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Assessing Soil Properties for Optimized Irrigation Development in Sudan, Northern Africa

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ABSTRACT. *Sustainable irrigation methods maximize agricultural productivity in Northern African countries like Sudan. This project evaluates soil properties to develop optimized irrigation strategies for Sudan's arid and semi-arid climate. Assessing soil characteristics such as texture, infiltration rates, and nutrient content informs the selection of modern irrigation systems. Data from 3192 locations, collected using GPS and ring infiltrometers for infiltration rates, alongside laboratory analyses for soil properties, were employed. A ranking system determined suitable irrigation systems for specific soil classes, considering factors like slope, wind, crop tolerance, available water capacity (AWC), drainage, germination, capital cost, labor cost, maintenance, and evapotranspiration (ET). The study evaluated the efficiency of three prevalent irrigation methods—center pivot, drip, and surface irrigation—across five soil types. Drip irrigation showed marked efficiency, ranging from 76% to 78% across three soil types, while Center Pivot Irrigation was optimal for Typic Haplsalids (gravelly) soil. Surface Irrigation consistently underperformed, with efficacy rates between 63% and 72%. Typic Haplsalids gravelly soil favored sprinkler irrigation, with 75% higher efficacy. Tailoring irrigation methods to specific soil types maximizes efficiency. Soil permeability variability emphasizes the need for tailored water management strategies, with subsurface irrigation posing challenges in coarser soils. Considering soil variability, ET, investment, and workforce expense when selecting irrigation methods is crucial for sustainable water management and efficiency. investment, and workforce expense when selecting irrigation methods is crucial for sustainable water management and efficiency.*

Keywords. *Efficient irrigation, soil properties, water management, sustainability irrigation, surface irrigation, sprinkler irrigation, drip irrigation*

Introduction

Sudan stands at a pivotal moment where modern irrigation technology presents an opportunity to transform its agricultural sector. Historically, agriculture has been a cornerstone of Sudan's economy, driving significant export revenues. However, the country's economic landscape shifted with the discovery of oil, leading to a decline in agricultural productivity and increased reliance on the oil sector (Ahmed, Sulaiman, et al., 2012). This shift exacerbated challenges posed by water scarcity, despite Sudan's vast agricultural potential. Globally, water scarcity is a pressing issue, particularly in regions heavily dependent on agriculture. Sudan faces the challenge of optimizing water use in farming practices with traditional irrigation methods proving insufficient and sometimes wasteful (Osman & Hag, 1974). Recent years have seen a gradual transition towards modern irrigation technologies, offering increased efficiency and productivity. However, adoption remains limited due to economic constraints and accessibility issues (Ahmed, 2004).

This paper explores the benefits and challenges of integrating modern irrigation technology into Sudan's agricultural practices, drawing upon existing literature and research findings. The significance of technology in improving irrigation management, enhancing water use efficiency, and mitigating the impacts of climate change is highlighted (Bansod et al., 2017; Brocca et al., 2018). Despite potential advantages, challenges persist, including prohibitive costs and limited access to technology (Cheng et al., 2022). Sudan's socio-economic development lags behind many other countries, complicating the adoption of modern irrigation technology (Ahmed, 2004). Addressing these challenges requires a comprehensive understanding of Sudan's agricultural context. By evaluating various technological interventions, this study aims to identify suitable approaches for sustainable agricultural development in Sudan (Mahmud & Nafi, 2020; Eisenhauer et al., 2021; Rastogi et al., 2021). This project offers a unique approach to support the agricultural industry in selecting the most suitable irrigation systems based on soil characteristics. By providing valuable insights into soil properties and irrigation requirements, this research will enable farmers and policymakers to make informed decisions about irrigation systems, leading to more efficient water use and improved crop yields.

One of the standout aspects of this project is its focus on large-scale irrigation development, particularly in Sudan, where irrigation management is crucial. By exploring the social and environmental implications of different irrigation systems, this research will contribute to the development of sustainable and equitable water management practices in Africa, with a specific focus on Sudan.

The overall goal of this study is to assess soil properties across Sudan, identify areas with the greatest potential for irrigation development based on soil characteristics, recommend suitable modern irrigation systems, and contribute valuable insights to stakeholders involved in agricultural development in Sudan. Sudan possesses extensive land and water resources, making it highly suitable for agriculture. Its primary water sources include surface water from rivers and underground aquifers, with the Nile River Basin being crucial for irrigation. However, lack of coordinated water management has led to unpredictable floods and water level fluctuations. The Zadi 1 agricultural project exemplifies Sudan's potential, with plans to transform unused land into a sustainable agricultural resource. Center pivot irrigation technology is poised to play a pivotal role in this project, offering efficient water consumption. However, effective implementation requires careful planning, considering factors such as soil properties, slope, water use, crop tolerance, and wind.

This study's main objectives are: 1. to conduct a comprehensive assessment of soil properties, encompassing texture, moisture content, infiltration rate, sodality, salinity, pH, Organic Matter (OM), and nutrient content (NPK, CO_2), across various regions of Sudan. 2.to identify areas with the greatest potential for irrigation development based on soil characteristics. This aims to maximize agricultural productivity while conserving water resources by pinpointing regions where optimized irrigation strategies can be implemented effectively. 3. to recommend suitable modern irrigation systems tailored to the specific soil properties of each region. These recommendations will focus on optimizing water management practices and enhancing agricultural productivity in Sudan. 4. to contribute valuable insights and awareness to policymakers, industries, farmers, and stakeholders involved in agricultural development in Sudan. This involves facilitating informed decision-making and promoting sustainable agricultural practices through the dissemination of research outcomes and clear communication of findings.

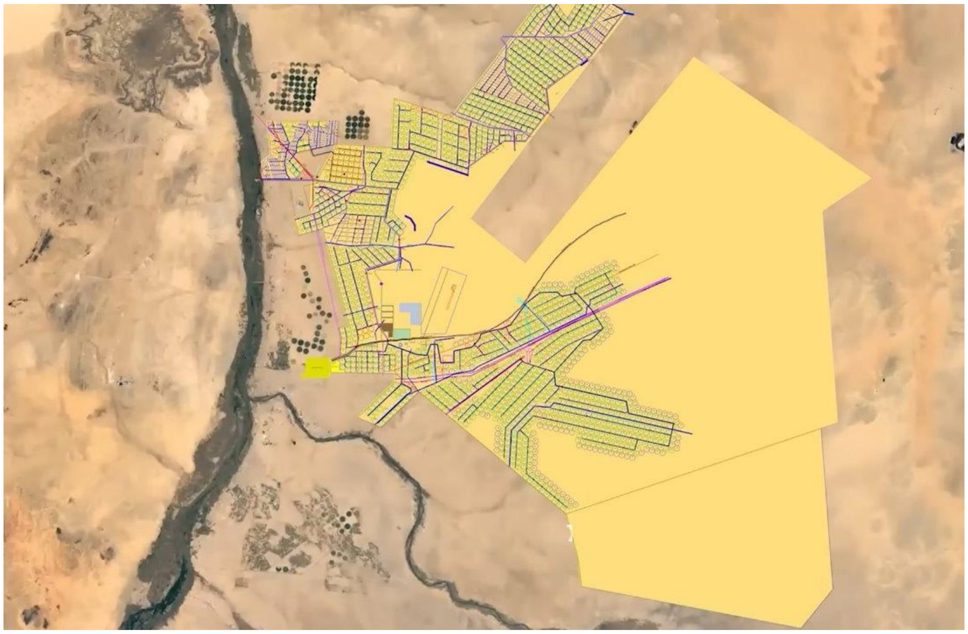

Figure 1. illustrates the irrigation system of the project and future development.

System Description: Zady 1 Project

The Zady 1 project encompasses a multifaceted approach to agricultural development and infrastructure enhancement in the River Nile State of Sudan. This comprehensive system integrates various elements to achieve its objectives, including livestock management, dairy production, poultry farming, residential infrastructure, and urban development. This system description provides an overview of the project's components, environmental considerations, water supply system, irrigation methods, crop selection process, and soil characteristics within the study area. The Zady 1 project aims to enhance agricultural productivity and infrastructure in the River Nile State of Sudan. Through a combination of livestock management, dairy production, poultry farming, residential infrastructure development, and urban expansion, the project seeks to transform the region's economic landscape.

Residential Infrastructure and Urban Development

To support its workforce, the project includes the development of 41 villages, providing residences for individuals involved in project activities. Furthermore, the project envisions the creation of three new cities to enhance regional infrastructure and livability (Zadna International Co.ltd for Investment 2023).

Environmental Considerations

The project site's geology comprises the Basement complex and the Nubian sandstone formation, with groundwater recharge occurring through limited precipitation and infiltration from seasonal streams. The region experiences a dry, desert climate, with distinct summer and winter seasons. Vegetation in the area is sparse, dominated by species adapted to arid conditions.

Water Supply System

The project's water supply system consists of 261 concrete foundations supporting 32 water pumps, which transport water from the main station to the primary canal and sub-channels. The primary canal, spanning 22 kilometers in its initial phase, features two lift stations to ensure a consistent flow of water to the project's lands. Gates along the canal system enable precise control over water distribution (Zadna International Co.ltd for Investment 2023).

Irrigation Methods

The project uses an extensive network of main and sub-canals, about 1,100 kilometers (about 683.51 mi) in length, to convey water to agricultural lands. The primary irrigation system employs pivot irrigation design, with 3,500 pivots covering 150 hectares each. Surface irrigation systems are also utilized on smaller farms to optimize water efficiency (Zadna International Co.ltd for Investment 2023).

Crop Selection Process

Crop selection is based on a comprehensive analysis of soil, water resources, climate conditions, and vegetation cover. Factors influencing crop selection are systematically analyzed and quantified to ensure optimal utilization of land resources. The decision-making process considers the interplay of numerous factors to align crop selection with the land's unique attributes.

Materials and Methods

Site Description and Sample Collection

Soil survey and analysis engineers at the Zadna Company Laboratory conducted extensive soil surveys, collecting samples at 3,192 observation sites. The process commenced by inputting the coordinates of the study area's boundaries into a satellite image. Subsequently, a square grid was established to denote the auger sites' positions and representative soil profiles. The survey, illustrated in Figure 1, was executed at a scale of 1:50,000 (semi-detailed), where sampling sites were spaced 500 meters apart. These samples were analyzed to assess land and crop suitability, informing the selection of suitable irrigation methods. Soil sample locations were determined using a Global Positioning System (GPS) device, specifically the Garmin 64sc, manufactured by Garmin Ltd. in the USA. In measuring infiltration rates, two ring infiltrometers, a plastic tank (36 liters) hammered into the ground, a stopwatch, and a measuring ruler were employed.

Samples were conveyed to the Zadna International Company for Investment laboratories. The soil profile samples were obtaining 100 g of soil before air dried for 24 hr , in order to compute moisture content at the oven 105 C for 24 hr . After air dried samples were ground and sieved to pass 2 mm diameter, then we kept on plastic packaging for contain and the subsequent analysis physical and chemical soil analysis for profile samples.

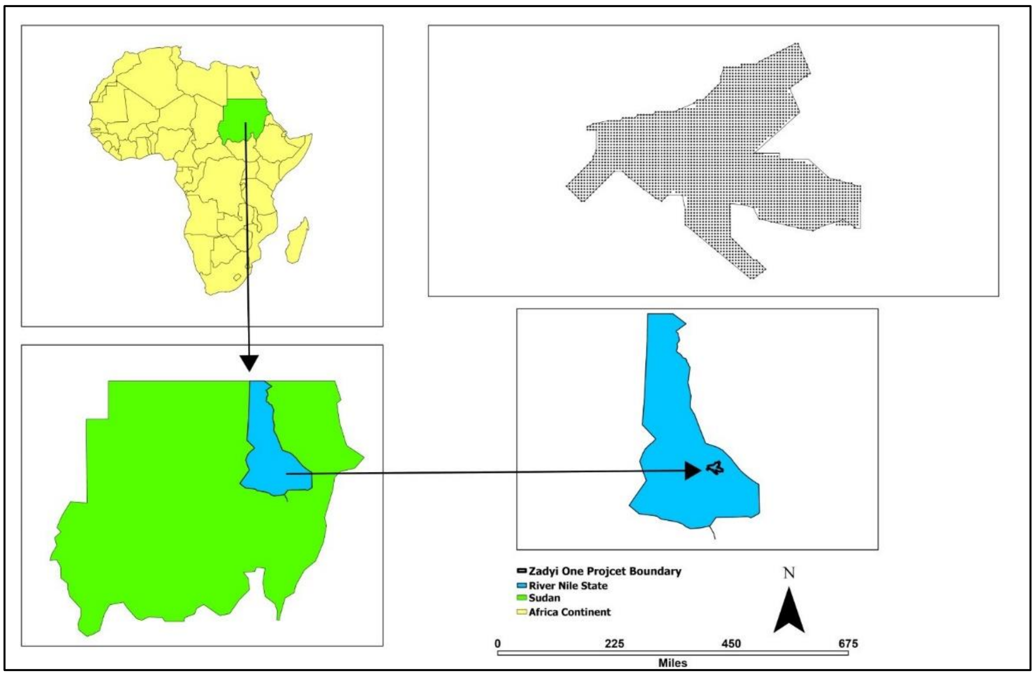

Figure 2. Location of Sudan and Sampling Zaydi one project

The project area is characterized by a geological composition comprising Basement Complex and the Nubian Sandstone Formation in the third terrace, belonging to the Quaternary period and Cretaceous age, respectively. Groundwater recharging in the sandstone is likely derived from minimal precipitation and seepage from seasonal streams such as Khors and Wadis. Situated within the desert ecological zone of Sudan, the area exhibits sparse vegetation. Dominant species include Salam (Acacia ehrenbergiana), Marrekh (Leptadenia pyrotechnica), Tundub (Capparis deciduas), Miskeet (Prosopis juliflora), and Ausher (Calotropis procera). According to Vander Kevei (1976) the project is located in dry and desert climate.

The study site is characterized by predominantly flat topography, with notable exceptions. In the central area of the project site, there are sections with steeper slopes, forming a natural watercourse that affects water flow dynamics. These variations in terrain range from 2% to 5% elevation, creating an intriguing landscape dynamic.

The study site was selected to represent a typical soil type in Noth Sudan. The project is in River Nile State north-east of Atbara city, Sudan. The soil samples were collected from the layers (0-90 cm) at the study sites of Zady 1 irrigation project. Topographic features were meticulously documented along with their precise coordinates. Soil auguring was conducted at three depth intervals: 0-30 cm, 30-60 cm, and 60-90 cm. Thorough descriptions of the auger samples were recorded, and 500 grams of each sample were carefully placed in labeled plastic bags, indicating the auger number, sample depth, and date of collection.

According to FAO,1976 and USDA soil survey, the auger samples were categorized based on their descriptions to identify a representative profile, typically located at the center of a mapping unit. This profile was subdivided into pedogenic horizons or layers, and each individual horizon or layer was meticulously described following the guidelines outlined by the Food and Agriculture Organization (FAO,1976). The depth of each horizon or layer was precisely measured and recorded. Where a profile was dug at 1 meter in length, 1.5 meters in width, and 1 meter in depth was excavated for further analysis. For each horizon or layer, one kilogram of soil was carefully extracted, placed in a plastic bag, and labeled with the profile number, depth of the horizon or layer, and the date of sampling. Furthermore, near the profile, an assessment of water infiltration rate was conducted as part of the comprehensive soil analysis process. It was done near the 120 sites. That represents the soil profile's locations. Before the experiment, any debris or large stones were removed from the soil surface, ensuring a clean and even surface for the infiltration measurements.

Soil Analysis Procedures

The soil analysis encompassed a comprehensive assessment of various physical, chemical, and textural properties to elucidate soil characteristics and suitability for agricultural use. The analytical procedures conducted on soil samples included as follows:

- **Particle Size Analysis:** Soil samples were treated with HCl to destroy calcium carbonate, washed to remove soluble salts, and dispersed chemically and mechanically. The hydrometer method was employed to determine clay and silt fractions.
- **Soil Textural Class Determination:** the FAO textural triangle was utilized to determine the textural class of soils based on particle size distribution.
- **Total Nitrogen (N%) Analysis:** the modified Micro Kjeldahl method was employed to determine total nitrogen content in soil samples.
- **Available Phosphorus (P) Determination:** available phosphorus content was determined using the Olsen sodium bicarbonate extraction method.
- **Soil pH Measurement:** soil pH was determined in saturated soil paste using a glass/calomel electrode system (Model Superfit TM Digital pH Meter).
- **Electrical Conductivity (ECe) Measurement:** ECe of saturation extract was determined using a conductivity meter (Model Janway 4510 Conductivity Meter).
- **Cation Exchange Capacity (CEC) Analysis:** CEC was determined by treating soil with sodium acetate, followed by extraction with ammonium acetate and flame photometry.
- **Soluble Cations and Anions Analysis:** soluble cations and anions were determined in saturation extract using various chemical methods including flame photometry and titration.
- **Exchangeable Sodium Percentage (ESP) Calculation:** ESP was calculated as the ratio of exchangeable sodium to CEC, multiplied by 100.
- **Sodium Adsorption Ratio (SAR) Calculation:** SAR was calculated using the formula incorporating soluble sodium, calcium, and magnesium concentrations.
- **Infiltration Rate:** infiltration rate was measured using the double ring method as described by Klute (1986) as steps illustrate below:

Double Ring Infiltrometer Setup:

Two double ring infiltrometers were used for the experiment. Each infiltrometer had two concentric metal rings with an inner and outer diameter of 30 and 60 cm (about 1.97 ft), respectively. The rings were driven into the soil at a consistent depth using a mallet, ensuring a tight seal with the soil to prevent water from leaking outside the rings during the experiment. Before each infiltration test, the inner ring of the infiltrometer was filled with water up to the level marked on the inside of the ring, approximately 100 mm (about 3.94 in) deep. The water was applied carefully to not disturb the soil inside the ring while filling it with water.

A 350 ml of water was added five times, once every 30 minutes on soil until reaching the perpetual time. And the water level was recorded by a ruler. The rate of water infiltration was measured by monitoring the drop in water level over time. The stopwatch was started as soon as the water level reached the marked depth in the inner ring at 5 cm (about 1.97 in), and the timer was stopped when the water level dropped to the same depth again. Then we obtain the total time and record the reading.

The infiltration rate was calculated as the amount of water infiltrated per unit surface area and time. By using following equations

$$IR = \frac{d}{\Delta t} = \frac{V}{A} \div \Delta t \tag{1}$$

$$a = \frac{\pi \times D^2}{4} \quad (2)$$

$$a = 3.14 \times 15 \times 15 = 706.5$$

Where:

IR = the infiltration rate
D = depth of water (mm)
V= volume of water (mm)
A= cylinder aera of 30 cm
a= the area of the inner ring of 15 cm
ΔT = average time (day) for volume of water to infiltrate

By dividing the added volume of water (350 ml) by the average time taken for infiltration at each step, the infiltration rate was determined for each measurement.

Soil and Land Classification

Soil classification in the study area was conducted according to Soil Taxonomy guidelines, considering diagnostic characteristics and properties at different levels including orders, suborders, great groups, and subgroups. Key diagnostic characteristics utilized in the classification process included horizonation, sub-surface diagnostic horizons, horizon differentiation, presence of calcium carbonates and gypsum, soil depth, ECe, ESP, and SAR (Keys to Soil Survey, 2003).

Land Suitability Assessment

The assessment of land suitability for agricultural use involved categorizing soils based on their suitability into orders, classes, subclasses, and units. This evaluation considered various soil and land characteristics including texture, depth, salinity, sodicity, pH, calcium carbonate content, erosion hazards, and slope. The FAO System of land evaluation categories was utilized to assess land suitability, with classifications ranging from "Suitable" to "Not Suitable" and degrees of suitability denoted as S1, S2, S3, N1, and N2 (El-tom and Kevie, 2003).

Irrigation Suitability Analysis

Irrigation suitability analysis was conducted using a ranking system to determine the most suitable irrigation system for specific soil classes. Factors influencing irrigation suitability such as slope, infiltration, wind, crop tolerance, available water capacity, drainage, germination, capital cost, labor cost, and maintenance, were assessed and ranked based on their significance. Weights were assigned to each factor to calculate the final sum for each soil class, ensuring a comprehensive evaluation of irrigation system compatibility and effectiveness (D. E. Eisenhauer, et al. ,2021; Waller and Yitayew ,2016). In our assessment of irrigation suitability, we utilized a ranking system to determine the most suitable system for specific soil classes. The process involved assigning ranks from 1 to 5 for each factor and then multiplying the rank by the weight of the factor to calculate the final sum for each soil class. According to the Natural Resource Conservation Service (1997), Chapter 5 of the Engineering Field Handbook provides guidance on methods and systems for applying irrigation water (652.0501 section). We applied similar methods, for example, the weights assigned to factors were determined based on their significance in influencing the irrigation system and considering the characteristics of different soil classes. The weights assigned to specific factors are as follows: slope of the land (0.10), infiltration (0.12), wind (0.02), crop tolerance (0.05), available water capacity (AWC) (0.12), drainage (0.07), germination (0.07), capital cost (0.14), labor cost (0.14), maintenance (0.14), and (0.05).Each factor's weight reflects its importance in affecting the irrigation system's efficiency. By assessing factors such as slope, infiltration, wind, crop tolerance, AWC, drainage, germination, capital cost, labor cost, maintenance, and ET, we aim to determine the most suitable irrigation system for each specific soil class.

Result and Discussion

The observed soil infiltration rates, presented in Table 1 below, highlight a diverse range of water absorption capacities within the studied soil classes. In the case of Typic Hsplsailk (Sandy Clay - Sandy Clay Loam), the infiltration rates vary from 0.55 to 0.71mm/s, with an average of 0.62mm/s. For Typic Haplsalids (gravelly) (Sandy Clay - Sandy Clay Loam), the range extends from 0.52 to 1.05mm/s, with an average of 0.75mm/s. Typic Haplcambids (Sandy Clay - Clay - Sandy Clay Loam) exhibits a broad range, spanning from 0.16 to 4.66mm/s, and an average infiltration rate of1.32mm/s. Similarly, Vertic Haplcambids (Sandy Clay - Sandy Clay Loam) presents rates ranging from 0.27 to 3.12mm/s, with an average of 1.31mm/s. Typic Haplargids (Sandy Clay - Clay - Sandy Clay Loam) demonstrates rates from 0.36 to 4.78mm/s, with an average of 1.48mm/s.

Table 1. ***Soil infiltration rates (mm/s) across different soil classes and textures.***

Soil infiltration rates				
Soil Classes	Textures	Min	Avg	Avg
Typic Hsplsailk	Sandy Clay - Sandy Clay Loam	0.55	0.71	0.62
Typic Haplsalids (gravelly)	Sandy Clay - Sandy Clay Loam	0.52	1.05	0.75
Typic Haplcambids	Sandy Clay - Clay - Sandy Clay Loam	0.16	4.66	1.32
Vertic Haplcambids	Sandy Clay - Sandy Clay Loam	0.27	3.12	1.31
Typic Haplargids	Sandy Clay - Clay - Sandy Clay Loam	0.36	4.66	1.48
Permanently not suitable (N2)	--	--	--	--

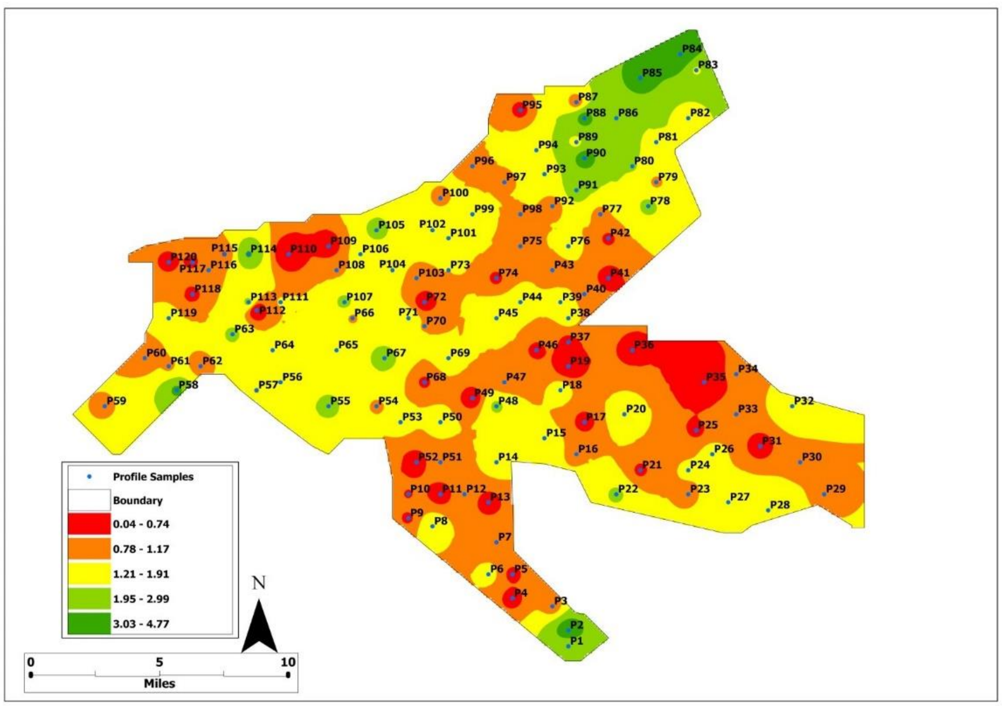

Figure 3. Illustration the infiltration rate (mm/s) and soil profile sample locations at Zadi One.

Table 2 and Fig. 4 depict the Soil Taxonomy Map of Zadi One, offering a comprehensive visual representation of the soil classifications within the region. Moreover, the study area is exclusively comprised of Aridisols. Deep soils, with an effective depth greater than 100 cm (about 3.28 ft), cover the vast majority, accounting for 96.4% of the total area. These deep soils provide ample space for root development and water storage, making them suitable for various land uses such as agriculture and urban development. Shallow soils, with depths ranging from 50 to 60 cm (about 1.97 ft), constitute a smaller portion, comprising 3.4% of the total area. Despite their limited depth, these soils may still support certain land uses but may require specific management practices for optimal productivity. Additionally, 2.1% of the total area is classified as "not suitable," indicating areas with inherent limitations that may restrict their suitability for certain uses. Understanding the distribution and characteristics of these soil depths is essential for informed land use planning and sustainable development within the study area.

Table.2 Extent area of the individual mapping units in hectares and as percentage of the total area

Soil Classification

Unit number	Classification (SG)	Area (hectare)	Percent (%)
1	Typic Hsplsailk	525.2	0.7
2	Typic Haplsalids (gravelly)	2751.1	3.4
3	Typic Haplcambids	38165.3	47.8
4	Vertic Haplcambids	10204.1	12.8
5	Typic Haplargids	25285.1	31.7
6	Permanently not suitable (N2)	1700.7	2.1
7	Out of the Scheme	1200.5	1.5
Total		79832	

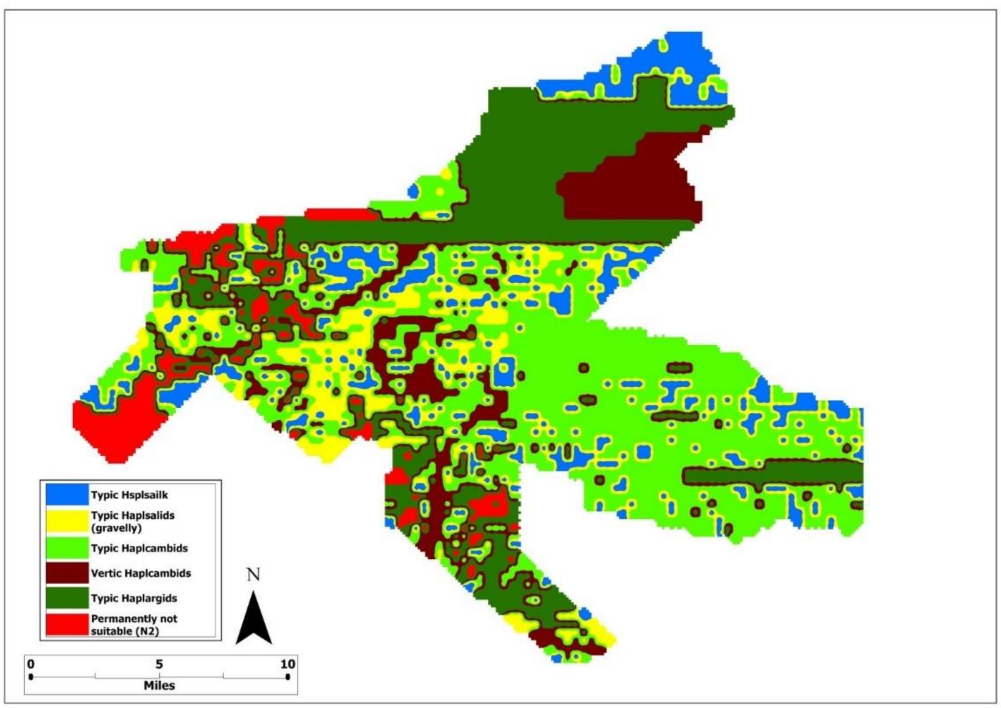

Figure 4. Illustration the Soil Taxonomy Map of Zadi One.

Table.2 Weight allocation for irrigation suitability factors in multi-criteria evaluation

Factor	Weights	Weights %
Slope	0.12	12
Infiltraion	0.12	12
Wind	0.02	5
Crop torance	0.05	5
AWC	0.12	12
Drainge	0.07	7
Germination	0.1	10
Capital cost	0.13	12
Labor cost	0.12	10
Maintenance	0.1	10
ET	0.05	5
Total	1	100

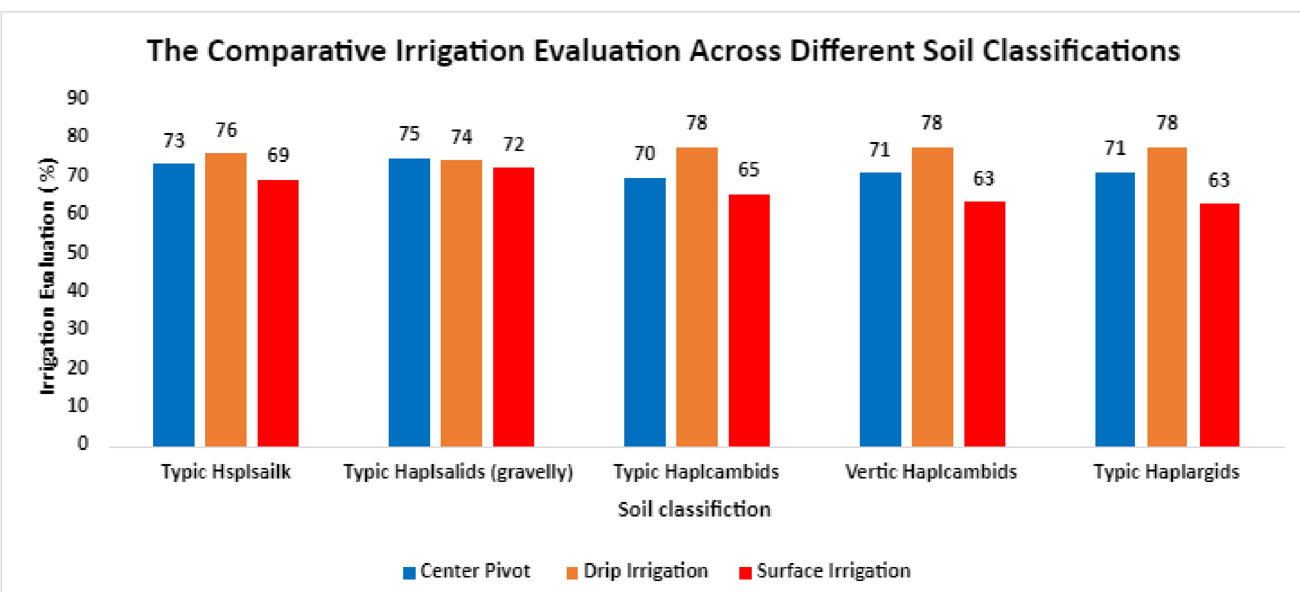

Figure 5. Illustration the comparative irrigation evaluation percentages across different soil classifications for center pivot drip and surface irrigation.

From fig 4 the results for different soil types using three irrigation methods (center pivot, drip irrigation, and surface irrigation) are presented in fig above showed that for the five soil types examined, drip irrigation emerges as the most efficient method for three of them (Typic Haplsailk, Typic Haplcambids, and Vertic Haplcambids), with sustainability values ranging from 76% to 78%. Center Pivot irrigation is the most effective method for Typic Haplsalids (gravelly) soil, with a sustainability of 75%, and performs comparably to Drip Irrigation for the other soil types. Surface Irrigation consistently records the lowest sustainability values, ranging from 63% to 72%, indicating it may be less suitable for these soil types.

For the Typic Hapludalfs soil type, as depicted in Figure 5, Drip Irrigation exhibits the highest sustainability at 76%, indicating its particular suitability for this soil. Both Center Pivot (73%) and Drip Irrigation show superior performance compared to Surface Irrigation (69%) within this soil unit. In the case of Typic Haplsalids (gravelly) soil, Center Pivot emerges as the most effective method with a sustaniability of 75%, whereas Drip Irrigation follows closely behind at 74 %. Surface Irrigation records the lowest evaluation percentage at 72 %, suggesting it may be less compatible with this soil type. For Typic Haplcambids soil, the Drip Irrigation and Center Pivot demonstrate comparable effectiveness at 78 %, 70 % respectively outperforming Surface Irrigation at 65 %. This soil type appears well-suited for multiple irrigation methods. In Vertic Haplcambids soil, both Center Pivot and Drip Irrigation display high sustainability at 75% and 76%, respectively, with Drip Irrigation slightly edging out. Surface Irrigation, while still effective, records a lower evaluation at 66% compared to the other methods.

Regarding Typic Haplargids soil, Center Pivot and Drip Irrigation again exhibit similar performance at 73% and 74%, respectively, with Drip Irrigation holding a slight advantage. Surface Irrigation records the lowest evaluation at 64%, suggesting potential limitations for this type of unit. The variability in soil permeability within the study area highlights the need for customized water management strategies that consider the unique water absorption characteristics associated with different soil textures and compositions. This heterogeneity is evident in the wide range of infiltration rates observed across various soil classes, as detailed in Table 1. Factors such as the presence of gravelly textures in Typic Haplsalids and the clay content in Typic Haplcambids and Typic Haplargids contribute to the divergent water absorption capabilities among soil types of units. Consequently, the selection of irrigation methods significantly influences efficiency, with Drip Irrigation often emerging as a favorable option, as illustrated in Fig.5. While Center Pivot irrigation generally proves effective, its performance may fluctuate depending on soil characteristics, as indicated in Table 1. In contrast, Surface Irrigation consistently demonstrates lower evaluation percentages, implying potential inefficiencies compared to other studied methods. These findings underscore the necessity of considering soil characteristics when choosing an irrigation method, as certain methods may prove more effective for specific soil types. The provided evaluation percentages offer valuable insights for making informed decisions regarding irrigation strategies tailored to the distinct properties of each soil classification.

The assessment of irrigation effectiveness across different soil classifications yields valuable insights for optimizing irrigation strategies tailored to specific soil types within the study area. The effectiveness of various irrigation methods varies significantly depending on soil characteristics, emphasizing the importance of considering soil properties when selecting an irrigation approach.

Our findings indicate that Drip Irrigation generally exhibits high sustainability across several soil types, particularly Typic Hsplsailk and Vertic Haplcambids, where it outperforms other methods. This suggests that Drip Irrigation could be a favorable choice for soils with diverse textures and compositions, ensuring efficient water delivery and uptake.

Center Pivot irrigation also demonstrates notable effectiveness across various soil types, particularly for Typic Haplsalids and Typic Haplargids. However, its performance may vary depending on soil characteristics, underscoring the need for careful consideration during implementation. Surface Irrigation consistently shows lower evaluation percentages compared to other methods, indicating potential limitations, especially for soils with higher infiltration rates. This suggests that while Surface Irrigation may be suitable for certain soil types, it might not be the most efficient choice in all scenarios.

The observed variability in soil permeability underscores the necessity of tailored water management strategies to accommodate the distinct water absorption characteristics associated with different soil textures and compositions. This variability, evident in the wide range of infiltration rates across soil classes, highlights the need for a nuanced approach to irrigation planning. Our results emphasize the importance of considering soil characteristics when selecting an irrigation method to maximize efficiency and minimize water waste. By accounting for soil variability, irrigation practices can be tailored to specific soil types within the project area, ultimately leading to more sustainable and effective water management strategies.

Limitations

One of the limitations of this project is that the weightage assigned to different irrigation systems was based on the expertise of irrigation specialists and associations, but there is a lack of published research on this topic. Despite searching, few papers were found that provide guidance on how to weigh the different factors for ranking analysis. However, this limitation can be overcome by relying on local expertise and experience, as well as soil and climate characteristics, to determine the most suitable irrigation system for a given area. The absence of published research on weightage assignment for irrigation systems is a challenge, but it also presents an opportunity to develop a new approach that can be applied to different areas. By relying on local knowledge and experience, farmers, policymakers, and irrigation experts can assign weights to different factors based on their specific context, including soil type, ET, and cost considerations. This approach can provide a general guideline for determining the most suitable irrigation system for a given area.

Despite the limitations of this project, the weightage assignment principle can still be applied to evaluate different irrigation systems. Farmers and irrigation experts can use their experience and knowledge to assign weights to various factors, considering the distinct characteristics of their soil, climate (including evapotranspiration (ET)), and cost constraints. This approach can offer valuable guidance for selecting the most suitable irrigation system, making it a helpful tool for farmers, policymakers, and the irrigation industry. Furthermore, our assumptions for the weight method were based on the specific needs of farmers in Sudan, where cost is a significant factor, and we assumed that all systems are well-designed.

Conclusions

This study has achieved significant strides in advancing agricultural productivity and water resource management in Sudan. Through a comprehensive assessment of soil properties encompassing texture, moisture content, infiltration rate, sodality, salinity, pH, organic matter, and nutrient content across various regions, it has established a fundamental understanding of the soil characteristics crucial for agricultural development.

Moreover, by identifying areas with the greatest potential for irrigation development based on soil characteristics, the study provides actionable insights to maximize agricultural output while conserving water resources. This strategic approach ensures that irrigation efforts are targeted where they can yield the most significant benefits, fostering sustainable agricultural development. The findings from our study highlight the sustainability of different irrigation methods across various soil types: Drip Irrigation generally exhibits high sustainability across multiple soil types, making it a favorable choice for soils with diverse textures and compositions. It ensures efficient water delivery and uptake, particularly in Typic Hapludalfs and Vertic Haplcambids soils. Center Pivot irrigation demonstrates notable effectiveness across various soil types, especially in Typic Haplsalids and Typic Haplargids soils. However, its performance may vary depending on soil characteristics, necessitating careful consideration during implementation. Surface Irrigation consistently shows lower evaluation percentages compared to other methods, implying potential limitations, especially for soils with higher infiltration rates. While it may be suitable for certain soil types, it might not be the most efficient choice in all scenarios.

Despite encountering limitations due to the lack of published research on assigning weightage to different irrigation systems, the project provided an opportunity to innovate and develop a new approach. Despite the challenge, leveraging local expertise, experience, and considering contextual factors such as soil type, evapotranspiration (ET), and cost proved crucial in determining the most suitable irrigation system for specific areas. The key aspect of this approach is its applicability across various locations, relying on their unique soil characteristics and local conditions. Moreover, it can be adapted to any area with the capability to be adjustable according to changing requirements and circumstances.

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