 4. The rate of cultivated areas of cooperatives in 2018.

Cooperative name	Agricultural area (ha)	2018 Cultivated area (ha)	Cultivated area (irrigation rate) (%)
Wad Ramli	2,320.5	863.1	37.19
Al-Khojalab	630	323.4	51.33
Al-Bagair El-Ailafon	1,730	504	29.13
Al-Sarorab West	233.52	199.92	85.61
Al-Dom	233.94	52.94	22.63
Seyal El-hawab	523.32	111.3	21.27
Al-jamuiye	3,204.6	2091.60	65.27
El-neye	93.24	33.18	35.59
Al-hamdab	193.20	71.4	36.96
Dabak El-tikena	840	375.9	44.75
Total	10,002.32	4,626.74	Average 42.97

In 2018, the cultivated area amounted to 863.10 ha, representing 37.19% of the cooperative's total area (Figure 3). Low irrigation rate is a result of poor irrigation efficiency. The expansion of irrigation with a 30% conveyance efficiency results in yield improvements of 1,2 t ha⁻¹ in the Mountain regions, 1,1 t ha⁻¹ in the hill regions, and 2,5 t ha⁻¹ in the Terai regions (Basukala, 2024).

Potatoes, onions, tomatoes, eggplants, cucumbers, squash, vegetables, and fodder are all cultivated at the Wad Ramli cooperative.

3.1.2. Al-Khojalab cooperative

The Al-Khojalab cooperative is situated 23 km from the capital of Khartoum on the east bank of the Nile River, north of the Khartoum North locality (Figure 3), an agricultural area of 630 ha (Table 4). Despite being close to the Nile River, wells remain the primary supply of water for irrigation in 2018.

The Nile River was the cooperative's primary water source before the major canal collapsed, the expense of rehabilitation is costly, and the government do not offer assistance, which caused the cooperative to depend on groundwater for irrigation.

In 2018, Al-Khojalab cooperative had 110 wells, each of which had a pump that could produce $60 \text{ m}^3 \text{ h}^{-1}$ of water at a capacity of 7.5 kWh. A single well has been drilled for every 2.1 ha. A study by (Mahjoubi, 2024), farmers that depend solely on groundwater for irrigation may have a greater willingness to pay for water, probably due to its perceived reliability as a consistent water source, in contrast to those who utilize both groundwater and dam releases.

As of 2018, the cooperative's cultivated agricultural area reached 323.4 ha, representing 51.33% of the total area (Figure 4). The Al-Khojalab cooperative grows fodder, tomatoes, and onions.

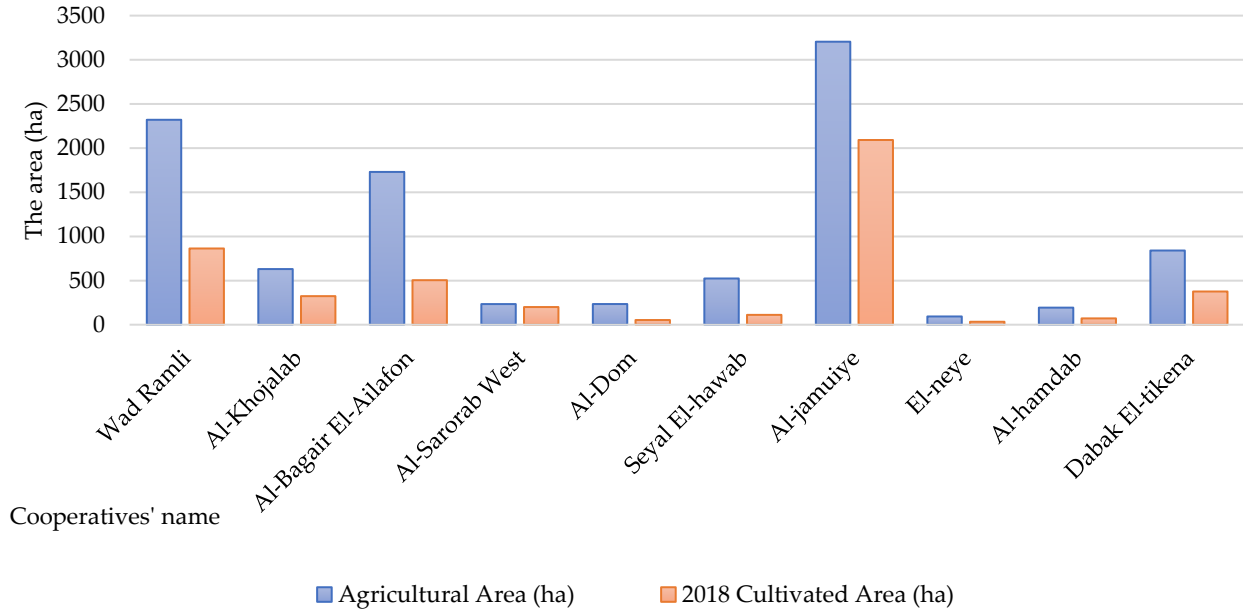


Figure 4. Cultivated areas of the cooperatives that were studied in 2018.

3.1.3. Al-bagair El-ailafon cooperative

The Al-bagair Al-ailafon Cooperative is situated 40 km from the center of Khartoum on the eastern bank of the Blue Nile, in the locality known as the Nile-East. (Figure 3). The cooperative area 1.730 ha (Table 4).

The primary water source is the Blue Nile. A pump with a 255 kW capacity and a $1 \text{ m}^3 \text{ h}^{-1}$ flow rate is used to irrigate the area. In 2018, the cooperative's cultivated area amounted to 504 ha, which represents 29.13% of its entire area (Figure 4). Onions, tomatoes, eggplants, okra, watermelons, filled vegetables, and fodder are all cultivated at Al-bagair Al-ailafon Cooperative.

3.1.4. Al-surorab West cooperative

Al-surorab West cooperative is situated 44 km from the capital of Khartoum on the west bank of the Nile River, east of the Karari locality (Figure 3). The cooperative area is 233.52 ha (Table 4).

The primary water source for irrigation is the Nile River. The cooperative has pump stations on the west bank of the Nile River with three pumps. One of the pumps have a power of 55 kW and $900 \text{ m}^3 \text{ h}^{-1}$ flow rate, while the other two have 22 kW each and $360 \text{ m}^3 \text{ h}^{-1}$ of flow rate. The two pumps frequently remain in standby and just one pump (55 kW) is operated.

The cooperative's cultivated agricultural area in 2018 had been 200 ha, representing 85.61% of the cooperative's total area (Figure 4). The beans, potatoes, onions, tomatoes, and fodder are all cultivated at Al-surorab West Cooperative.

3.1.5. Al-Dom cooperative

Al-dom cooperative is situated 50 km from the center of Khartoum on the east bank of the Nile River, in the north of the Khartoum North locality (Figure 3). The cooperative's area 233.94 ha (Table 4).

The primary water source for irrigation is the Nile River. Along the Nile River's bank there are two pumps. The main pump has a 45 kW capacity and a 900 m³ h⁻¹ flow rate. The other standby pump has a 360 m³ h⁻¹ flow rate and its capacity 37 kW.

In 2018, the cooperative's cultivated agricultural area amounted to 52.94 ha, which represents 22.62% of the cooperative's total area (Figure 4). The Al-dom agricultural cooperative produces broad beans, onions, tomatoes, and fodder.

3.1.6. *Seyal El-hawab cooperative*

The Seyal El-hawab cooperative is situated 28 km from the center of Khartoum in the Nile-East locality (Figure 3). The agricultural area of the Seyal El-hawab cooperative is 523.32 ha (Table 4).

The main source for water is the Blue Nile. Water from the Blue Nile is used to irrigate crops through the main canal of the Al-Silet agricultural project. The pump station contains three pumps. The primary pump has a 55 kW capacity and a 660 m³ h⁻¹ flow rate. The combined capacity of the two standby pumps is 18.6 kW. Excessive irrigation water consumption adversely affects the ecosystem. Certain copper salts used to manage insects have a high solubility level (Prisa, 2024). Additionally, applying irrigation water with the correct criteria allows for the highest efficiency in nitrogen (N) use (Meloni, 2025).

In 2018, the cooperative farmed 111.30 ha, representing 21.27% of its entire area (Figure 4). The cooperative produces broad beans, tomatoes, cucumbers, and fodder.

3.1.7. *Al-jamuiye cooperative*

Al-jamuiye cooperative is situated 44 km from the center of Khartoum in the southern portion of the Omdurman locality, on the west bank of the White Nile (Figure 3). The agricultural area of the Al-jamuiye cooperative is 3,204.6 ha (Table 4).

The main source for water is the White Nile. On the banks of the White Nile, there is a pump station containing three pumps. Each pump has a 225 kW capacity and a 1 m³ s⁻¹ flow rate. One pump is turned on while the others are kept in standby.

In 2018, the cooperative's cultivated area 2,091.6 ha, which represents 65.27% of the cooperative's total area (Figure 4). Okra, broad beans, onions, eggplants, tomatoes, fruit trees, cucumbers, and fodder are all cultivated at Al-Jamuiye cooperative.

Al-Jamuiye cooperative has to deal with inadequate irrigation channel design and pumping station issues. It has been observed that the irrigation procedure presents challenges in significant areas of the cooperative. Furthermore, flooding affects a significant portion of the area.

Cooperative farmers' primary concern is the issue of irregular irrigation water delivery (Alento, 2006).

3.1.8. *Al-hamdab cooperative*

The Al-hamdab cooperative is situated 49.5 km from the center of Khartoum on the east bank of the Nile River, north of the Khartoum North locality, between the Wad Ramli and Al-dom cooperatives (Figure 3). The cooperative has an area of 193.20 ha (Table 4).

The primary water source for irrigation is the Nile River. A pumping station with three pumps is located on the Nile river's bank. One pump has a 30 kW capacity and a 660 m³ h⁻¹ flow rate; the other two pumps have 22 KW capacities and 360 m³ h⁻¹ flow rates. However, in 2018, while the pump with 22 kW power and 660 m³ h⁻¹ flow rate was working, the others remained on standby.

In 2018, the cooperative's cultivated area 71.4 ha, as well as 36.96% of the cooperative's total area (Figure 4). Al-hamdab cooperative cultivates fruits trees, fodder, potatoes, onions, and vegetables.

3.1.9. *Dabak EL-tikena cooperative*

The Dabak El-tikena cooperative situated in the northernmost region of the Khartoum North locality, on the east bank of the Nile River, about 8 km north of Wad Ramli cooperative and 70 km from the center of Khartoum (Figure 3). The cooperative has an area of 840 ha (Table 4).

The cooperative's main source of irrigation water is the Nile River. The pump station contains 2 pumps; each pump has a 55 kW capacity and a 900 m³h⁻¹ flow rate. While the other pump is kept on standby, one pump is being utilized continuously.

The cooperative's cultivated area in 2018 was 376 ha, representing 44.75% of the cooperative's total area (Figure 4). Dabak El-tikena cooperative grows fodder, tomatoes, potatoes, and onions.

3.1.10. El-neye cooperative

El-neye cooperative is situated 46 km from the center of Khartoum on the east bank of the Nile River, northwest of the Khartoum North locality (Figure 3). The cooperative's agricultural area is 93.24 ha (Table 4). The Nile River is main source for irrigation water. The pump's station contains two pumps. The main pump has a power of 22 kW and a flow rate of 360 m³h⁻¹ and the other pump has a power of 45 kW and a flow rate of 360 m³h⁻¹.

In 2018, the El-neye cooperative's cultivated area was 33.18 ha, representing 35.59% of its total area (Figure 4). The El-neye cooperative grows fodder, onions, and tomatoes.

4. Discussion

4.1. The irrigation activity of Khartoum state cooperatives

4.1.1. Irrigation systems and facilities

The Nile River and its tributaries are the primary sources of irrigation water for the cooperatives under study in Khartoum State, with the exception of Al-Khojalab cooperative, which relies on groundwater due to canal collapse. Flood irrigation is the common irrigation system in all cooperatives that have been examined.

Table 5, shows some technical details regarding the cooperatives' pump stations. Among the cooperatives that were investigated, Al-bagair El-ailafon, Al-jamuiye, and Wad Ramli cooperatives had the highest water flow rate (3,600 m³h⁻¹) and the highest pump capacity (255 kW) for the duration of 2018. Both traditional irrigation system and lack of an irrigation plan contribute to excessive water use. According to (Kelley and Johnson 1991). Inadequate irrigation performance and a poorly planned water distribution system constituted the reasons of excessive water use.

Table 5. Khartoum State agricultural cooperatives' water facility details.

Cooperative name	Details of the water station				2018 operating pump flow rate (m ³ h ⁻¹)
	No of pumps	Pump power (kW)	Total pump power (kW)	Pump's flow rate (m ³ h ⁻¹)	
Al-bagair El-ailafon	1	255	255	3,600	3,600
Al-sarorab West	3	22	55	360	360
		55		900	
		37		360	
Al-dom	2	45	45	900	900
		18.6		–	
Seyal Al-hawab	3	18.6	55	–	660
		55		660	
Al-Khojalab	110	7.5	7,5	60	60
		255		3,600	
Al-jamuiye	3	255	255	3,600	3,600
		255		–	
El-neye	2	22	22	360	360
		45		360	
Al-hamdab	3	22	22	360	360
		30		660	
Wad Ramli	4	255	255	3,600	3,600
Dabak El-tikena	2	55	55	900	900
		55		900	

4.1.2. *The Cooperatives' Electricity Expenses*

In the research area, the electricity costs for 2018, were derived from the inventory records of the cooperatives under investigation (Table 6). USD is used to replace Sudanese pound (SDG) as the unit of measurement for electricity fees. (\$1 = 18 SDGs) based on Central Bank of Sudan projections from 2018 (CBOS, 2019).

The highest annual electricity costs are \$33,333 year⁻¹ for Al-jamuiye cooperative, \$15,972 year⁻¹ for Wad Ramli cooperative, \$6,111 year⁻¹ for Al-bagair El-ailafon cooperative, and \$5,556 year⁻¹ for Dabak EL-tikena cooperative, as (Table 6) shows. These numbers are compatible when considering the irrigated areas and the pump power of the cooperatives evaluated for 2018 (Tables 5 and 6). Because in 2018, the cooperatives with the biggest cultivated areas and maximum pumping capacities are Al-jamuiye, Wad Ramli, and Al-bagair Elailafon.

Table 6. Khartoum State agricultural cooperatives' annual electricity costs estimated.

Cooperative name (locality)	2018 cultivated area (ha)	Annual calculated electricity fee (SDG. year ⁻¹)	Annual calculated electricity fee (\$·year ⁻¹)
Al-bagair El-ailafon (The Nil East)	504	110,000	6,111
Al-sarorab West (Karari)	199.92	17,500	972
Al-dom (Khartoum North)	52.92	58,750	3,264
Seyal El-hawab (The Nil East)	111.3	6,000	333
Al-jamuiye (Omdurman)	2,091.6	600,000	33,333
El-neye (Khartoum North)	33.18	39,540	2,197
Al-hamdab (Khartoum North)	71.4	17,000	944
Wad-Ramli (Khartoum North)	863.2	287,500	15,972
Dabak EL-tikena (Khartoum North)	376	100,000	5,556
Al-Khojalab (Khartoum North)	323.4	132,000	7,333.33
Total	4,626.74	1,368,290	76,016

4.1.3. *The cooperatives' annual energy consumption*

According to the cooperatives investigated in the study, the assessments that were conducted by considering the 2018 electrical energy consumption, unit (kWh) cost, pump power, pump flow rates, and irrigation areas supplied in most of the cooperatives are reported in (Table 7).

Table 4.3 shows that the total annual electricity consumption of all the studied cooperatives was 1,693,306 kWh, with an associated energy price of \$76,015. The Al-Khojalab cooperative has the highest energy usage (825,000 kWh), while the Seyal El-hawab cooperative has the lowest, at 3,750 kWh.

By switching from flood irrigation to pressured irrigation, water use can be reduced by 10% to 66%. Less water was pumped and less energy was utilized as a result of increased water use efficiency (Jackson et al. 2010).

Table 7. Khartoum State cooperatives' estimated annual energy consumption.

Cooperative name	Annual calculated electricity fee (\$·year ⁻¹)	Unite price (\$·kWh ⁻¹)	2018 Energy consumption (kWh)
Al-bagair El-ailafon	6,111	0.0889	68,750
Al-sarorab Bati	972	0.0889	10,938
Al-dom	3,264	0.0889	36,719
Seyal El-hawab	333	0.0889	3,750
Al-jamuiye	33,333	0.0889	375,000
El-neye	2,197	0.0889	24,713
Al-hamdab	944	0.0089	106,250
Wad-Ramli	15,972	0.0889	179,688
Dabak EL-tikena	5,556	0.0889	62,500
Al-Khojalab	7,333	0.0089	825,000
Total	76,016		1,693,306

4.1.4. *Te amounts of withdrawn water and annual pump operating times of cooperatives*

Table 8 displays details on the annual pump operating time and potential water drawn by the cooperatives. The data shows that the total duration of operating of the pump in cooperatives are 9,875 hours, the maximum operating time are 4,105 h year⁻¹ and 1,250 h year⁻¹ in Al-hamdab and Al-jamuiye cooperatives respectively, while the minimum operating time in Seyal El-hawab were 58 h year⁻¹.

Theoretically, 16.5 million m³ of water might be extracted annually based on the cooperatives' pumps flow rates. Al-Khojalab cooperative had the largest water withdrawal amount at 5.6 million m³, followed by Al-jamuiye at 4.5 million m³ and Wad Ramli cooperative at 2.2 million m³. Seyal Al-hawab cooperative has the lowest water extraction amount 38,250 m³. Al-Khojalab cooperative was first in terms of the theoretical amount of water withdrawn even though it did not have the highest pump operating time. One of the primary causes of poor irrigation efficiency is the widespread use of flood irrigation (Yildirim et al. 2016) observed that most farmers applying flood irrigation methods consumed excessive irrigation water, with the maximum irrigation efficiency recorded at 43%. The Al-Khojalab cooperative has the biggest number of pumps, which helps to explain why.

Table 8. Khartoum State cooperatives' annual electricity expenses.

Cooperative name	Pump operating time (h)	Theoretical water drawn amount (m ³)
Al-bagair El-ailafon	229	825,000
Al-sarorab Bati	169	60,852
Al-dom	694	624,219
Seyal El-hawab	58	38,250
Al-jamuiye	1,250	4,500,000
El-neye	955	343,728
Al-hamdab	4,105	1,477,841
Wad-Ramli	599	2,156,250
Dabak EL-tikena	966	869,318
Al-Khojalab	850	5,610,000
Total	9,875	16,505,458

4.1.5. *Cooperatives' unit area energy and unit water expenses*

Table 9, displays that, when taking into consideration the entire irrigation area of all the cooperatives that were examined, the average energy cost per unit irrigation area is 490.35 kWh. The cooperative that consumes the greatest amount of energy is Al-Khojalab 2,551 kWh, while Seyal Al-hawab cooperative has the lowest energy consumption 33.69 kWh. Actually, the yearly water withdrawal amounts from these cooperatives are the greatest and lowest, respectively.

Table 4.5 shows that the average energy cost of 1 m³ of water in the cooperatives under investigation is 0.0067 \$ m⁻³. The Al-sarorab west cooperative has the highest energy cost, at 0.016 \$ m⁻³, while the Al-hamdab cooperative has the lowest 0.0006 \$ m⁻³. According to observations, there is relatively little difference (\$0.0154) in the energy cost of one unit (1 m³) of water between the highest and lowest values.

Table 9. Khartoum State cooperatives' unit area energy and unit water costs.

Cooperative name	Energy cost per unit irrigation area (\$ kWh ⁻¹)	1 m ³ of water's energy cost (\$ m ⁻³)
Al-bagair El-ailafon	74.40	0.0074
Al-sarorab Bati	74.40	0.0160
Al-dom	156.96	0.0052
Seyal El-hawab	33.69	0.0087
Al-jamuiye	179.29	0.0074
El-neye	486.28	0.0064
Al-hamdab	972.99	0.0006
Wad-Ramli	208.19	0.0074
Dabak EL-tikena	166.27	0.0064
Al-Khojalab	2,551.02	0.0013
Total	490.35	0.0067

Conclusions

In recent decades, global climate change has increased water scarcity in many geographies by putting more pressure on available freshwater resources.

The Africa is among the geographic areas with the most evident water-related issues. Water use in agriculture has significant challenges due to the sharing of water resources across countries, pollution of water bodies, and management issues arising from the application of irrigated agriculture. Sudan is among the countries having the highest rate of agricultural irrigation issues. Because of the country's arid climate, irrigation is essential for agricultural production, poor use of agricultural technologies, inefficient irrigation, contamination of scarce water resources, and significant problems with water use.

Regarding the overall assessment of the abovementioned results;

- The agricultural sector is the largest consumer of water. Excessive water use for irrigation should be minimized in order to protect and ensure the sustainability of water resources. Both water productivity and irrigation efficiency should rise as a result.
- The scarcity of precipitation in Khartoum state makes irrigation essential for agricultural productivity. The majority of agricultural projects in Khartoum state depend on irrigation water from the Nile River and its tributaries, the Blue and White Niles. Thus, hydrological studies and pumping station rehabilitation are the government's responsibilities. Due to the Nile's recession phenomenon which puts most of the pumping stations along the Nile River and its tributaries out of service during the summer. This issue needs to be resolved.
- Support and incentives for modern, highly efficient irrigation systems have to be offered. In agricultural areas across Sudan and Khartoum State, land use planning and the selection of suitable plant patterns are essential.

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