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Evaluation of Long Furrow Field Irrigation in Rahad Agricultural Corporation, Sudan

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ABSTRACT

Due to the near-depletion of Sudan's shared Nile water resources, expanding irrigated agriculture requires optimizing and implementing water-saving measures within existing irrigation networks. This study monitored and evaluated the performance of a long-furrow surface irrigation system within the Rahad Agricultural Corporation. To ensure repeatability, field data, including inflow rates via siphons, advance recession times at 20-meter stations, and infiltration using the blocked furrow method, were collected from three randomized furrows over six irrigations and analyzed in Excel to compute performance indicators (Ea, Es, DP RO, CU) and water productivity. Observations revealed that the furrows lost their original parabolic shape, becoming deeper at the head and flatter at the tail area. Measured discharges ranged from 3.9 to 5.27 lps, with advance and recession times being significantly longer during the first irrigation due to soil dryness and recent tillage. The application efficiency ranged from 58% to 72% (mean 65%), with the majority of losses occurring as surface runoff (26%-39%, mean 33%). Deep percolation was minimal, averaging less than 2%, which is typical of surface irrigation performance on clay soils. While storage efficiency (86% - 97%) and uniformity coefficients (84% - 94%) remained acceptable, land productivity was only 10% of research potential, resulting in a low water productivity of 0.083 kg/m³. System performance can be enhanced by implementing measures to reduce runoff, such as cutback or surge irrigation, furrow bunds, and tailwater reuse.

1. INTRODUCTION

The water demand is rapidly increasing due to population growth, escalating food demands, and dwindling per capita water supplies. Consequently, nations—particularly developing agricultural economies—must optimize water resources, implement efficient application methods to increase crop yields, and minimize irrigation losses. In Africa, Sudan possesses the third-largest irrigated area, with approximately 1.3 million hectares irrigated from the Blue Nile alone. The agricultural sector serves as the backbone of Sudan's economy, with the majority of the population directly or indirectly dependent on the income and employment generated by farming.

However, reports from the Ministry of Irrigation and Water Resources (MOIWR) warn of severe water scarcity in Sudan by 2030. Addressing this impending crisis requires maximizing crop yield per unit of water, an objective that cannot be achieved without regular, field-level evaluations of existing large-scale irrigation systems.

While substantial literature exists on the macro-level hydraulics of the Blue Nile and main canal delivery systems in Sudan, there is a critical shortage of empirical, field-level performance evaluations for localized surface irrigation practices within the major schemes. Specifically, Vertisols (Black Cotton Soils), which characterize the central clay plains, exhibit heavy cracking and high initial infiltration rates that drastically alter furrow geometries, advance times, and tailwater runoff during consecutive irrigation cycles.

Previous studies in similar arid environments (Yitayew, et al., 1985), Heermann and Solomon (2007), Kannan & Abate, (2015), Oprescu et al., (2023) and HAMID et al., (2009) have established that furrow topography and soil hydraulic properties heavily dictate application uniformity (CU) and efficiency (Ea). However, the exact field performance, operational losses, and water productivity of the long-furrow system under standard farmer management in the Rahad Agricultural Corporation remain unstudied and unmonitored.

Without field-validated parameters such as explicit furrow infiltration functions, cut-off times, and inflow thresholds, it is impossible to design actionable water-saving strategies, such as surge irrigation or cutback systems, to curb the heavy runoff typical of these open-ended networks. This study addresses this exact gap by conducting rigorous, real-time monitoring of long-furrow field irrigation in the Rahad Agricultural Corporation to establish baseline performance indicators and practical optimization pathways.

While substantial literature focus has been dedicated to macro-level canal water distribution networks in Sudan's major agricultural schemes (Gamri and Elkhidir (2025), Ibrahim, et al., (2023), El Gamri, and Elkhidir, (2025), and Elkreem and Jaspars (2025), empirical, field-level performance evaluations of long-furrow irrigation on heavy vertosols remain critically scarce. The novelty of this work lies in the real-time, high-resolution monitoring of localized field hydraulics—specifically capturing how open-ended long furrows deform structurally over a season under standard farmer management, and evaluating the cascading impacts of these deformations on infiltration opportunity time, tailwater runoff, and overall crop water productivity. This provides field-validated baseline data that has historically been omitted from macro-level national water management strategies.

This research hypothesized that under conventional bi-weekly rotational irrigation scheduling, open-ended long furrows on heavy clay soils experience significant structural degradation (head scouring and tail siltation). This deformation alters advance and recession rates over consecutive irrigation cycles, leading to high field tailwater runoff losses and low crop water productivity, despite acceptable application uniformity and storage efficiencies. Therefore, this research is designed to answer the following questions

1. To monitor and quantify the seasonal changes in furrow cross-sectional geometry from the head to the tail of the field.
2. To determine the empirical infiltration function constants for the first and subsequent irrigation cycles on central clay Plain vertisols using the blocked furrow method.
3. To evaluate field-level surface irrigation performance indicators, specifically application efficiency, storage efficiency, deep percolation, runoff losses, and the uniformity coefficient
4. To assess current crop land productivity and water productivity for sunflower seeds under existing farmer management practices.
5. To propose actionable field management interventions (such as cutback irrigation, surge irrigation, or tailwater reuse) to optimize water-saving potential in the Rahad Agricultural Corporation.

2. MATERIALS AND METHODS

The study area

The Rahad Agricultural Corporation is a major public irrigation network located south-east of Wad Medani town in east-central Sudan. It is situated on the eastern bank of the Rahad River and commands a total administrative area of approximately 150,000 hectares. Geographically, the scheme extends between latitudes 13° 30" and 14° 23" north, spanning 140 km from south to north and 15 to 25 km from east to west. The region is bioclimatically classified as arid to semi-arid, featuring heavy, cracking alkaline vertisols (Black Cotton Soils) with clay contents exceeding 60% (Meheissi, 2017).

Due to the highly seasonal flow of the Rahad River, irrigation water supply relies on a dual-source framework: gravity diversion during the flood season and high-capacity electrical pumping stations on the Blue Nile at Meina to meet crop demands when the Rahad River flow declines. The delivery network is structurally organized into a hierarchical conveyance system starting from the main canal, branching down to major canals, minor canals, and finally to a common field ditch locally termed an '*abuishreen*'.

The specific field experiment was executed at Field Section 44, *abuishreen* 4, off Minor Canal 21. To evaluate the localized hydraulics of open-ended long furrows on heavy clay plains, three test furrows separated by non-experimental buffer furrows were randomly selected and consistently monitored across six sequential irrigations. The experimental block was cultivated with sunflower (Helianthus annuus L.), which has emerged as an increasingly vital oilseed crop within the rotational crop intensive strategies of Sudan's irrigated agricultural sector (Faridi, et al 2020)

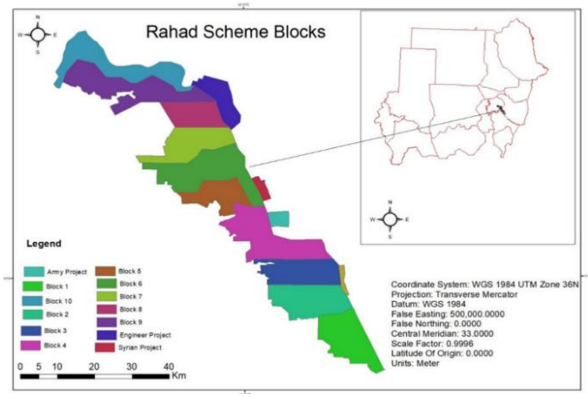

Figure1. Rahad Agricultural Corporation, Sudan

Characterization of experimental soil, crop, and field conditions

The experimental field block is situated on the expansive Central Clay Plains of Sudan, characterized taxonomically as heavy, cracking, alkaline vertisols (locally designated as 'black cotton soils'). Soil core samples were collected from the experimental plot at incremental root-zone depths (0–30\ cm, 30–60\cm, and 60–90\cm) to determine baseline physical properties:

The soil matrix exhibits extreme structural homogeneity, with a dominant clay fraction exceeding 60%, a silt fraction of approximately 28%, and a sand fraction of under 12%, classifying texturally as a heavy clay soil.

The average dry bulk density within the upper tilled layer (0–30/ cm) was measured at 1.25g/cm3, rising to 1.42g/cm3 in the lower subsoil profiles due to natural overburden compaction.

The mean field capacity was determined to be 42.0% on a dry weight basis, while the permanent wilting point averaged 22.0%, establishing a total available water capacity of approximately 20.0% (200mm/m of root depth).

The saturated hydraulic conductivity is low, averaging 0.15cm/hr (0.0025cm/min). This confirms a highly impermeable boundary layer once the soil matrix hydrates and swells.

The irrigation layout evaluated represents the standard macro-block structural configuration implemented by the Rahad Agricultural Corporation:

The experimental plot consisted of open-ended, long furrows featuring an engineered length of 270 meters and a uniform center-to-center baseline spacing of 0.80 meters. The initial tilled furrow profile was uniformly parabolic, with a nominal design depth of 0.25 meters.

The macro-topography of the field block features an average longitudinal slope of 0.05 (0.0005 cm/m), reflecting a nearly flat, precision-graded plain designed to facilitate uniform, slow-velocity advance phases along extended runs.

The experimental block was cultivated with a commercial sunflower hybrid (*Helianthus annuus L.*). High-resolution hydraulic monitoring commenced at the early vegetative growth stage (approximately 20 days after emergence) and concluded during the late flowering and seed-formation phases, capturing the dynamic changes in crop canopy cover, root elongation, and furrow surface roughness.

The field operated under the conventional, rigid administrative rotation of the scheme, dictating a nominal bi-weekly (14-day) irrigation interval. Water application was performed manually using siphons drawing from the common field ditch (*abuishreen*), with the total depth and cut-off times dictated by the farmer's visual assessment of advance front completion at the tail end.

Experimental design

The field experiment was conducted using a randomized block layout consisting of three designated test furrows across six sequential irrigation events. The selection of three experimental furrows was carefully evaluated and justified based on the deep, heavy, cracking alkaline vertisols consisting of a uniform clay fraction exceeding 60%. These central clay plains are highly contiguous texturally, exhibiting minimal spatial micro-variability in texture, bulk density, and baseline topography within a single *abuishreen* (field ditch) command area. In accordance with established surface irrigation evaluation methodologies, monitoring a triad of adjacent, representative furrows (isolated by non-experimental buffer furrows) is the recommended benchmark for diagnostic field audits. This layout effectively isolates the center furrow from lateral subsurface wetting interference while capturing typical operational inflow variations from the head ditch. Real time data collection during an active irrigation cycle requires simultaneous, high-frequency measurements of siphon discharges, advance rates across 20-meter intervals, recession fronts, and blocked-furrow infiltration depths. Limiting the intensive monitoring to three test furrows ensured data precision and prevented human error

Inflow Measurement:

Three-inch inner diameter siphon tubes are used to irrigate the field. Each furrow has a dedicated siphon drawing water from Abuishreen (head ditch) into the head of that furrow. To measure the flow rate (Q), the head difference between the siphon outlet and the water surface in the common ditch is measured. The flow rate, Q (lps), is obtained from the multiplication of a coefficient, the cross-sectional area and the velocity, which is obtained from the head difference.

$$Q = 650\,\pi\,R^2\sqrt{2\,g\,\Delta h} \qquad (1)$$

Where R is the radius of the siphon and Δh is the head difference, both in meters.

Infiltration Measurement:

Soil infiltration plays an important role in irrigation design, management, and selection of irrigation methods. The cylinder infiltrometer and ponding methods for measuring infiltration do not simulate the geometric conditions in a furrow. Infiltration from a furrow occurs around the wetted perimeter, which means that a significant portion of the total infiltration moves laterally through the furrow sides rather than vertically downward (Criddle et al., 1956). Recognizing this problem, the blocked furrow method is used. The infiltrometer consists of float valve, a reservoir, and a water stage recorder using a metal container. Two plates are used to isolate one meter length of the furrow. A plastic membrane is used to cover this length. A hook gauge is placed on one plate to keep the water surface elevation constant. The volume in a container of known dimensions is registered. The test begins with the release of water in furrow by pulling the plastic membrane from underneath the water. Thereafter, the water level in the furrow is kept constant by releasing water from the container and registering the drop of water in the container with time. Although there are several expressions for the infiltration function (Shirini and Raghuwanshi, 1999) the Kostiakov-Lewis infiltration equation is selected because of its simplicity and the way its variables are determined (Jensen, 1983).

$$Z = K\,t^a + Ct \qquad (2)$$

The parameters (C, K and a) are determined from the field test. The constant C is the infiltration rate after prolonged test. The other two values are determined by plotting Z-Ct against time on a log-log paper and fitting a power function.

Advance Phase:

Distance marked wooden stakes are driven along the test furrow to measure the rate at which the advancing front moves along a surface-irrigated long furrow field. The spacing of these stakes is 20 m to provide a sufficient number of measuring points. The clock time is recorded when the irrigation water is diverted into the field (first stake or station) and time to reach each station was registered.

Depletion Phase:

The depletion phase begins at the time of cutoff, after which the ponded water surface elevation declines and it is recorded periodically. The depletion phase ends when any portion of the ground surface is bare of water (Jensen, 1983).

Recession Phase:

The recession phase starts when surface water disappears at each measuring station. The time difference at each station between the advance and recession is the opportunity time for infiltration to occur (Walker 2003).

Required water (D_{req}):

The design of irrigated projects in the central clay plains of Sudan is based upon application of 20 cm for the first irrigation and 10 cm for subsequent irrigations. Danny (1995) states that the correct amount of water to apply at each irrigation depends on the amount of soil water used by the plants between irrigations, the water holding capacity of the soil and the depth of the crop roots (stage of growth). The rate at which water goes into the soil varies from one irrigation to the next and from season to season. The first irrigation requires more water as the soil profile is dry and freshly tilled. In general, it is recommended to apply water when the crop has used about one half of the readily available water in the root zone. Determination of the total amount of water applied will help determine whether the irrigation was adequate and when the next irrigation should commence. Irrigation management decisions should be made based on the amount of water applied and how this relates to the consumptive use considering demands of the plants and the soil water holding capacity.

Application efficiency:

Among the factors used to judge the performance of an irrigation system or its management, the most common are application efficiency (**E_a**), storage efficiency (**E_s**) and uniformity coefficient (**CU**). These parameters have been subdivided and defined in a multitude of ways (Jensen, 1983; Walker, 2003; Eldeiry et al., 2004). Application efficiency is the ratio of the volume of irrigation water stored in the root zone (V_{rz}) and available for crop use (evapotranspiration) to the volume delivered from the irrigation system (V_a). This ratio is always less than 1.0 because of losses due to evaporation, wind drift, deep percolation, lateral seepage (interflow) and runoff, which may occur during irrigation. It is calculated using the following equation:

$$E_a = V_{rZ} \,/\, V_a \qquad (3)$$

To compute the applied depth of irrigation, it is necessary to identify the amount of water required in the root zone. This implies that the moisture content before and after irrigation must be determined. The farmer irrigates on fixed interval of 14 days; therefore, the difference of soil moisture will render the expected amount of depletion from the soil profile.

Storage Efficiency:

There is no one single parameter that adequately defines irrigation performance. Conceptually the storage efficiency (E_s) is the rate of satisfying the required amount of irrigation water (D_{req}). It can be determined from the equation:

$$E_s = V_{rZ}/D_{req} \qquad (4)$$

Field Losses:

Field losses are divided into losses which occur as deep percolation (DP) below the root (V_{dp}, excess depth greater than D_{req}) and losses occurring as surface runoff (RO) or tailwater (V_{ro}**).** DP is the ratio of water that goes deeper into the soil below the roots of the crop being irrigated to the total applied water. This water then becomes unavailable and useless to the crop. Large deep percolation losses occur where the soil is gravelly or sandy and when water is stagnant for prolonged time. Surface runoff occurs at the lower end of the furrow. It usually happens when the water which is not yet absorbed into the soil runs off either intentionally or inadvertently. When using the open-ended furrow system, runoff is actually expected. This is because in many cases no runoff means that an insufficient amount of water was applied at the furrow end.

$$DP = V_{dp}/V_a \qquad (5)$$

$$RO = V_{ro}/V_a \qquad (6)$$

Uniformity Coefficient (CU):

Under surface irrigation systems, water is distributed by gravity flow over the soil surface. The uniformity of water application (CU) is strongly dependent on the surface topography and the soil hydraulic properties. The growers must use precision land grading practices to minimize the effects of topography. However, soil characteristics and irrigation management may lead to uneven infiltration opportunity time along the field and hence deviation of infiltrated depth from the mean. CU is a measure of deviation of infiltrated depth at each station, z_i, from the mean z_{mean} (Michael, 1978).

$$CU = 100\left(1.0 - \frac{\sum_1^n |Z - Z_{mean}|}{n\, Z_{mean}}\right) \qquad (7)$$

Where n is the number of stations.

Reviews are comprehensive, critical descriptions on the present knowledge of actual research subjects or technological developments. The division is left to the author(s); otherwise the explanations under 2.2 are valid. Reviews are frequently submitted on invitation; however they are of course accepted from other authors too. The term "A review" should be added below the title.

3. Data Analysis:

The raw hydraulic parameters and field monitoring observations collected during each irrigation event were compiled and processed using Microsoft Excel. To provide a rigorous evaluation and allow for accurate statistical comparison across the six seasonal irrigation events, the data analysis framework was structured as follows:

The parameters of the Kostiakov-Lewis infiltration function, specifically the intercept constant (K) and the dimensionless exponent (a), were determined by applying a log-log power-function regression model. For each irrigation cycle, the cumulative infiltrated volume depth minus the steady-state term (Z−Ct) was plotted against time (t) on a logarithmic scale. Linear least-squares regression was then executed on the transformed log-data to fit the power curve and compute the empirical coefficients, establishing distinct infiltration equations for both the first and subsequent irrigations.

Built-in algebraic models were developed within Excel to evaluate standard surface irrigation performance efficiencies using equations (3) through (7). These equations quantified application efficiency (E a), deep percolation percentage (DP), surface runoff percentage (RO), storage efficiency (E s), and Christiansen's uniformity coefficient (CU) for every stations across the 270-meter test furrows.

Due to the deterministic nature of furrow-by-furrow hydraulic tracking, a descriptive statistical analysis framework was used to compare irrigation performance across the season. For each performance criterion, the seasonal trend was evaluated by calculating the arithmetic mean (μ) to establish baseline operational benchmarks, alongside the mean absolute deviation (MAD) to quantify the operational variability and stability of the irrigation performance under routine farmer management.

4. RESULTS AND DISCUSSION

Summary

The evaluation of standard performance indicators demonstrated a stark imbalance between application uniformity and operational efficiency across the season: The seasonal average Ea was low at 65.03% (ranging from 58.29% to 72.07%). This performance is highly typical of unmanaged surface irrigation practices on clay fields in Sudan, mirroring baseline values reported by Abdel Wahab (1996).

The primary path of water depreciation was surface runoff, which averaged a massive 32.58% of total applied volumes (peaking at 38.74% in irrigation 5). Under standard farmer management, open-ended furrows are kept flowing continuously to ensure water reaches the lower ends of the field, sacrificing water efficiency to meet required root-zone depths. This excess tailwater is structurally utilized downstream by unauthorized vegetable growers using localized pumps, proving that while on-farm efficiency is poor, regional water reuse occurs informally.

Conversely, deep percolation losses were negligible, averaging a mere 2.39%. This tightly validates irrigation models developed by Eldeiry et al. (2004), which establish that heavy, fine-textured clay plains form a nearly impermeable boundary layer once initial cracks are sealed, virtually eliminating downward seepage losses.

Despite poor application efficiencies, Christiansen's uniformity and storage efficiency remained high, averaging 91.20% and 94.81%, respectively. The lowest uniformity occurred during the first irrigation (83.54%) due to severe discrepancies in intake opportunity times over the newly tilled soil profile.

A critical finding of this study is the extreme disconnect between hydraulic distribution and crop performance. To sustain the sunflower crop across six cycles, a substantial seasonal depth of 9,778m3/Ha was delivered. However, this high water consumption yielded a meager 833 kg/ha of seed mass.

This result is a low water productivity index of only 0.085kg/m^3. According to crop benchmarks established by Salah and Abdel Wahab (2013), regional land productivity for irrigated sunflowers ranges between 0.8 to 1.5 tons/ha, against a controlled research potential of 3.5 tons/ha. The field evaluated in the Rahad Agricultural Corporation operated at the bare minimum of this regional standard, achieving just 10% of its true biological research potential.

This low productivity proves that the farmer's rigid, unmonitored bi-weekly irrigation scheduling, which changes siphon counts haphazardly without assessing actual soil moisture depletion or crop growth stages, induces prolonged crop water-stress and heavy tailwater losses. Raising water productivity from 0.085kg/m3 requires shifting away from open-ended continuous flows toward precision cutback stream management, surge irrigation protocols, or localized tailwater collection and reuse systems.

Inflow:

The farmer added irrigation water without observing the real need of the plant to water at each irrigation. Water is rotated among farmers on bi-weekly basis. Results show that the inflow ranged from 3.9 to about 5.3 liter/sec (lps) as shown in Table (1). A study conducted by Onishi, et al., (2019) indicates that shortening furrow length might be an effective way to save water with a low inflow rate, and in contrast, that it is necessary to extend furrow length with a high inflow rate. Fluctuation of discharge is due to change of head difference between the supply ditch and the field; however, the fluctuation was small after the first irrigation. The first irrigation demanded more water due to the dry soil profile and resulted in slow advance phase due to the newly tilled soil. The farmer used two syphons after the first irrigation, perhaps to mitigate the long advance time. The discharge was not doubled due to the fall of the water level in the supply ditch as users increased during subsequent irrigations. The number of pipes and irrigation number has a significant impact on how fast the water advanced along the field and the amount of water being applied. Without knowing the amount of water being applied, it is difficult to make decisions on when to stop irrigating or when to irrigate next.

Table (1): Inflow characteristics.

Irrigation No.	Mean inflow (lps)	inflow time (min)	Inflow Volume (m^3)
1	3.91	430	100.88
2	5.13	203	62.48
3	5.21	174	54.39
4	5.15	180	55.62
5	5.27	210	66.40
6	5.13	215	66.18

Infiltration Function:

The rate at which soil will absorb water varies with time. At first, water will penetrate rapidly into the soil but as time progresses, it will decrease to a rate which stays relatively constant. Figure (2) illustrates (Z-Ct) versus time for the first and subsequent irrigations. The test results are shown in equation (8). The Parameter C of the Kostiakov-Lewis equation was estimated from the test as the minimum rate of infiltration. Although the soil is tilled before the first irrigation, the initial infiltration is greater for subsequent irrigations; perhaps due to the cracks which are a feature of the Black Cotton Soils of the Central Clay Plains of Sudan. The slope of the second curve is smaller; indicating that most of the infiltration is due to the constant infiltration rate and the contribution of the first term became quickly insignificant as cracks are sealed. The constant infiltration rate is a characteristic of the soil; however, it was higher for the first irrigation due to the influence of the soil tillage. Reza et al., (2021) states that the temporal variability resulted in a significant reduction in application efficiency and distribution uniformity.

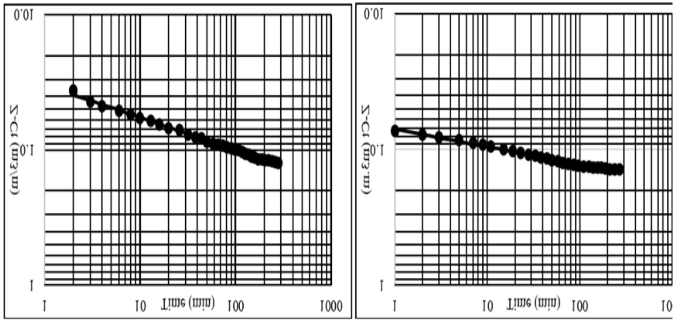

Figure (2): Infiltration for the first (left) and subsequent irrigations.

$$Z = 0.033\ t^{o.34} + 0.00015\,t\ (firt\ irrig,)$$

$$Z = 0.07\,t^{0.13} + 0.00013\,t \quad (8)$$

Advance, Recession and Infiltrated Volume:

The results for each irrigation are the mean for three test furrows during six irrigations. The advance in the first irrigation is longer than the others because the field was dry, ploughed and newly sown. Advance time depends on soil infiltration characteristics, roughness of the soil surface, inflow rate, furrow slope and shape.. The advance for the next five irrigations was lower. Recession took longer time for the first irrigation due to the large amount of water added to the field as it took more than two hours especially at the middle because of depressions formed there. Recession is difficult to observe for the lack of clear front. Figure (3) shows the advance and recession for all irrigations as well as the consequent applied volume at every station. The difference between recession and advance represents the infiltration opportunity time (t_{op}). The value is greater for the field head. The value of t_{op} was used to calculate the applied volume at each station. The dotted horizontal line represents the required volume per unit length. The value is obtained by multiplying the irrigation depth by 1.5 m which is the spacing of furrows. Excess water below this line represents deep percolation while deficit is the amount between the line and the tip of the infiltrated volume above it at that station.

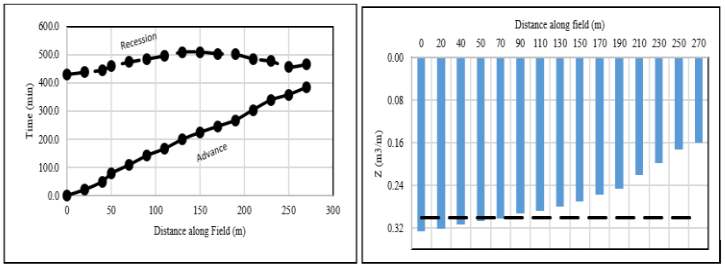

Figure (3): First irrigation advance recession, infiltrated and required volume.

Deep percolation occurred at few stations at the head while runoff was high as a large part of the furrow has reached the constant infiltration rate. Moreover, the distribution of water over the field was not similar. Figures (4) to (8) show the advance, recession, infiltrated and required volume for the subsequent irrigations. The distribution of infiltrated volume is different from that of the first irrigation, however, there is clear similarity between these irrigations.

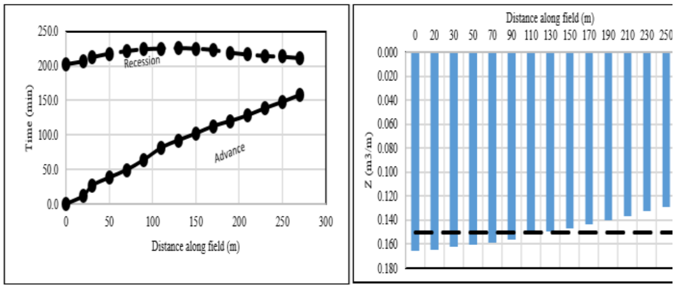

Figure (4): Second irrigation advance recession, infiltrated and required volume.

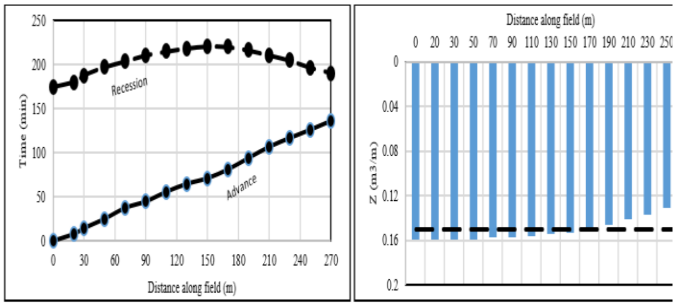

Figure (5): Third irrigation advance recession, infiltrated and required volume.

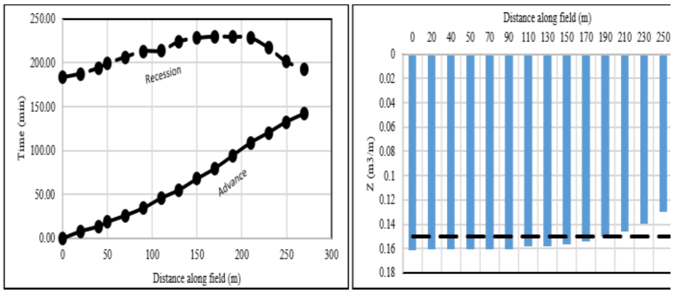

Figure (6): Fourth irrigation advance recession, infiltrated and required volume.

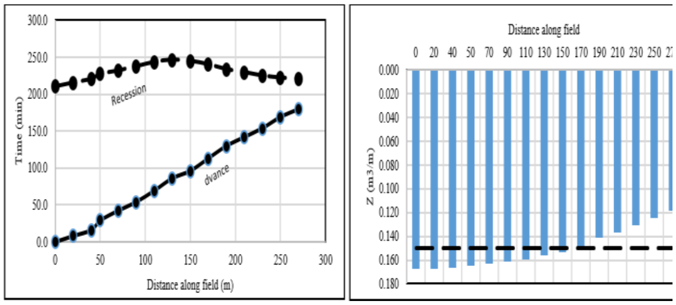

Figure (7): Fifth irrigation advance recession, infiltrated and required volume.

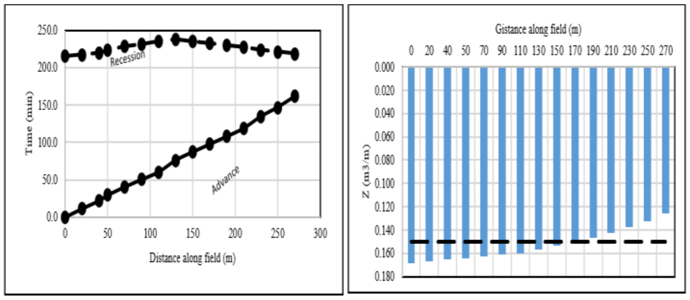

Figure (8): Sixth irrigation advance recession, infiltrated and required volume.

Performance Indicators:

Several criteria are used collectively to indicate the performance of an irrigation event. Irrigation efficiency is a measure of the effectiveness of an irrigation system to deliver the desired amount of water evenly over the whole field with minimum losses. Accordingly; the efficiency has the indicators expressed in the previous section and Table (2). Perhaps, the most used indicator is the application efficiency, E_a. It ranges from about 70.1% to 58.3% with an average of about 65% and a mean deviation of 5.08% for the season. The mean E_a value is typical value for surface irrigation (Abdel Wahab, 1996) and requires improvement. Components of improvement are inflow rate, advance time and cutoff time. This combination should be managed to produce a better application efficiency. Possible practices are cutback irrigation, surge irrigation and cutoff before the advance reaches the end of the field. Although application efficiency is the ratio of the useful part of irrigation water to the total amount, it also produces the combined share of losses for the irrigation. Major losses of surface irrigation are deep percolation (DP) and surface runoff (RO). Deep percolation varied from 1.2% to about 3% with an average of about 2.4% and a mean deviation of 0.55%. It is expected for clay soil to produce limited deep percolation. Runoff loss was large as it ranged from 25.7% to 38.7% with an average of 32.6% and a mean deviation of 4.82%. The endeavor to supply the desired depth resulted in a large runoff which should be addressed by measures such as inserting low dikes across the furrows or any of the measures used to improve the application efficiency. Observation of the general area showed the presence of flowing drains upon which several vegetable growers have installed pumps and actively growing bumper crops on the runoff water; a practice not sanctioned by the management though improves the overall water use efficiency. Another critical criterion is the storage efficiency which ranged from 86.4 % to 97.3% with a mean of about 95% and a mean deviation of 2.82%. The poorest result was for the first irrigation while the values for subsequent irrigations were above 90%. Farmers would like to distribute water evenly over the area of the field. The uniformity coefficient ranged from 83.5% for the first irrigation to 93.8% with an average of 91.2 and a mean deviation of 2.68%. The low uniformity of the first irrigation was mainly due to the large range of the intake opportunity time.

The field evaluation revealed an application efficiency ranging from 58.29% to 72.07%, with a seasonal average of 65.03%. To evaluate the relative performance of the Rahad Scheme's long-furrow system, these values were benchmarked against similar surface irrigation studies conducted locally in Sudan and across other global arid regions. Our observed mean 65% closely aligns with historical studies conducted in Sudan’s large-scale public irrigation sectors. In Gezira Scheme, where heavy vertisols and open-ended field ditches (*Abuishreen*), multiple evaluations (Adam et al., 2017; Hamid, S. O., 2024) reported on-farm application efficiencies for traditional surface irrigation ranging between 55% and 68%. Similarly, investigations in the New Halfa Agricultural Scheme yielded average efficiencies of 60% to 63% under conventional siphon management. The marginal efficiency advantage observed in the Rahad Scheme (72% peak in later irrigations) can be attributed to the engineered 270-meter-long furrow layout.

On an international level, an average application efficiency falls within standard performance intervals for unmanaged, continuous-flow surface irrigation systems operating on heavy clay plains (Acar, 2019; Roldan-Canas et al., 2021; Singh et al., 2024).

Table (2): Summary of performance indicators for all irrigations

Irrigation No.	Performance Criteria (%)				
	Appl. Eff., Ea	PDP	PRO	Storage Eff., Es	Uniformity, CU
1	69.38	1.22	29.41	86.36	83.54
2	62.15	2.04	35.81	95.68	92.41
3	72.07	2.24	25.69	96.89	93.84
4	68.90	2.91	28.18	97.29	93.74
5	58.29	2.98	38.74	95.55	90.80
6	59.41	2.93	37.66	97.11	92.84
Mean	65.03	2.39	32.58	94.81	91.20

Water Productivity:

The crop needed six irrigations with a total amount of 9778 m^3/hectare. The yield was about 833 kg/hectare. The water productivity was found to be about 11.7 m^3/kg or 0.085 kg/m^3. The land productivity of sunflower in the irrigated sector of Sudan ranged from 0.8 ton/ha to 1.5 ton/ha with a research potential of 3.5 ton/ha (Salah and Abdel Wahab, 2013). The current land productivity is about the minimum of the range.

Validation of infiltration

The statistical outputs for both the initial and subsequent irrigation cycles are summarized in Table 3. The goodness-of-fit metrics indicate high correlation between the field-measured cumulative infiltration depths and the values predicted by the regression. For the first irrigation, the R2 demonstrates that the model accounts for approximately 95% of the total variance in soil water intake during the initial wetting phase on freshly tilled soil.

For subsequent irrigations, the goodness-of-fit is even stronger. This statistical precision confirms that the log-log linear transformation accurately captures the rapid, early-stage intake typical of macro-cracked clay vertisols, as well as the stable baseline basic infiltration phase that governs the system after soil swelling seals the soil matrix. These statistics verify that the presented equations are highly reliable for future hydraulic modeling, simulation, and predictive design applications within the Rahad Agricultural Corporation.

Table 3: Goodness of fit for the furrow infiltration

Irrigation Category	Z	R^2	RMSE (m3/m)
First Irrigation	$Z = 0.033\ t^{0.34} + 0.00015\ t$	0.948	0.0031
Subsequent Irrigations	$Z = 0.070\ t^{0.13} + 0.00013\ t$	0.972	0.0019

5. Implications of the Study

The empirical findings of this study carry profound operational, economic, and institutional implications for the management of the Rahad Agricultural Scheme and the broader strategic planning of irrigated agriculture in Sudan. The discovery that surface runoff constitutes the majority of water depreciation, while deep percolation remains negligible,, completely shifts the operational focus required for system optimization. On heavy, fine-textured vertisols, conventional assumptions regarding downward seepage losses do not apply once the initial macro-cracks swell and self-seal. Therefore, field management protocols must focus entirely on surface tailwater control rather than root-zone seepage mitigation.

Furthermore, the dynamic structural deformation of the furrows implies that uniform siphon discharges across the entire irrigation event are hydraulically incompatible with the field's changing geometry. Maintaining a constant inflow rate guarantees severe tailwater losses because the scoured head accelerates advance times, while the silted tail delays water advance and increases stagnation or runoff.

The contrast between the massive volume of water delivered and the poor seed yield highlights a critical water-productivity paradox. Operating at a mere 10% of the crop's biological research potential demonstrates that current water distribution is highly inefficient.

For the farmer, this inefficiency translates directly into depressed economic returns, low land productivity, and unnecessary labor costs associated with extended siphon monitoring. Haphazardly altering siphon counts without assessing soil moisture depletion or specific crop growth stages indicates that the rigid, calendar-based bi-weekly rotation is actively inflicting moisture stress on the crop, likely through alternating phases of prolonged waterlogging (due to poor drainage and tailwater stagnation) and severe drying.

Field managers should introduce a simplified cutback irrigation technique. Farmers can use two siphons per furrow during the initial advance phase to push water rapidly to the tail end, minimizing the discrepancy in intake opportunity time. Once the advance front reaches the 270-meter mark, one siphon must be removed or throttled. The Rahad Agricultural Corporation should transition from administrative scheduling to a demand-driven framework utilizing simple soil-moisture indicators. Extension services can equip farmers with manual soil augers or basic tensiometers to monitor the root zone. Because heavy vertisols exhibit deep macro-cracking when drying, the emergence of surface cracks wider than 1–2 cm should serve as a clear visual trigger for scheduling the next irrigation event, rather than relying on a strict bi-weekly interval.

6. Conclusion and recommendations

This study evaluated the field-level hydraulic performance of an open-ended long-furrow irrigation system under standard farmer management in the Rahad Agricultural Corporation. The investigation revealed several critical insights: Open-ended long furrows undergo significant morphological changes across a season, scouring deeply at the head and silting up at the tail end. Due to the severe macro-cracking characteristics of central Sudan's heavy vertisols (clay soils), soil infiltration rates are paradoxically higher during subsequent irrigations than the initial cycle, dropping sharply only after the clay swells and self-seals. While the system achieves high storage efficiency (95%) and application uniformity (91%), it suffers from low application efficiency (65%). This is primarily driven by massive tailwater runoff losses averaging 33%, while deep percolation remains negligible (2%). A critical disconnect exists between water delivered and crop yield. The sunflower crop consumed a substantial seasonal depth of 9,778 m^3/ha but yielded only 833 kg/ha. This represents just 10% of the crop's biological research potential and results in an exceptionally low water productivity index . Ultimately, the conventional, unmonitored bi-weekly irrigation scheduling used by local farmers sacrifices large volumes of water to runoff to achieve adequate root-zone wetting at the lower end of the field. This research recommends implementing cutback irrigation (reducing the siphon inflow rate once the water front reaches the end of the furrow) or surge irrigation (intermittent, pulsed water applications) to drastically reduce the 33% tailwater runoff loss and prevent head scouring. It also recommends introducing temporary blocks or dikes at the tail end of the furrows to convert the open-ended network into a semi-closed system, trapping water and increasing infiltration opportunity time at the lower end without relying on continuous over-irrigation. Farmers should adjust siphon operation times based on real-time soil moisture depletion and specific crop growth stages rather than uniform intervals.

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