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Mapping of Center-Pivot Irrigation Systems in Sudan Using Remote Sensing and GIS Techniques: A Case Study of the Al Waha Project

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ABSTRACT

This paper presents the mapping of center-pivot irrigation systems in Sudan using remote sensing and GIS techniques to support national and regional agricultural auditing, water and energy use management, and policy development. Landsat-8 imagery with 15 m spatial resolution was employed to identify and map individual pivots. A total of 1,373 active pivots covering approximately 70,078.2 ha was recorded in 2020, located in the River Nile, Northern, Khartoum, Kordofan, and Gazira states (774, 296, 248, 49, and 6 pivots, respectively). A detailed case study of a commercial agricultural project in Khartoum State documented an increase in pivots from 29 to 105 between 2009 and 2020, respectively covering about 5,972 ha. The calculated map accuracy was 96.4% and NDVI was demonstrated to delineate planted area and evaluate within-pivot biomass. Map layers of irrigation networks, soil types, and crop distribution were prepared, showing that the project is irrigated by Blue Nile pump stations and canals; soils are classified mainly as loam and sandy-clay-loam, and Rhodes, alfalfa and corn are cultivated on 79, 20 and 6 pivots, respectively. The pivots consumed both water and energy; an estimated 3,625.83 m^3/ha-year (water) and 176.7 L/ha-year (diesel) for alfalfa, while an estimated 3,429.84 m^3/ha-year (water) and 167.1 L/ha-year (diesel) for Rhodes. The estimated irrigation efficiency based on CROPWAT/CLIMWAT revealed seasonal variations; alfalfa averaged ~70% (57–87%), while Rhodes averaged ~77%, peaking at ~99–100% in July–August and declining to ~49–55% in September–October. This study demonstrated the opportunity of using RS and GIS derived data to provide direct agro-informatics insights and support more efficient management of water, energy and other applications, thereby strengthening agricultural decision-making, improving productivity, and enhancing resource sustainability in Sudan.

1. INTRODUCTION

The world needs urgently to change the way it produces and consumes food. In the coming decades, the global agricultural system must find ways to meet pressing needs. Farmers must provide enough food for a growing population [1]. This is because the world's population is projected to reach more than nine billion people in 2050 [2]. The increasing need to produce crops due to the growing population is the main reason for the increasing expansion of irrigation use around the world. The crop needs water for optimal growth and for high productivity. Some studies have shown that the use of water resources is not optimized due to the low irrigation efficiency, which leads to increasing water losses and applying more water to crops than needed.[3]. As a result, agricultural producers are being forced to implement better irrigation management practices, and they are turning to modern irrigation systems to accomplish this. Despite the many advantages center-pivot irrigation systems offer agricultural producers such as efficiency, convenience, and resource conservation their effective management and control require the integration of monitoring tools and technologies.

Systems such as Geographic Information Systems (GIS) and remote sensing are essential for providing accurate feedback and data analysis, enabling both governed and non-governed sectors to optimize performance and make informed decisions. Center-pivot irrigation systems consume large quantities of both water and energy. They are widely recognized as indicators of intensified industrial agriculture and large-scale investment[4]. Consistently employed satellite remote sensing to monitor the diffusion of this innovation over both geographic space and a relatively long period was used to produce a comprehensive database of center-pivot irrigation systems.

Satellite-based remote sensing represents the only viable tool for deriving agricultural information at the spatial and temporal resolutions require recognized for regional and national scale description [5]. Remote sensing of active crop extent provides the first step for downstream product development, including the mapping, monitoring, and modeling of crop types, growth patterns, irrigation requirements, pest outbreaks, and yield quality and quantity. While maps of individual agricultural fields and their distribution are considered a pathway to achieve within-field agronomic and phenotypic information, they are often informative in their own rights, especially when assessed as a time series [6]. Unfortunately, agricultural map products at individual field scales are often lacking in developed, let alone developing, countries. Even where they may be available, they rarely exist at the spatial and/or temporal resolutions required to make informed management decisions or assess the impact of policy initiatives. It is recommended to target cropland mapping in the most vulnerable and data-poor countries and identified accurate maps on the extent and spatial distribution of agriculture as essential information towards efforts to improve food security.

Most arid and hyper arid parts of the world, including the Middle East and North Africa region, fall within the category of vulnerable and data-poor countries. Furthermore, many of these regions rely on unsustainable abstraction of non-renewable fossil groundwater for agricultural production, often manifested in the form of center-pivot irrigation systems [7], so knowledge of such baseline data would provide a pathway towards more accurate assessment of groundwater use. To do this, timely spatial agro-informatic insights will be needed to facilitate informed management decisions at regional, national, and global scales [8]. At a fundamental level, the mapping of agricultural fields forms a basis for a range of such insights, including food production planning, assessment of irrigation requirements [9], and yield predictions, all of which are essential variables for local, regional, and country-wide food and water security purposes [10]. Knowing the extent and distribution of agricultural fields is also important for biosecurity purposes in order to predict the location and potential spread of pest outbreaks, e.g., due to blight, beetle, and locust infestation [11]. It also provides supply chain information and tracing capabilities, which have proven to be particularly important in 2020 due to the COVID-19 pandemic [12].

The launch of Landsat-1 in 1972 led to a multitude of attempted applications of satellite remote sensing in both agricultural and non-agricultural disciplines. In the former case, researchers addressed problems such as rangeland monitoring, soil classification, cropland classification agricultural land use, diseased crops, and others. However, one particular type of irrigation system, "Center-pivot," can be identified on Landsat imagery with relative ease. This is due both to its distinctive shape and the vegetative biomass under irrigation [13]. In Sudan, the first center-pivot machine was installed in the year 2006 [14]. DAL Company introduced this system two years later, in 2008, as shown in historical satellite imagery of Landsat-8. It was introduced recently in Sudan, but it has found its way to spread in Khartoum, River Nile, and Northern states compared with other states [15]. Over the last 10 years, more than $300m has been invested in 57,000 ha of center-pivot irrigation projects in Sudan, mostly by investors from the GCC [16].

The main objective of this study:

- To establish a geospatial database for center-pivot irrigation systems in Sudan, utilizing medium-resolution satellite imagery to facilitate agricultural planning and policy formulation.
- To delineate and analyze the spatial distribution and extent of center-pivot irrigation systems in key agricultural regions (River Nile, Northern, Khartoum, Kordofan, and Gezira) utilizing remote sensing and GIS techniques.
- To perform an in-depth case study on Al Waha commercial agricultural initiative in Khartoum State, examining system configuration, crop varieties, soil properties, irrigation infrastructure, and resource utilization (water and fuel).
- To assess the temporal evolution of center-pivot systems in the case study area from 2009 to 2020, utilizing multi-temporal satellite imagery.

2. MATERIALS AND METHODS

2.1 Study area

The study covers the entirety of Sudan, focusing on five states along the Nile: River Nile, Northern, Khartoum, Kordofan, and Gezira. These regions are characterized by high temperatures and low rainfall which have seen rapid expansion of center-pivot irrigation, necessitating systematic monitoring of water and crop management. A detailed case study was conducted at Al Waha project in Khartoum State (15.2 – 15.4° N, 32.8 – 33.0° E; 395 m a.s.l.). The project covers 5,762.3 ha, drawing water from the Blue Nile via a six-pump station (total discharge 10.56 m^3/s). This pilot informs a national geospatial database for sustainable resource planning.

2.2 Raw data

Landsat-8, launched on February 11, 2013, is part of the long-running Landsat program jointly managed by NASA and the U.S. Geological Survey (USGS). Such medium-resolution imagery is well suited for regional agricultural surveys, capturing spectral bands (visible and NIR) needed to calculate the Normalized Difference Vegetation Index (NDVI).

Landsat-8 carries two key sensors the Operational Land Imager (OLI) and the Thermal Infrared Sensor (TIRS)designed to capture medium-resolution images of the Earth's surface for applications in land use, agriculture, hydrology, and environmental monitoring [17]. The size of each downloaded image was approximately 1 GB (Figure 1). Table 1 lists key technical specifications of Landsat-8. Its 12-bit radiometric resolution and 15 m spatial resolution enable detection of fine spectral variations in agricultural areas.

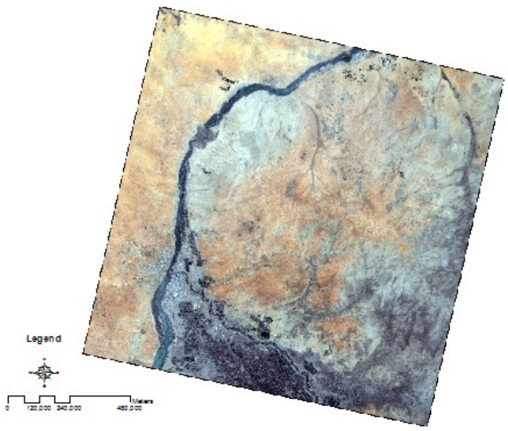

Figure 1. Landsat8 image from USGS, 15m resolution

Table1. Landsat 8 satellite and image specifications [18]

NAME	LANDSAT
Date of launch	Feb. 11, 2013
Altitude	~705 km
Orbit	Sun-synchronous, near-polar; repeats every 16 days (233 orbits per cycle)
Swath Width (km)	~185 km
Dynamic Range	12-bit radiometric resolution
Projection	Universal Transverse Mercator (UTM), Polar Stereographic, or WGS 84
Datum	WGS 84 (World Geodetic System 1984)

2.3 Methodology

To establish a base map of center-pivot irrigation systems, ArcGIS 10.3 software was used to generate feature data for the study area. A medium-resolution satellite image from Landsat 8 with 15 m spatial resolution and three bands was used [19].

2.4 Data acquisition

To accomplish the research objectives, satellite images of the study areas were obtained from the USGS Landsat-8 platform on 2020. Additional data for the case study area were acquired through visits to the project management offices. The collected information included:

General project details (name, geographic location, ownership classification, establishment date, soil type, and crop type).

Irrigation infrastructure, including the pumps used, their respective capacities, and water sources.

Monthly irrigation operation data (operating hours, fuel consumption, and water use).

Monthly climatic data, obtained from the CLIMWAT 2.0 database using records from the FAO meteorological station at Khartoum: Minimum temperature (2 m, °C), Maximum temperature (2 m, °C), Precipitation (mm day^{-1}), Relative humidity (2 m, %), Wind speed (10 m, km day^{-1}), and Sunshine (hours)

2.5 Satellite Image Processing

Landsat 8 OLI imagery was processed through a series of steps to ensure data quality before spatial analysis. Pan-sharpening was applied to enhance the 30 m multispectral bands to 15 m resolution using the 15 m panchromatic band (Band 8). The Brovey transform algorithm was employed to enhance visual contrast in both high and low ranges of the histogram, as expressed by:

$$DNF=\frac{P-IW\times I}{RW\times R+GW\times G+BW\times} \quad (1)$$

where the inputs are

- DNF = Normalized Difference Filter
- P = panchromatic image
- R = red band
- G = green band
- B = blue band
- I = near infrared
- W = weight.[20].

The Normalized Difference Vegetation Index (NDVI) was derived from the Landsat-8 OLI imagery to enhance vegetation features and separate irrigated crops from surrounding land cover. NDVI is computed using the near-infrared (NIR) and red (R) spectral bands, according to the following formula:

$$NDVI=\frac{NIR-R}{NIR+R} \quad (2)$$

where the inputs are:

- NDVI = Normalized Difference Vegetation Index
- NIR = Near-infrared band (Band 5 for Landsat 8 OLI)
- R = Red band (Band 4 for Landsat-8 OLI)

NDVI values range between –1 and +1, with higher values indicating dense and healthy vegetation, while lower or negative values represent bare soil, water, or non-vegetated surfaces [21].

2.6 Analysis approaches

The satellite imagery and field data were processed and analyzed using spatial, temporal, and quantitative approaches to achieve the study objectives:

- Spatial analysis: Identify pivot locations and generate thematic map layers for field layout with NDVI map, irrigation canals, soil classes, and crop distribution in ArcGIS.
- Quantitative analysis: Use Excel to compute average monthly water (m^3) and fuel (L) consumption per crop, and irrigation efficiency.
- Temporal analysis: Track changes in pivot counts and irrigated areas from 2009 to 2020 to reveal expansion trends of center-pivot projects.

3. RESULTS AND DISCUSSION

The study's main findings are summarized in Table 2, which lists the number of center-pivots and the corresponding irrigated area across five states in Sudan in 2020. This information was obtained after a comprehensive survey of Sudanese agricultural land using ArcGIS software.

A total of 1,373 active pivots were recorded in Sudan as of 2020. The River Nile, Northern, Khartoum, Kordofan, and Gezira States contained 774, 296, 248, 49, and 6 pivots, respectively (see Figures 2-7). The total irrigated area under pivot systems reached 70,078.2 ha, with the same states accounting for 39,019.7, 15,589.1, 12,688.2, 2,506.5, and 274.7 ha, respectively. In Northern State, only 76 pivots were distributed across nine projects in 2015 [14], representing a nearly fourfold increase within five years.

Table 2. Numbers and area of center-pivot systems in Sudan (2020)

State	Pivot	Area, ha
River Nile	774	39,019.7
Northern	296	15,589.1
Khartoum	248	12,688.2
Kurdufan	49	2,506.5
Gazira	6	274.7
Total	1,373	70,078.2

3.1 Fields Layout

This case study in Khartoum focused on the private agricultural project Al Waha, which contains 105 pivots covering a total area of 5,970 ha cultivated with different crops, while independent field measurements (ground truth) indicate a cultivated area of 5,762.3 ha. The relative mapping error was calculated as:

$$Error\,\% = \frac{Mapped\,area - Measured\,area}{Measured\,area} \qquad (3)$$

which yields approximately 3.6%. Accordingly, the map accuracy, defined here as 100% Error %, is approximately 96.4%. These results show that the derived pivot map reproduces the actual field layout with good accuracy and is suitable for subsequent analyses of irrigation performance.

In addition, Normalized Difference Vegetation Index (NDVI) imagery was used to delineate planted area and assess within-pivot biomass. Comparable national-scale studies, conducted in Saudi Arabia applied rigorous accuracy assessments, achieving overall accuracies above 90%. These provide a methodological benchmark for future Sudan-focused efforts [22]. Figure 8 demonstrated Al Waha field layout and NDVI map. The Figure clearly shows three main features on the map; the river, the planted pivots, and the bare areas.

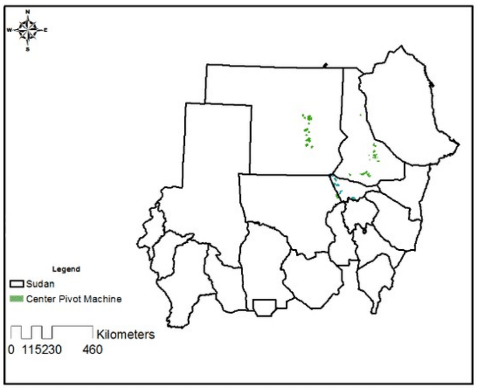

Figure 2. Map of center-pivots in Sudan

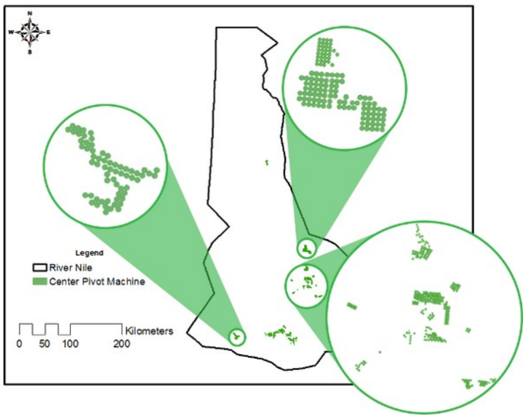

Figure 3. Map of center-pivot in River Nile

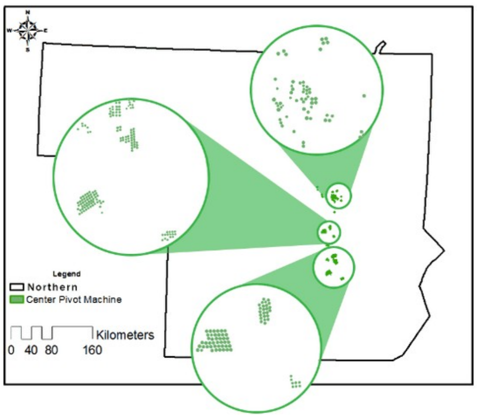

Figure 4. Map of center-pivots in Northern

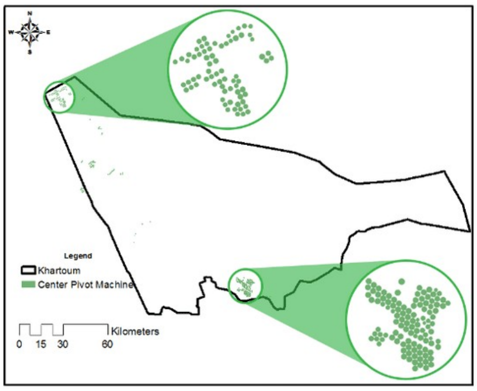

Figure 5. Map of center-pivots in Khartoum

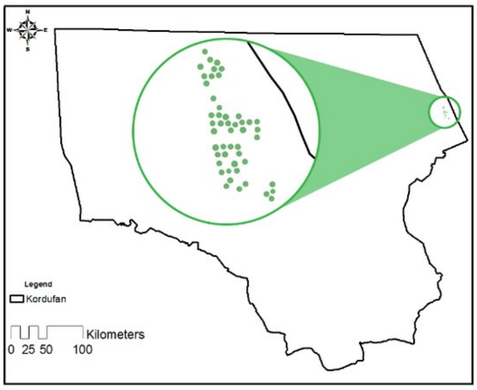

Figure 6. Map of center-pivots in Kordufan

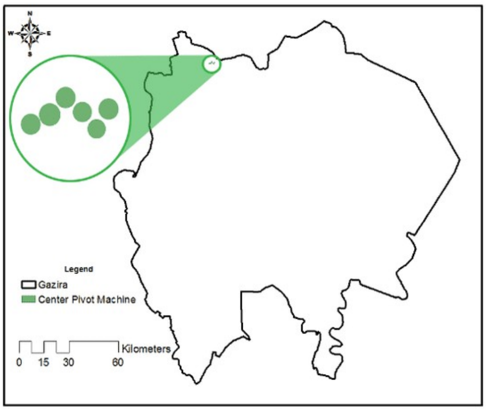

Figure 7. Map of center-pivots in Gazira

3.2 Irrigation and Water Supply in Al Waha.

Water is extracted from the Blue Nile by a pumping station comprising six identical units, each with a capacity of 3.52 m^3/s. Three units operate concurrently, yielding a total flow rate of 10.56 m^3/s an elevation of 5 m above river level. The water enters the main canal, then flows into sub-canals, followed by secondary canals, and finally reaches the pivot intake points for field application. Figure 1 depicted Al Waha irrigation system network, while Table 3 summarized the canals lengths. Table 3 lists the lengths of Al Waha's irrigation canals by type. It shows that the secondary canals were 44.48 km total length, far longer than the main canal (4.79 km) and sub-canals (23.81 km).

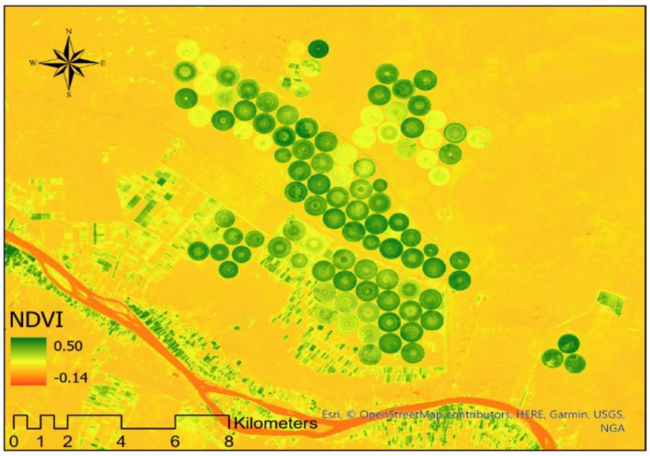

Figure 8. Al Waha field layout and NDVI map

Table 3.lists the canals at Al Waha

Type of canal	Main	Sub	Secondary
length km	4.79	23.81	44.48

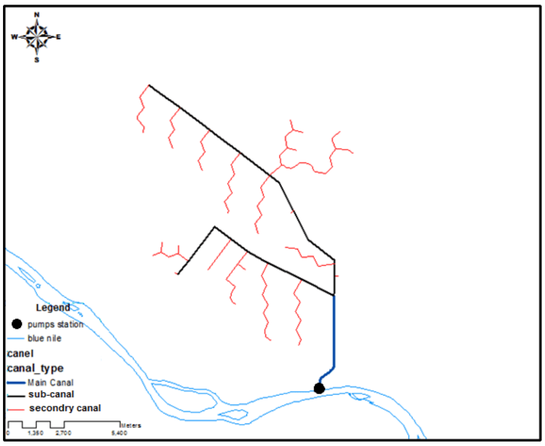

Figure 9. Al Waha Irrigation system network

3.3 Soil Maps Production

The project soil consists mainly of alluvial sediments transported by the Blue Nile, originating from the Ethiopian Highlands. This forms part of Sudan's expansive central clay plain. Two main soil types were identified: loam clay and clay. Approximately 90% of the project area is loam clay soil (see Figure 10). Soil class significantly affects yield, although management practices such as irrigation, fertilization, and weeding also play an essential role.

3.4 Crops map.

In Al Waha project, three types of crops were grown, which mainly produce forage for cattle feed. These crops were Alfalfa, Rhodes, and Corn. Alfalfa and Rhodes were among the perennial crops that remained on the ground for several years, which were grown for feed production under a pivot irrigation system. Corn is a seasonal crop that is used in the production of fodder and corn grains, and it is cultivated in this project in a limited manner. Figure 11 presents the crop distribution layer, while Table 4 lists the number of pivots cultivated by various crops in the commercial project. Rhodes is cultivated over a larger area (79 pivot). Rhodes accounts for the largest number of pivots 79, followed by Alfalfa (20 pivots) and corn (6 pivots). This result clarified the trend of this sector to adopt modern irrigation technologies to produce animal feed and forage for export to obtain the highest returns. It is well known; alfalfa and Rhodes are export crops with very profitable returns for agricultural investors.

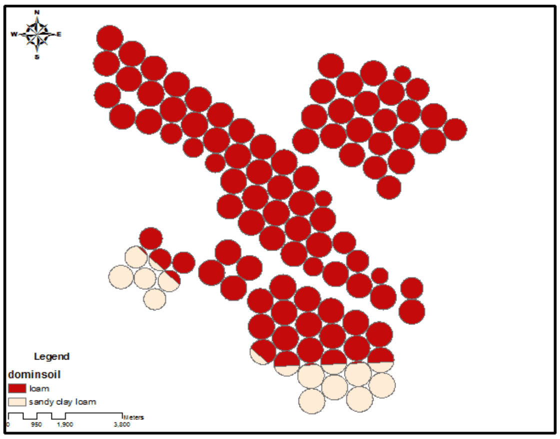

Figure 10. Al Waha - Soil type map

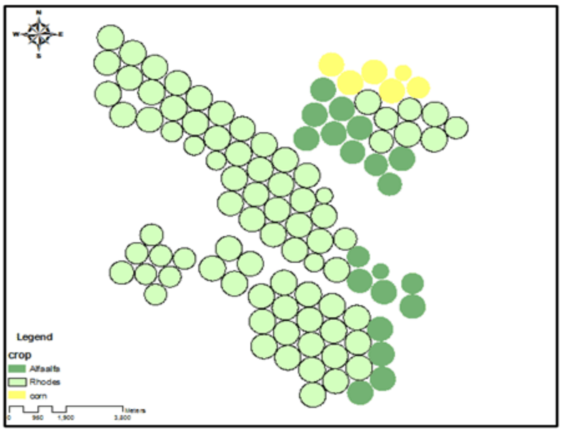

Figure 11. Al Waha - Crop type map

Table 4. Number of pivots cultivated by crops in the Al Waha commercial project

Crops	Number pivots cultivated
Alfalfa	20
Rhodes	79
Corn	6

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3.5 Irrigation Water Used and Fuel Consumption

Irrigation water demand is determined by crop type, soil, climate, and system efficiency, while fuel consumption depends on the energy needed to run pumping stations and pivots. Since pumps rely on diesel generators, fuel use is a key factor for sustainability and operating costs.

Table 5 shows the monthly operating time, water use, and fuel consumption per pivot for alfalfa. The Alfalfa's pivot showed maximum monthly operating conditions during April–June period; These maximum working conditions were attributed to peak growth and high evapotranspiration during these hot months. This is followed by the moderate monthly operating conditions during Oct. –Jan. period. These moderate working conditions were attributed to transition and cooler months. The Alfalfa's pivot showed low monthly operating conditions during July and Sep. months.

Table 5. Monthly operating time, fuel consumption , and water used for Alfalfa per pivot

Month	**Operation hours**	**Water, m³**	**Fuel, liters**
Jan	300b	99000b	4800b
Feb	330a	108900a	5280a
Mar	350a	115500a	5600a
Apr	360a	118800a	5760a
May	370a	122100a	5920a
Jun	350a	115500a	5600a
Jul	270c	89100c	4320c
Aug	150d	49500d	2400d
Sep	270c	89100c	4320c
Oct	300b	99000b	4800b
Nov	320b	108900a	5280a
Dec	320b	105600b	5120b
Total	3700	1221000	59200

High (a), Moderate (b), Low (c), Very Low (d)

Table 6. Monthly operating time, fuel consumption and water used, for Rhodes per pivot

Month	Operation hours	Water, m³	Fuel, liters
Jan	300b	99000b	4800b
Feb	320b	105600b	5120b
Mar	330a	108900a	5280a
Apr	350a	115500a	5600a
May	350a	115500a	5600a
Jun	340a	112200a	5440a
Jul	260c	85800c	4160c
Aug	150c	49500c	2400c
Sep	210c	69300c	3360c
Oct	300b	99000b	4800b
Nov	300b	99000b	4800b
Dec	290b	95700b	4640b
Total	3500	1155000	56000

High (a), Moderate (b), Low (c), Very Low (d)

These reduced operating conditions were due to less demanding irrigation on the rainy months. Finally, the minimum monthly operating conditions during August, where maximum rain and least demanding irrigation for Alfalfa's field were required.

Similarly, Table 6 shows the monthly operating time, water used and fuel consumption and water used for Rhodes per pivot. The Rhodes's pivot showed maximum monthly operating conditions during March–June period; These maximum working conditions were attributed to high evapotranspiration during these hot months. This is followed by the moderate monthly operating conditions during Oct. – Feb. period. These moderate working conditions were attributed to transition and cooler months. Finally, the minimum monthly operating conditions during July–Sep. period. These minimal operating conditions were due to less demanding irrigation on the rainy months.

Table 7. Comparison of annual water used and fuel consumption for Alfalfa and Rhodes under different locations

Country	Alfalfa		Rhodes		Average	
	water m³/ha-year	Fuel L/ha-year	Fuel L/ha-year	Fuel L/ha-year	water m³/ha-year	Fuel L/ha-year
Al Waha project	3,625.83	176.7	3,429.84	167.1	3,527.8	171.9
Saudi Arabia [23]	6,636	-	6,255	-	6,445.5	-
Nebraska [13]	-	-	-	-	3,806.51	496

Table 7. summarizes the comparison of annual water used and fuel consumption for Alfalfa and Rhodes under different locations. As shown in Table 7 the annual water consumption in Al Waha was 3,625.83 m³/ha-year for and 3,429.84 m³/ha-year for Rhodes, values close to Nebraska center-pivots (3,806.51 m³/ha-year) but much lower than Saudi Arabia pivots for Alfalfa (6,636 m³/ha-year) and Rhodes (6,255 m³/ha-year). Fuel consumption in Al Waha for Alfalfa and Rhodes were 176.7 L/ha-year and 167.1 L/ha-year, respectively, far below Nebraska (496 L/ha-year) due to the reliance on Nile surface water rather than deep well pumping. These discrepancies in values are mainly explained by differences in sites locations, soil types, climatic conditions and irrigation water sources.

3.6 Irrigation Efficiency Assessment

CROPWAT and CLIMWAT were used to evaluate the performance of the pivot irrigation system at Al Waha. The applied water volume was compared to crop water requirements (ETc), using long-term climatic data (1971–2000) from Khartoum station.

Table 8 summarizes the average climate at Al Waha by month. It highlights that there is virtually no rainfall from October through May, whereas rainfall peaks in July–August (~46–75 mm/day) with high relative humidity. This confirms a semi-arid climate with a short-wet season; irrigation needs are high for much of the year but naturally decrease during the rainy months.

Table 9 and Figure 12 illustrate the required water versus applied water and rainfall for alfalfa through the year. A clear peak in irrigation demand occurs in March–June when precipitation is nearly zero. In July–August, applied irrigation drops dramatically as rain largely meets the crop's needs. The estimated irrigation efficiency for Alfalfa revealed seasonal variations and average of 70% (57–87%).

Similarly, Table 10 and Figure 13 provide a visual summary of Rhodes irrigation throughout the year. It clearly shows the sharp rise in efficiency during July–August when rain alone nearly satisfies crop demand. The estimated irrigation efficiency for Rhodes revealed seasonal variations; averaged ~77%, peaking at ~99–100% in July–August and declining to ~49–55% in September–October.

Table 8. Average climate data of the Al Waha Project collected monthly between 1971-2000 from Khartoum land station [24].

Month	Rain mm/ Day	Relative Humidity (%)	Min Temp °C	Max Temp °C	Wind Speed Km/Day	Sun Shine Hours
Jan	0.0	34	15.0	30	346	9.7
Feb	0.0	20	11.5	38.9	491	11.8
Mar	0.0	15	14.5	42.4	484	13.1
Apr	0.4	14	17.9	44.3	448	13.7
May	4.0	21	22.5	44.9	378	13.2
Jun	5.4	29	24.9	44.1	368	13.0
Jul	46.3	47	23.8	41.8	455	12.1
Aug	75.2	59	22.9	39.9	407	11.4
Sep	25.4	53	22.8	41.1	312	11.6
Oct	4.8	36	21.2	41	303	11.3
Nov	0.7	27	16.1	38.8	428	10.7
Dec	0.0	29	12.3	36.8	453	10.1

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Table 9. Required water, applied water, rainfall water, and irrigation efficiency for alfalfa per pivot

Month	Required water (m³)	Appli-cation (m³)	Eff. Rainfall (m³)	Total (m³)	Irrigation Efficiency (%)
Jan	128,820	99,000	0.0	99,000.0	76.85
Feb	149,910	108,900	0.0	108,900.0	72.64
Mar	189,753	115,500	0.0	115,500.0	60.87
Apr	189,126	118,800	226.8	119,026.8	62.94
May	195,396	122,100	2,268.0	124,368.0	63.65
Jun	179,550	115,500	3,061.8	118,561.8	66.03
Jul	160,455	89,100	24,324.3	113,424.3	70.69
Aug	152,703	49,500	37,535.4	87,035.4	57.00
Sep	151,677	89,100	13,834.8	102,934.8	67.86
Oct	155,838	99,000	2,721.6	101,721.6	65.27
Nov	125,685	108,900	396.9	109,296.9	86.96
Dec	130,929	105,600	0.0	105,600.0	80.65

3.7 Development of the project per year:

Al Waha Project, launched in 2009 by DAL Company Ltd. and was established to support livestock production through the cultivation of cattle feed. The project has witnessed significant expansion in its pivot irrigation systems, as illustrated in Table10.

Figure 14 plots the cumulative growth in the number of pivots over time. The analysis of the Compound Annual Growth Rate (CAGR) between 2009 and 2020 shows an increase from 29 to 105 pivots, resulting in a CAGR of approximately 13.8% per year. This indicates a strong and consistent expansion of the project over more than a decade, with relative stabilization in pivot numbers during the period from 2016 to 2020.

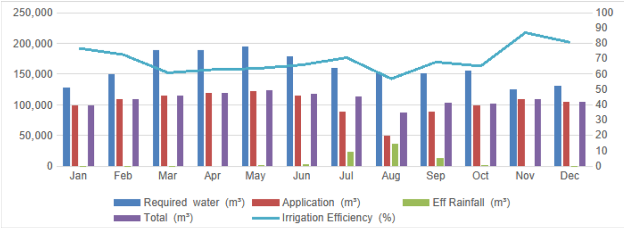

Figure 12. Required water, applied water, rainfall water, and irrigation efficiency for Alfalfa

Table10. Required water, applied water, rainfall water, and irrigation efficiency for Rhodas per pivot

Month	Required Water, (m³)	Appli-cation (m³)	Eff. Rainfall (m³)	Total (m³)	Irrigation Efficiency, (%)
Jan	108299.43	99000	0.0	99000.0	91%
Feb	128537.28	99000	0.0	99000.0	77%
Mar	162687.69	105600	0.0	105600.0	65%
Apr	165596.40	108900	226.8	109126.8	66%
May	167458.59	115500	2,268.0	117768.0	70%
Jun	163134.00	115500	3,061.8	118561.8	73%
Jul	137560.95	112200	24,324.3	136524.3	99%
Aug	123566.31	85800	37,535.4	123335.4	100%
Sep	130045.50	49500	13,834.8	63334.8	49%
Oct	130404.60	69300	2,721.6	72021.6	55%
Nov	126813.60	99000	396.9	99396.9	78%
Dec	112275.18	99000	0.0	99000.0	88%

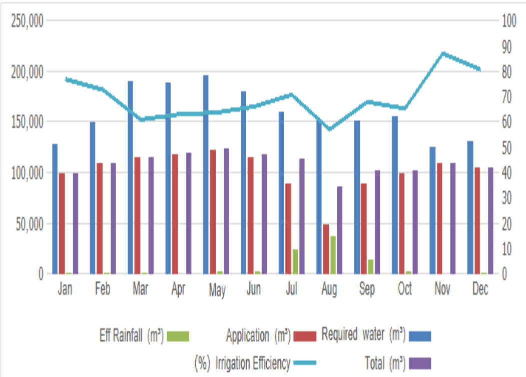

Figure 13. Required water, applied water, rainfall water, and irrigation efficiency for Rhodes

Table 11. Annual development of the Al Waha project

Year	Number of pivots
2008	0
2009	29
2010	49
2011	79
2012	84
2013	84
2014	92
2015	98
2016	105
2020	105

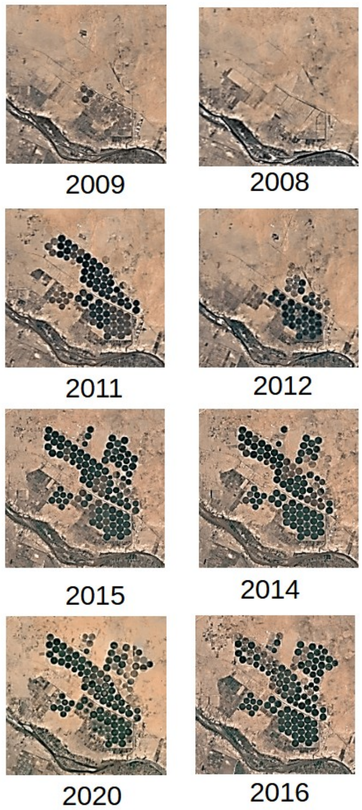

Figure 14. Al Waha pivots growth during 2008-2020

CONCLUSIONS

- Mapping of center-pivot irrigation systems in Sudan using RS and GIS techniques with case study on the Al Waha project was successfully developed and presented to support agricultural auditing, water and energy use management, and policy development.
- A geographic object-based image analysis approach was developed to document the annual total number and extent of individual center-pivot fields in Sudan, using Landsat-8 imagery (2020) and a multi-temporal dataset covering 2009-2020 at case study Al Waha project in Khartoum.
- Digital maps of center-pivot irrigation systems covered major Sudanese states, identifying 1,373 pivots covering approximately 70,078.2 ha in Sudan across the River Nile, Northern, Khartoum, Kordofan, and Gazira (774, 296, 248, 49, and 6, respectively).
- The calculated maps accuracy was 96.4% and NDVI was demonstrated to delineate planted area and evaluate within-pivot biomass.
- The Al Waha project was documented to have grown from 29 to 105 pivots during 2009–2020, covering about 5,927 ha. It also mapped the irrigation network, soil classes, and annual and seasonal crop

distribution: Rhodes, Alfalfa, and Corn (79, 20, and 6, respectively).

- The pivots consumed great quantities of both water and energy; an estimated 3,625.83 m³/ha-year (water) and 176.7 L/ha-year (diesel) for alfalfa, while an estimated 3,429.84 m³/ha-year (water) and 167.1 L/ha-year (diesel) for Rhodes

The estimated irrigation efficiency for Alfalfa revealed seasonal variations and average of 70% (57–87%).

- The estimated irrigation efficiency for Rhodes revealed seasonal variations; averaged ~77%, peaking at ~99–100% in July–August and declining to ~49–55% in September–October.
- This study demonstrated the opportunity of using RS and GIS derived data to provide direct agro-informatics insights and support more efficient management of water, energy, and related applications, thereby strengthening agricultural decision-making, improving productivity, and promoting resource sustainability in Sudan.

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